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THE SOILING OF MATERIALS IN URBAN AREAS

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LIST OF ABBREVIATIONS

a e d	aerodynamic equivalent diameter
BSI	British Standards Institution
BSS	British Standard Smoke
CBA	Cost Benefit Analysis
DERV	Diesel Engine Road Vehicle
EPA	Environmental Protection Agency
GLC	Greater London Council
GNP	Gross National Product
HGV	Heavy Goods Vehicle
Hi-Vol	High Volume
HVS	High Volume Sampling
LA	Local Authorities
m.p.g.	miles per gallon
NAAQS	National Ambient Air Quality Standards
NSCA	National Society for Clean Air
OECD	Organisation for Economic Cooperation and Development
nitro-PAH	Nitro-polycyclic Aromatic Hydrocarbons
PANH	Nitrogen containing Polycyclic Aromatic Hydrocarbons
PASH	Sulphur containing Polycyclic Aromatic Hydrocarbons
PEC	Particulate Elemental Carbon
PM_{10}	Particulate Matter less than 10 μm in diameter
PSA	Property Service Agency
SEF	Solvent Extractable Fraction
SEM	Scanning Electron Microscopy
SOF	Solvent Organic Fraction
TOE	Total Organic Extract
TSP	Total Suspended Particulates
TPM	Total Particulate Mass

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ABSTRACT

This thesis considers the sources of airborne particulate matter and dark smoke in the UK and its implication in the soiling of materials. The role of particulate elemental carbon receives special consideration. Results of emission inventories reveal that diesel emissions are responsible for 60% of dark smoke in urban areas and 25% on a national level. Particulate emissions have been identified as being largely responsible for the soiling of building fabric in urban areas. It is now being increasingly accepted that vehicle exhaust emissions make major contributions to this fabric soiling as well as to the deterioration of atmospheric quality within the urban environment.

Field work has been carried out at nine locations within metropolitan London, where a variety of materials was displayed. The materials' reflectance was measured at regular intervals together with pollution and meteorological conditions for a period of eighteen months. Soiling rates in the range of -0.02-4.5 yr^{-1} were recorded. Particulate samples were collected by a variety of methods and soiling rates were measured in a traffic tunnel to assess the rate of soiling in the absence of rainfall. Soiling rates of -0.5-0.8 yr^{-1} were recorded. Daily soiling rates for sheltered and exposed materials were measured in a third field study.

A cost-benefit analysis of the building soiling problem was also undertaken. The costings were achieved by a survey of UK stone cleaning companies to identify their turnover, market characteristics, mode and cleaning frequencies. The benefits were obtained by interviewing typical clients of the stone cleaning companies to ascertain the amount they spent per annum on stone cleaning and the benefits accrued as a result of cleaning.

CHAPTER ONE

INTRODUCTION AND OVERVIEW

1.1 Research Context

This thesis describes research carried out over a three year period (1985-1988) into several aspects of the soiling of materials in urban areas.

Primarily, the study was concerned with the measurement of soiling rates of certain materials in and around metropolitan London. Identification of the causes of current soiling were also examined using source emission data and inventories. This was complemented by a number of experimental fieldwork programmes, where soiling rates were measured for a variety of locations. A cost-benefit analysis of the current soiling of buildings for the United Kingdom was also undertaken.

As a research project, this study falls into several categories in relation to current research interests in the field of air pollution. The soiling of materials is one of the most obvious manifestations of air pollution, yet surprisingly there is a dearth of information in this field. This lack of information extends not only to quantitative baseline scientific data such as rates of soiling, but also in terms of definite causes, costs to the public and effects on the environment in general.

However, it has increasingly been recognised that the soiling process and its sources are aspects warranting closer scrutiny and research. Calls for further monitoring programmes and research into the soiling process have recently been made by, amongst others, the Royal Commission on Environmental Pollution in its Tenth Report (1984)(1) and the National Society for Clean Air's (NSCA) evidence to the House of Lords Select Committee on pollution from diesel vehicles (1987).(2) Thus, this research has been an initial attempt to develop methods by which soiling rates and their economic impact may be evaluated.

The main objectives of this research project have therefore been :

(i) to measure the rates of soiling for a range of materials at nine sites in and around metropolitan London;

(ii) to measure and model the rate of soiling by smoke deposition in a 'closed' environment - a road traffic tunnel - where the action of rainfall is absent;

(iii) to assess the role of rainfall in cleansing soiled materials as determined by data from a programme of daily measurements of soiling and rainfall in a suburban location;

(iv) to compare these experimental results for soiling rates with previous theoretical models for soiling;

(v) to investigate the main sources responsible for urban soiling using fuel source emission inventories and chemical analysis of deposited soiled material and airborne particulate matter at certain locations;

(vi) to identify the costs of building soiling as identified from (a) stone cleaning companies turnover and (b) the amounts spent during 1986/87 on this problem within the private and public sectors in the UK, together with their frequency and reasons for building cleaning.

(vii) to quantify the range, nature and allocation of benefits that might accrue from cleaning and control programmes which may alleviate the soiling process.

1.2 Thesis Content

This thesis consists of nine chapters of which this, the first, provides a context for the reasearch, as well as listing the principal objectives of the research and outlining the contents of the thesis.

Chapter Two investigates the sources of black smoke previously and currently experienced in urban areas. Both natural and anthropogenic sources of particulate matter are reviewed and their soiling potential assessed. Emission factors for black smoke production are given for different fuel sources so that an assessment of black smoke production for the entire UK can be deduced and compared with the sources and production of black smoke derived for a metropolitan city such as London. The method by which smoke levels are recorded for the UK is reviewed and compared with other methods used to record ambient particulate levels. Trends in smoke and black smoke production are reviewed over the period 1971 to 1986.

The third chapter assesses the chemical composition of airborne particulate matter and describes the carbonaceous component of such aerosols in terms of its physical and chemical properties. The atmospheric lifecycle of Particulate Elemental Carbon (PEC) is discussed with respect to soiling. The mass emitted and relative contribution of PEC from combustion sources in the UK during 1971 to 1986 have also been calculated and are discussed. Ambient levels of PEC are given for a variety of locations and situations and the other impacts of such emissions upon the general environment is briefly reviewed.

Chapter Four reviews previous experimental work on soiling rates and two of the existing theoretical models for estimating soiling rates are assessed in terms of the parameters used in their formulation. A generalised formulation for describing soiling rate in terms of a soiling potential is introduced. The nature of soiling in the ambient environment is considered as is the effect and role of rainfall on buildings; existing literature in this field is reviewed.

The fifth chapter introduces the method used in this project to determine soiling rates and discusses the results achieved for an experimental programme carried out in a road traffic tunnel where soiling rates for certain exposed materials were measured in the absence of rainfall.

The sixth chapter describes results for soiling rates obtained from a suburban roof top location where daily soiling measurements for sheltered and exposed materials and rainfall measurements were recorded. Results are given for soiling rates obtained from an eighteen month exposure period for a variety of materials exposed at nine sites on a transect originating from Central London to the perimeter of the green belt area of North London. Finally, predictions from the models for estimating soiling rates are compared with these experimental results.

Chapter Seven describes previous methods that have been used in attempting to assign costs to urban soiling. These techniques are assessed and the methods used in this research introduced. The results of a questionnaire, sent to identify stone cleaning companies market characteristics, are given and an estimate of stone soiling costs based on the market's turnover within the UK is reported.

The eighth chapter reviews the findings of the surveys undertaken to assess the costs currently experienced by building owners from the private and public sectors in the UK for stone cleaning. The possible nature and allocation of benefits resulting from building cleaning and control programmes are described. An initial cost-benefit analyis is presented.

The final ninth chapter summarises the major research findings and conclusions from this project and makes future research recommendations within these fields.

CHAPTER TWO

SMOKE IN THE UK ATMOSPHERE

2.1 Soiling and Airborne Particulate Matter Definitions

Air pollutants can affect materials through soiling or chemical deterioration. High smoke levels are associated with the soiling of clothing and structures. Acidic particles, especially those containing sulphur, can contribute to corrosion of materials such as electrical contacts, damage paint and textiles and erode masonry. The effect of exposure on cotton from the experimental programme described in Chapter Six is given in Appendix A.

An early and formidable indictment of the effects of air pollution on materials was voiced by John Evelyn in 1661 (3) in which he called attention to:
"horrid smoke which obscures our churches and makes our palaces look old, which fouls our clothes... with its black and tenacious quality, spots and contaminates whatever is exposed to it". It was only in 1984 when the American Environmental Protection Agency (EPA) Workshop on research strategies on the soiling of materials (4) defined soiling as "what is undone by cleaning".

Lodge(4) noted in the latter report that the term 'soiling' has been applied indiscriminately to two very different phenomena. The first of these and the one which truly deserves the name, is the permanent blackening of relatively light-coloured structures, clothing etc. on exposure to polluted atmosphere. The second, less deserving of the name is 'dustiness' which is probably the better term to describe the temporary settling of very coarse particles on to (predominantly) horizontal surfaces causing, at sufficiently high surface concentrations, a colour change and/or reflectance change (depending on colour and surface gloss). These definitions will be used hereafter in this discussion.

Amongst the constituents of the atmosphere, particulate matter is one of the most complex. Particulate pollutants are very diverse in character and cover a size range from 0.001 μm to 100 μm. Airborne particulate matter results not only from direct emissions of particles, be they from natural or anthropogenic sources; but also from emissions of certain gases that either directly condense as particles or undergo chemical transformations to a species that condenses as a particle.

The major proportion of the aerosol smaller than 2 μm in size generally emanate from anthropogenic sources, for example sulphates formed from the oxidation of sulphur dioxide and lead from vehicle exhausts using leaded petrol. Particles greater than 2 μm in diameter are mostly derived from natural sources such as wind-blown soil or sand and plant pollen. However, this classification should not be treated as a rigid one and will be discussed in more detail in Sections 2.2 and 2.3.

Figure 2.1. shows a widely used classification of the sizes of some atmospheric constituents. Particles less than 2 μm in diameter are generally referred to as "fine" whilst those greater than 2 μm are described as "coarse".

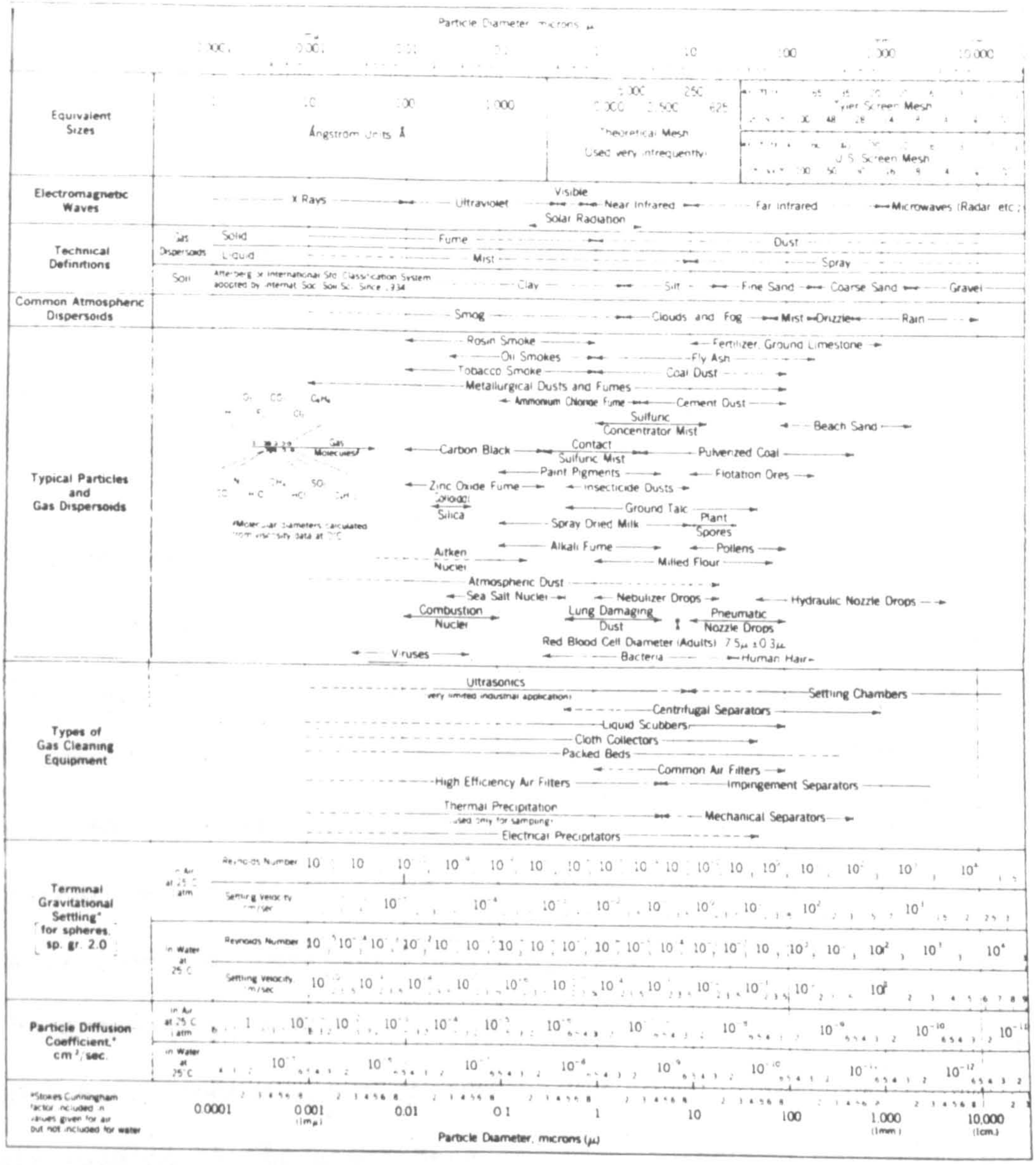


Figure 2.1 <u>Characteristics of particles and particle dispersoids</u>$^{(5)}$

It is worth noting that particles produced as a result of combustion processes have a size range between 0.01 and 0.1 μm. Some of the other terms given in Figure 2.1 will be explained in subsequent chapters. The sampling of particulates may be achieved either from suspension in the air using techniques such as filtration or impingement, or by the collection of deposited particles as they fall out of the atmosphere; this is known as dustfall. As is shown in Figure 2.1, the velocity at which particulate matter falls through the atmosphere under gravity is a function of particle size. A 10 μm particulate has a settling velocity of less than 1 cm sec^{-1} and consequently fine particulate matter is not collected in dustfall as efficiently as coarse particulate matter.

Also, the division can be dependent upon such factors as meteorological conditions, and particle density. Precipitation also has a major influence on particulate matter air quality. Rainfall has the effect of reducing re-entrainment of particles and washing particles out of the air.

Varying terms describing atmospheric particulate loadings have arisen from the different measuring techniques used. Smoke is defined as suspended particulate air pollutants (of less than 15 μm in diameter) as measured by determining the staining capacity of the air. A major material, increasingly deemed responsible for the staining of air filters, is Particulate Elemental Carbon (PEC). This arises substantially from the incomplete and inefficient combustion of fossil fuels. The propensity of PEC's contribution to this phenomenon is given in Section 3.4.4. Another term commonly used to describe the particulate loading of the atmosphere is Total Suspended Particulates (TSP). TSP levels are assessed by collecting particulate matter (usually less than 45 μm in diameter) by filtration and then the mass is determined gravimetrically with precautions for humidity effects etc., irrespective of the relative staining capacities of the collected particulate on the filter. Further experimental details are given in Section 2.4.

2.2 Natural Sources of Particulate Matter and their soiling potential

In order to assess the sources of potentially soiling particulate matter, all sources should be evaluated be they natural or anthropogenic in origin. Indeed, it should be noted that on a world-wide mass basis, emissions of particulate matter from natural sources greatly exceed those from anthropogenic emissions. Significant natural sources of particulate matter include soil and rock debris (terrestrial dust), volcanic action, sea spray, natural fires and reactions between natural gaseous emissions. Vegetation emits organic vapours that react in sunlight to yield very small particles of tarry material. Except near intense sources, natural emissions result in low atmospheric concentrations, but the sources are so extensive that their total emitted mass is greater than that from man-made sources, as illustrated in Table 2.1.

As stated in section 2.1, particles from most natural sources are predominantly above 2 µm in diameter. Their size has important consequences in respect to their impact on air quality. For example, natural dust, though responsible for nearly a quarter of the total mass injected into the atmosphere, has a relatively small impact on air quality. This is because dust particles generally have a diameter greater than 10 µm and are fairly dense, consequently they quickly settle out of the atmosphere as a result of gravity induced sedimentation. As was illustrated in Figure 2.1, the larger the particle in diameter, the greater is its settling velocity from the atmosphere. The permanence of particle removal from the atmosphere is affected by the nature of the surface on to which they are deposited,

Table 2.1. Rate at which total suspended particulate matter of radius less than 20 μm are produced in or emitted into the global atmosphere per year(6).

	Rate (10^9 kg $year^{-1}$)
Natural particles	
Soil and rock debris	100 - 500
Forest fire and slash-burning debris	3 - 150
Sea salt	300
Volcanic debris	25 - 150
Gas to particle conversion:	
Sulphate from natural sulphur gases	130 - 200
Ammonium salts from ammonia	80 - 270
Nitrate from NO_x	60 - 340
Hydrocarbons from plant exhalations	75 - 200
SUBTOTAL	773 - 2,200
Anthropogenic particles	
Particles by direct emissions	10 - 90
Gas to particle conversion:	
Sulphate from SO_2	130 - 300
Nitrate from NO_x	30 - 35
Hydrocarbons	15 - 90
SUBTOTAL	185 - 415
TOTAL	958-2,615
Extraterrestrial	0.5 - 50

the composition and structure of the particles as well as meteorological and other factors. In assessing their soiling potential, the physical and chemical properties of such particles must additionally be considered. The preferential removal of large particles by rainfall is consistent with some of the correlations between rainfall and the soiling/cleaning of materials which have been observed in this research and are reported in Chapter Six. Also, dry deposition on to very smooth solid surfaces can be reversed almost completely by strong wind action. The chemical composition of the particles is also an important factor, in that water-soluble material such as some soil derived components are more likely to be dissolved in rainfall and removed from the surface. However, particles which are hydrophobic and immiscible with water i.e. sticky and tarry in nature, such as oil-fired particulate emissions, are less likely to be removed from surfaces by the action of wind or rainfall. The role of rainfall in removing soiled material from surfaces is more fully discussed in Chapters Four and Six.

Finally, an obvious point that should be noted is that the colour of naturally produced particles is generally not as dark as those which are anthropogenically derived, especially those from the combustion of fossil fuels. Also, the colour of the deposited matter observed upon building facades in urban areas is darker in appearance than those emanating from many of the natural sources of particulate matter, which usually contain more siliceous and less carbonaceous matter than those from combustion derived sources.

Soiling is a long-term process, so despite natural sources giving rise to a greater proportion of total particulate mass on a world-wide basis than man-made sources, the former's effect on soiling in the urban environment may be limited because of their global distribution, size and chemical composition and hence removal mechanisms from the atmosphere and surface on which they are deposited. However, such particles may contribute to the soiling occurring on areas of building facades which are sheltered from rainfall and protected from wind action and if the particles are sticky in nature they may act as an adhesive surface which can entrap on to the surface other particulates which otherwise would have been easily removed.

Natural sources may often give rise to 'nuisance' dustfall such as Saharan sand storms, but such deposits are usually removed from surfaces following a subsequent fall of rain(7). Such events although not a significant source of soiling matter, may produce a damaging pitting of building surfaces for with wind speeds of up to 70 km hr^{-1}, their action is abrasive in nature. Indeed, machine sand-blasting techniques have been and still are used to clean buildings, further details of which are given in Chapter Seven. As will be illustrated in the following section, certain anthropogenic sources of particulate matter are deemed to be more responsible for urban soiling because of their size, chemical composition and their disproportionate distribution within the ambient urban environment.

2.3 Anthropogenic sources of particulate matter and their soiling potential

Emissions of particulate matter from human activities can be divided into four main categories

(i) industrial process based fugitive particulate emissions;

(ii) non-industrial fugitive sources (roadside dust - from paved and unpaved roads, wind erosion of cropland, etc);

(iii) fuel combustion and industrial processes;

(iv) transportation sources.

2.3.1 Industrial fugitive emissions

Process fugitive particles are not emitted from a point source such as a chimney and this makes their quantification and environmental impact harder to assess. For example, industrial fugitive dust emissions may result from the wind erosion of storage piles of materials used, unpaved plant roads and from vehicular traffic using them. They also result from industrial related operations such as material handling, loading and transfer operations. It has been estimated that for a modern integrated iron and steel works about 15% of the TSP emissions are from stacks, 25% from fugitive process emissions and 60% are fugitive dusts from paved and unpaved roads from inside the plant complex and from storage piles.(7) Whilst it is estimated that fugitive dust emissions from both industrial and non-industrial sources exceed those from stationary point sources in most areas, their impact is limited because the emissions comprise large particles (usually above 10 µm in diameter) which settle a short distance from the source.

So despite industrial operations giving rise to particulate matter, their large diameter size and hence limited dispersion within the ambient atmosphere mean that fugitive emissions usually give rise to a local dust problem rather than a general soiling within the urban environment. Especially since a majority of industrial complexes are now usually sited on the peripheries of our cities and away from large residential areas. The emissions from certain industrial chimneys do give rise to particulate matter which may contribute to the proportion of soiling material in the atmosphere. Such sources may be derived from the raw materials being processed or from the combustion of fuel used as an energy source to drive the operation. The latter is likely to be more responsible for such emissions on a mass basis as well as for any soiling effect the emissions may cause since it would be presumably uneconomical to "waste" the raw materials in this way. The contribution of particulate matter arising from fuel combustion is given in section 2.3.3.

2.3.2 Non-industrial fugitive emissions of particulate matter

These emissions are commonly termed fugitive dust and are predominantly caused by traffic entrainment of dust from public paved and unpaved roads, agricultural operations, building construction and fires. With the exception of the latter, the sources entail dust entrainment by the interaction of machinery with materials and by the forces of wind on the materials.

A large variety of studies have examined pollution levels (concentrations and loadings) on road surfaces. However, most of these studies have been carried out in order to assess the impact of street surface runoff and its effects on receiving stream water quality. Despite the emphasis on water pollution, data from such research can be used to extrapolate the likely contributions to airborne particulate matter.

Such studies have highlighted the fact that the amount of contaminant material on any street surface will vary considerably from place to place and from time to time, depending upon a number of dominant factors which include street surface condition and type, land use, land activity and management. For example, Roberts et al(9) observed greater emissions of particulate matter below 10 μm from American unpaved dusty roads compared to highways with an average of 10.5 g per vehicle kilometer being emitted on dusty roads. This is reduced to an average of 1 g per vehicle kilometer on highways and central business districts respectively at vehicle speeds of 40 kilometers per hour. Theoretical drift distances as a function of particulate diameter and mean wind speed have been computed for unpaved road emissions. Such results indicate that for a typical mean wind speed of 16 km hr^{-1}, particles larger than about 100 μm are likely to settle out within 6-9 m from the edge of the road. Particles that are 30-100 μm in diameter are likely to undergo impeded settling. These particles, depending upon the extent of atmospheric turbulence, are likely to settle within 80 metres from the road. Smaller particles especially those less than 10 μm in diameter have much slower gravitational settling velocities and are much more likely to have their settling rate retarded by atmospheric turbulence. Other American workers have also found significant contributions to airborne particulate concentrations close to roads due to the entrainment of surface road dust by vehicle-induced air turbulence.(10)(11) The former reports emission factors ranging from 1 to 15 g $(vehicle\text{-}km)^{-1}$ depending on the silt loading of the road surfaces although there is no mention of particulate sizes emitted.

Measurement of silt (sub-63 μm particles) on a transect from central to suburban London found surface loadings on most roads, excluding kerbs, to be in a range up to 0.1 kg km^{-1}, only a few high values of up to 4 kg km^{-1} were recorded for less-used and less-maintained roads.(12) Taking 0.1 kg km^{-1} as an estimate of the surface density for sub-63 μm particles as found in London, Ball et al deduced the corresponding emission factor to be 0.1 g $(\text{vehicle-km})^{-1}$.(12). Particulate matter loadings in the range of 4 kg per kilometer have been reported for commercial areas of US cities, which correspond to the upper limit recorded for London. Such differences would be expected between various locations because of factors such as meteorology, street cleaning practices and local geography. Taking the value of 0.1 g $(\text{vehicle-km})^{-1}$ as an order of magnitude emission factor for reentrainment of road dust, Ball et al(12) predicted total emission in London of 2,500 tonnes per annum, which compares approximately to the 1,419 and 9,360 tonnes of dark smoke emitted from petrol and diesel vehicles respectively in 1980 (as given in Table 2.3). Ball's value was deduced for silt particles less than 63 µm in diameter and the proportion of fine particles with a diameter of less than 2.5 µm was not assessed. Thus the figure of 2,500 tonnes per annum as the contribution from roadside dust to airborne particulate matter should be considered as a maximum figure. It is unlikely that 100% of the sub-63 µm particles will become airborne and hence possibly exert a soiling effect. Also, the soiling effect of such particulates which are predominantly siliceous is lighter in colour than most anthropogenic emissions. The relative importance of the two mechanisms is difficult to evaluate. Experimental results carried out in this research which may help to further elucidate the contributions of such sources to urban soiling are given in Chapter Six.

2.3.3 Fuel combustion, industrial processes and vehicle exhaust emissions

Combustion is the most widely used and yet one of the least understood chemical reactions at our disposal. It is defined as the rapid union of a substance with oxygen accompanied by the evolution of light and heat. Combustion is primarily used for heat by changing the potential chemical energy of the fuel to thermal energy. It is an especially complex source of primary particulates in that it can produce particulates having a very divergent chemical composition as well as a wide range of particle sizes (0.01 to 1.0 µm). Black smoke is produced by the incomplete combustion of carbonaceous fossil fuels. Physically it consists of fine particles (0.01 to 1.0 µm) of soot borne in a stream of air and flue gases. Upon microscopic examination, the carbonaceous particles appear as agglomerates of porous balls as shown in Figure 2.2. In many cases the particles are not pure carbon, but contain highly condensed aromatic hydrocarbons of very low hydrogen content, such as anthracene and pyrene and their derivatives. The presence of the latter type of compounds in combustion products and their possible effects on human health is briefly reviewed in Section 3.6.3.

Although carbon is a main component of particulate matter in smoke, other matter is also usually present. For example, both coal and oil smoke contain fly ash from the noncombustible mineral fraction in the fuel. Smoke is formed when the combination of fuel used and the method of burning is such that incomplete combustion results. All fuels can be burnt without the production of smoke, though some with more difficulty than others. Indeed, the molecular structure of the hydrocarbon is one of the major parameters determining the amount and rate of soot formation. Other important parameters include the fuel/oxidant ratio, gas temperature and pressure. When hydrocarbons are burnt with the oxygen in air, the carbon component is converted into carbon dioxide and hydrogen into water vapour. Ideally, when a fossil fuel is burnt the end products of the reaction would be carbon dioxide and water. This would be described as the stoichiometric equation, below is the expression for octane ($C_8 H_{18}$).

$$C_8H_{18} + 12\tfrac{1}{2}\, O_2 \longrightarrow 8\, CO_2 + 9H_2O$$

However, stoichiometric reactions are rarely achieved when fossil fuels are burnt. The conditions conducive to this do not occur because the system is kinetic in nature and contaminants and other by-products formed from within the fuel prevent stoichiometry. Thus when octane is burnt other products are also formed :

$$C_8H_{18} + O_2 \longrightarrow CO_2 + H_2O + CO + NO + OH^{\bullet} + H^{\bullet}$$

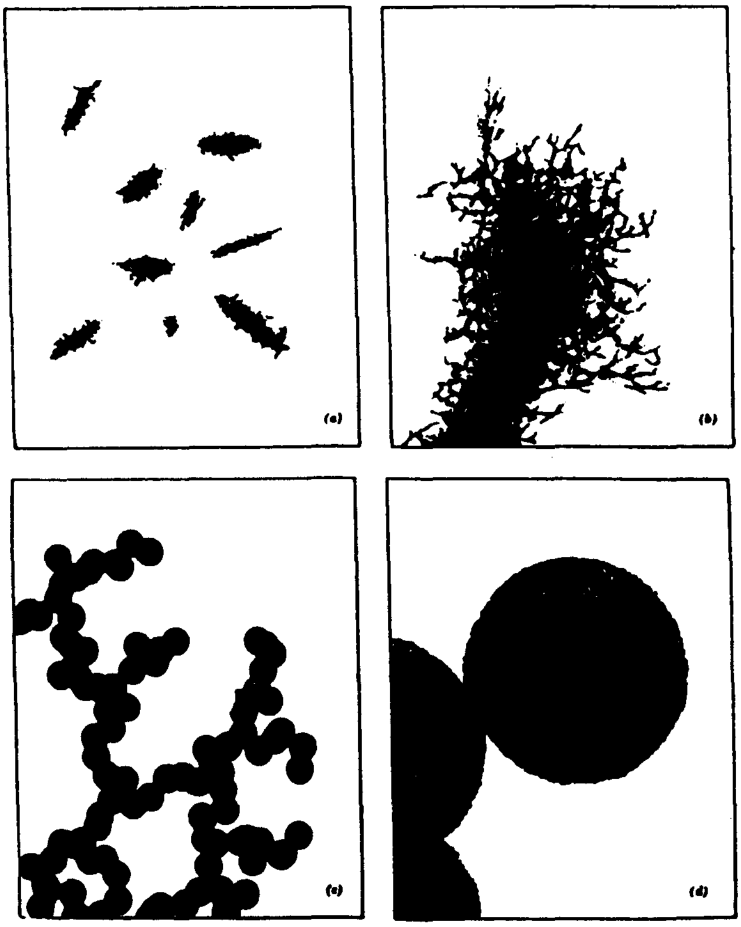


Figure 2.2 Particles of soot (0.01 µm to 1.0 µm) under the microscope. (a) Particles of soot x 86. (b) Edge of soot particle x 860. (c) Edge of soot particle showing chainlike structure of carbon particles x 86,000. (d) Nature of packed crystallite structure making up carbon particle x 860,000.(13)

A fuel produces smoke when it has been heated to a sufficiently high temperature to decompose a portion of the fuel to finely divided carbon and other products, but not high enough or in the presence of sufficient oxygen to burn the carbon to form carbon dioxide. Thus, only partially decomposed fuel molecules polymerize to produce carbon nuclei which are very often of sub-micron character. The fundamental requirements for smokeless combustion are sufficient temperature for the reaction to occur, sufficient time to allow the reaction to go to completion, adequate turbulence for good mixing and a sufficient supply of oxygen. These are commonly referred to as "T, T, T and O". For instance, gaseous and atomized liquid fuels smoke when insufficient air is present, when fuel and air are poorly mixed or when the flame is chilled before combustion is complete. In these cases, the unburned fuel is cracked to carbon and hydrogen, with the carbon forming the basic smoke constituent.

For example, diesel engines operate at different air/fuel ratios depending upon the power required. There is no throttle, so theoretically air consumption per stroke never varies: thus a weak mixture produces low power, a rich mixture high power, unlike the petrol engine which burns at a constant air/fuel ratio. To achieve complete combustion, each droplet of fuel must have sufficient air. At full load all the available air is burnt and there is no excess. If perfect mixing does not take place, there are some areas in the combustion chamber which are richer and weaker than the stoichiometric mixtures. The rich areas burn fuel incompletely and this causes smoke and carbon monoxide to be emitted in the exhaust. Perfect mixing is almost impossible, mainly because the time available for mixing is so short (1/400th of a second). Thus diesel fuel is considered to have a higher smoke emission factor (percentage by mass) than petrol as is illustrated in Table 2.2, section 2.5.

To obtain the proper conditions of time, temperature, turbulence and oxygen, one must have equipment designed and operated for the specific fuel under consideration. Proper combustion is important, not only from an air pollution view, but also from an economic one, since smoke represents a loss of heat and a subsequent waste of energy. Indeed, the emission of smoke is a lost opportunity to convert our limited fuel resources to useful energy.

The smoke produced as a result of combustion has significant soiling implications because smoke contains not only soot but also tarry viscous materials which may aid in the adherence of a particle on to a surface.(14)(15)(16) The small size in comparison with other sources of particulate matter is important because such particles may be deposited on to a surface by impaction but are less efficiently removed from it, through the action of wind or rainfall or by gravitational influences, than are larger sized particles. Also, particles emitted from vehicular exhausts occur in local populated areas and because they are disproportionately distributed within such a confined area compared with natural global emissions, they give rise to locally elevated atmospheric concentrations. Thus, the most serious air pollution problems usually occur in urban areas and it is in these areas that most people live; more people to generate air pollution and more people to be exposed to the air pollution generated. For example, 13% of the population of the United Kingdom live in London which represents 1% of the land area. Thus, it is not surprising that buildings may soil more quickly in urban areas than at rural sites. Variations of soiling rates according to varying locations were measured in this research project and are presented in Chapter Six. The frequency of building cleaning as recommended by stone cleaning companies for urban and rural locations is given in Chapter Seven. These results lend circumstantial evidence that it is man-made sources of particulate matter generated from within urban conurbations rather than natural sources which are responsible for the increased soiling rates which have been reported. The precise contribution from source to smoke for London and the UK is given in Section 2.5.

2.3.4 Additional transportational sources of particulate matter

Transportation source emissions occur in the two categories, (i) vehicle exhaust and (ii) vehicle related particles from tyre, clutch and brake wear. In this section only the latter will be evaluated. The previous section has indicated why vehicle exhaust emissions may occur from incomplete fuel combustion and Section 2.5 evaluates this contribution to UK atmospheric smoke levels.

In addition to vehicular exhaust emissions and surface dust entrainment into the atmosphere, debris from rubber tyres has also been identified as a contributor to airborne particulate concentrations near busy roads. The release of pollutants from tyre wear is considered as an important source of highway pollutants. Christensen and Guinn (1979) note that zinc in the form of zinc oxide is used as an accelerator in the manufacture of tyres. They subsequently recorded that the deposition of zinc on the road surface was 0.003 g of zinc $(\text{vehicle km})^{-1}$ in addition to 0.0049 g lead $(\text{vehicle km})^{-1}$ from petrol where the leaded content was 0.4 g l^{-1}.(17) Studies by Cadle and Williams (1978) have presented a more detailed account of tyre emitted pollutants. They report that hydrocarbon and sulphur gases are emitted continuously from car tyres under normal wear conditions. The hydrocarbons (styrene, butadrine, isoprene and vinylcyclohexene) are probably monomers used in the tyre tread, which suggests that the gases are formed from the degradation of the polymer during the tread wear process.(18) Cadle and Williams (1978) have shown that the temperature generated at the tyre contact patch is sufficient to attain this polymer pyrolysis. The contribution of gases from tyre wear was found to be some 6% of the exhaust emissions if all the wear products were gaseous hydrocarbons.(19) The evaluation of the total emissions of gases from tyres is definitely overwhelmed by exhaust emissions.

Results have further indicated that most tyre wear particles are not suspendable and that less than 5% of the wear products are airborne particulates. The higher percentage of rubber found in dustfall in comparison to air grab samples, suggests that the larger particles are merely temporarily suspended. Subramami (1971) reported an emission factor of 0.12 g km^{-1} for airborne particulate matter evolved from the wear of rubber tyres under American driving conditions.(19)

Ball and Caswell (1983) used this above factor for London and their result suggested that tyre wear contributes some 3,000 tonnes per annum of particulate, on the basis of an annual vehicle movement of $25x10^9$ km.(12) This latter report also notes the work of Pierson and Brachaczek (1974) which states that much of the tyre wear is in the form of non-suspendable particles, deposited on or near the road and that, depending on driving conditions, the amount of airborne tyre-particulate averages just 20% of the amount of exhaust particulate from petrol engines burning leaded fuel.(20) Recent work by Noll et al (1987) reports the mass median diameter for particulates from rubber tyres to be 25 μm.(21) This evidence further suggests that the impact of particulate emissions from tyres to airborne particulate concentrations may be small because of the comparatively large particle size and thus limited long-term residence in the ambient atmosphere. Much of this particulate matter will not be recorded by a smoke shade apparatus and thus the figure of 3,000 tonnes per year for London substantially over-estimates the contribution of tyre wear particulate emissions to dark smoke. These emissions are likely to be a lesser source of soiling particulate than vehicular exhaust emissions whose contributions are fully assessed in Section 2.5. Indeed, from examination of the data in Table 2.3 the mass of dark smoke emitted from petrol and diesel vehicles in London (1980) was over 1,419 and 9,360 tonnes respectively.

Contributions to other vehicle contaminant sources have been assessed by Ward et al (1977) to include heavy metals from body work and engine wear. Other than lead from petrol, quantities of cadmium, nickel, copper, zinc, iron, asbestos, manganese and chromium have been found in road surface particulates.(22) Nickel and chromium are frequently used in chrome plating for car bumpers and window sealings and degradation of the plate leads to the build-up of these metals. However, the size of these particulates and their emission factors have not been studied in sufficient detail for their contribution to airborne particulate matter to be assessed. However, their impact as soiling particulates can be assumed to be low in comparison with the propensity of such particulates from the vehicle's exhaust itself.

2.4 Analysis of airborne particulate matter

This section reviews widely used methods that have been employed for the analysis of ambient particulate matter. Greater emphasis and detail has been given to techniques used in this research.

2.4.1 Light reflectance method

In assessing the soiling potential of atmospheric particulate matter the apparatus used in the National Survey of Air Pollution in the UK is most apt. This method of sampling particulate pollution (including smoke) operates by collecting it on filter paper by drawing a sample of contaminated air through a filter, which is held in a clamp such as illustrated in Figure 2.3. The suction pump draws about 2 m^3 of air per day through the equipment. The inlet, an inverted funnel was shown in wind tunnel studies to have a cut off point of 13.5 μm and 10.8 μm at a wind speed of 2 km h^{-1} and 8 km h^{-1}.(23) In general particles

(>10 µm aerodynamic diameter) do not efficiently penetrate the system to the filter. Particulate matter is filtered out and the Drechsel bottle which contains dilute hydrogen peroxide removes sulphur dioxide contamination.

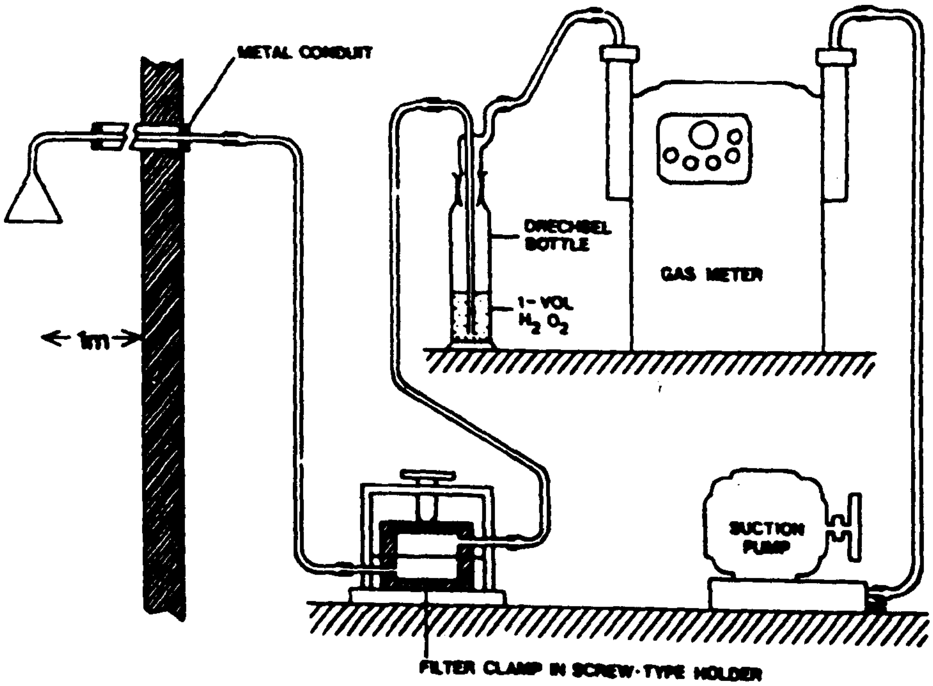


Figure 2.3 Schematic arrangement of standard daily smoke and SO_2 sampling apparatus.(24)

Determinations are generally made with this apparatus over a period of 24 hours but the period may be shortened in highly polluted atmospheres and increased in relatively clean atmospheres without loss of accuracy.

At the end of the test period the paper is removed from the clamp and the blackness of the stain assessed by means of a photoelectric reflectometer. This instrument consists of a light source and a photo-sensitive element mounted together in a measuring head. Light reflected back from the filter paper falls on the surface of the photo-sensitive element and the current generated is measured by means of a milliammeter. Thus, the darker the stain the lower the intensity of the reflected light. The result is then converted for the volume of air passed and the area of the stain (i.e. the internal diameter of the filter clamp). By means of a calibration which relates the stain-density (the darkness index) to the weight of the smoke per unit area of stain the approximate smoke concentration in the air may be calculated into concentrations of 'standard smoke', usually expressed in terms of microgramme per cubic metre ($\mu g\ m^{-3}$).

The method has been calibrated by operating two sampling lines in parallel, one operating at the standard air flow of approximately 2 m^3 per day and a second line operating at an air flow sufficient to collect an amount of particulate matter which can be weighed. Such calibrations have been undertaken for a variety of locations where there was a predominance of particulate emissions for varying sources such as steel and cement works, and whose emissions would contribute a different colour to the particulate matter than combustion derived sources. An example of such calibration curves is given in Figure 2.4.(25) A series of calibration curves were obtained using Whatman No.1 filter papers and the Eel Reflectometer for sites in very different areas such as Glasgow, Islington, Greenhithe and Sheffield. These two latter sites were situated in cement and steel works districts respectively.

The calibration curve of each site was brought to coincide over the range of darkness index of 0 to 50 and the mean curve for each site is given in Figure 2.4.

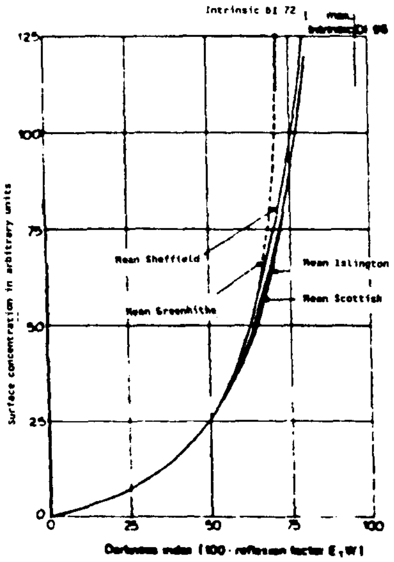


Figure 2.4 <u>British smoke calibration curves</u>(25)

From such measurements a mean British curve was obtained. In 1969 the British Standards Institution (BSI)(25) curve was fixed and it is from this curve that UK smoke levels are calculated and have been used in the experimental work described in Chapters Five and Six. However, within the EEC, some of the other member countries still use the Organisation for Economic Cooperation and Development (OECD) calibration curve of 1964. In order to compare and convert BSI to OECD smoke measurements the following linear relationship should be used :

$$C_{OECD} = \frac{C_{BSI}}{0.85}$$

The light reflectance method is suitable for most routine air pollution monitoring work but due to doubts about the reliability of the method for determining the total amount of particulate matter sampled, a gravimetric technique can be employed as the standard method for the determination of total particulate concentrations. The techniques are compared in Section 2.4.4.

2.4.2 TSP Gravimetric method

As mentioned in Section 2.1, total suspended particulate (TSP) is one indicator of suspended particles in the ambient air. TSP is measured using a high volume sampler (Hi-Vol) which collects suspended particles ranging up to approximately 45 micrometers in diameter. Air is drawn into a covered housing and through a filter (20 cm x 25 cm) by means of a high flow-rate blower at a flow rate of 1.1 to 1.7 m^3 min^{-1} for 24 hours which allows suspended particles with an aerodynamic diameter of less than 45 μm to pass to the filter surface. The mass concentration of suspended particulate in the ambient air (μg m^{-3}) is computed by measuring the mass of collected particulate matter and the volume of air sampled. The fact that the filter and the volume of air sampled is comparatively large, ensures that there is usually a sufficient amount of material on the filter to be chemically analysed. Thus, much additional information can be obtained from such samples such as metallic and hydrocarbon ambient levels, etc.

The accuracy with which the sampler measures the true average concentration depends upon the degree of constant air flow rate maintained in the sampler. The air flow rate is affected by the concentration and nature of the dust in the atmosphere which may clog the filter and significantly reduce the air flow rate. For example, particulate matter that is oily, such as photochemical smog or wood smoke, may block the filter and cause a rapid drop in air flow at a non-uniform rate. Dense fog or high humidity can cause the filter to become too wet and severely reduce the air flow through the filter. Under such conditions, the error in the measured average concentration may be as much as 50% or more of the true average concentration, depending on the amount of reduction of air flow rate and on the variation of the mass concentration of dust with time during the 24 hour sampling period. (26)

High volume samplers are not well suited to continuous measurement surveys by virtue of the man hours involved to maintain them and the consequent scheduling problems. Buckman and Rubino (27) investigated the errors incurred during passive sample exposure periods and found that the magnitude of the error in part depends on the length of time the filter is exposed both before and after sampling. Normally an expended collection filter is picked up and replaced with a clean filter some time after each 24 hour sampling interval. This is usually every six days, hence each clean filter will remain in the sampler where it is exposed to the elements (i.e. wind, rain, acidic gases) for a five day period before sampling begins. Filters run for a period longer than 24 hours may be unrepresentative of the TSP, by virtue of the fact that the system filters high volumes of air through it which can quickly result in the overloading and clogging of the filter. Thus, high volume sampling is generally more useful in obtaining short term measurements of TSP.

In America, annual and 24-hour National Ambient Air Quality Standards (NAAQS) for particulate matter were set up in 1971 using TSP as the indicator pollutant. However, since 1987, a new annual and 24 hour standards for particulate matter, PM_{10} has been adopted. This measurement includes only those particles with aerodynamic diameter smaller than 10 micrometers. It is these smaller sized particles which are deemed to be more responsible for adverse health effects because of their ability to reach the lower regions of the respiratory tract. Further details of related health effects are given in Section 3.6.3.

2.4.3 Size selective methods

A widely used technique for collecting airborne particles prior to examination is known as impaction or impingement. The principle is much the same as the filtering mechanism of impaction, namely, when a moving aerosol changes direction, the particles bend because of their inertia, to continue in the same direction they were going. If the change in direction of the aerosol was caused by a diverting body, some of the particles may impinge upon that body and be collected. A particle-collecting device based on this principle can be designed to collect a single deposit of particles with each operation or to classify the particles into several fractions according to size. Particle size data obtained in this way are best interpreted and expressed in terms of equivalent or aerodynamic size. The equivalent (or aerodynamic) size of any particle regardless of its shape or density, is defined as the diameter of a unit density (1 g cm^{-3}) sphere having the same settling velocity as the actual particle when subjected to a gravitational or centrifugal force field.

The Cascade Centripeter has been designed to sample airborne particles and to separate them into a number of size ranges according to the aerodynamic sizes of the particles. Usually, a 50 µm elutriator is placed over the entrance, to serve as a cut off point for particles greater than 50 µm. In essence, the instrument consists of three stages. Each stage is comprised of an orifice and a nozzle placed behind it. Each nozzle holds a filter paper serving as a collecting surface. The orifice, the nozzles and the distances between them are successively smaller in dimensions, so that their air velocity at each orifice is increased and particles in smaller size ranges are deposited in successive stages when air is drawn through the centripeter at a constant flow rate of 30 litres min^{-1}. Particles too small to be retained by the last centripeter stage are collected on a final stage consisting of a high efficiency glass fibre filter paper. The contaminants within the ambient aerosol are collected on a form suitable for some chemical analysis, as a flat deposit on a filter paper which is a few square centimeters in area.

Interferences are mainly operational problems caused by leaves, insects, etc. which block part of the sampler inlet or part of an impactor nozzle. Condensation of water or other vapours or the evaporation of volatile matter from the collection surface can also be an interference. Particle bounce off from the collection surface or any type of particle losses can be considered interferences. Indeed as part of the calibration, wall losses have been determined so that the concentration and particle size distribution can be reconstructed.

The weight gained by each impactor stage collection surface and by the filter are divided by the corrected total sampled volume of air and the results expressed as $\mu g\ m^{-3}$. For the centripeter first stage, the interpretation of particle weight collected is amount ($\mu g\ m^{-3}$) of particulate matter of equivalent size greater than the first stage nozzle 50% cut-off point. A mean size should not be associated with this size fraction. For the centripeter second stage, the interpretation of particle weight collected in amount ($\mu g\ m^{-3}$) of particulate matter greater than the second 50% cut-off point but less than the first stage 50% cut-off point. The third and latter stages are calculated in the same manner as for the second stage. Filter mass is calculated as $\mu g\ m^{-3}$ and interpreted as particulate matter of the size less than the last stage 50% cut-off point. The particle weight fractions are then summed up to get the total particle concentration. The data is then plotted as a cumulative distribution curve on a normal or log probability plot. A smooth curve or straight line is then drawn through the actual data points. The particle of distribution Mass (weight) Median Diameter (MMD) is read directly off the distribution curve at the point where the curve crosses the 50% line. The per cent and quantity ($\mu g\ m^{-3}$) of particles by weight in any particular size range can be estimated by using a best fitting smooth curve or straight line through the cumulative data plot points.

Numerous centripeter measurements of ambient air have shown that it is the smaller sized particles less than 2 µm in diameter that have the greatest soiling effect as observed on the filters used to sample the air and to fractionate into particle sizes. A study carried out in Sydney, Australia, on the urban aerosol involved simultaneous smoke shade measurements with the normal technique and also with a device in the sampling line which permitted the collection of only particles < 1 µm in diameter. Both measurements yielded approximately the same smoke shade values, showing that the sub-µm particles dominate the soiling of the filter paper.(28) Hogan et al (29) also observed that all the blackness for background aerosol was attributable to particles in the nuceli size range. Caswell(30) found from centripeter measurements of the London aerosol, the fine fraction was comprised of much darker material than the coarse fraction. For example, surface loadings in the region of 80-90 $\mu g\ cm^{-2}$ of fine particles smaller than 1.4 um diameter produced very dark stains with Darkness Indices in the range of 80-90 Whilst greater loadings of coarse particles in the range of 200-400 $\mu g\ cm^{-2}$ produced Darkness Indices in the range of 30 to 60. Caswell found that the darkest particles were smaller than 1.4 µm in diameter and by mass constituted 50% of the aerosol.

Bailey and Clayton (1982) investigated the relationship between standard smoke concentrations and particle size. They noted that the mean ratio of standard smoke to gravimetric particle concentration increases with decreasing particle size, indicating that the black particles are associated with the smaller particle size ranges. This may be expected, because a large proportion of combustion derived particles are in the smaller particle size ranges.(31)

2.4.4 Relationship between TSP and Smoke Shade Methods

It was clear in the early 1960s that, with very few exceptions, the suspended particulate matter in the atmosphere was dominated by coal combustion products. It is because of this that an acceptably consistent relationship was found between darkness index and mass of suspended particles in 1963, thus allowing a definition of Equivalent Standard Smoke and the reliable use of a simple indirect measure of particle concentration.

Since 1963, there have been considerable changes in the use of fuel (as is illustrated in Section 2.5) and consequently in the emission and composition of particles. Thus it may be expected that the smoke stain calibration would have changed, especially in areas which are subject to extensive smoke control measures.

Furthermore, the relationship between TSP gravimetric and standard smoke concentrations can be very site specific. For example, an evaluation of methods for measuring suspended particulate matter in the air by Lee, Caldwell and Morgan (1972)(32), found that in smokeless zone areas and clean background regions the smoke shade measurement underestimates the concentration of suspended particulate in the air.

Figure 2.5 gives the average weekly particulate concentration as determined by a variety of techniques.* It is interesting to note the sharp increase in suspended particulate concentration recorded during late April and May. This large concentration increase was observed by the hi-vol sampler, the membrane filter sampler but the smoke shade measurements and the soiling index showed only slight increases if any during this time. This could have been attributable to the presence of tree pollen in the atmosphere in spring.(32)

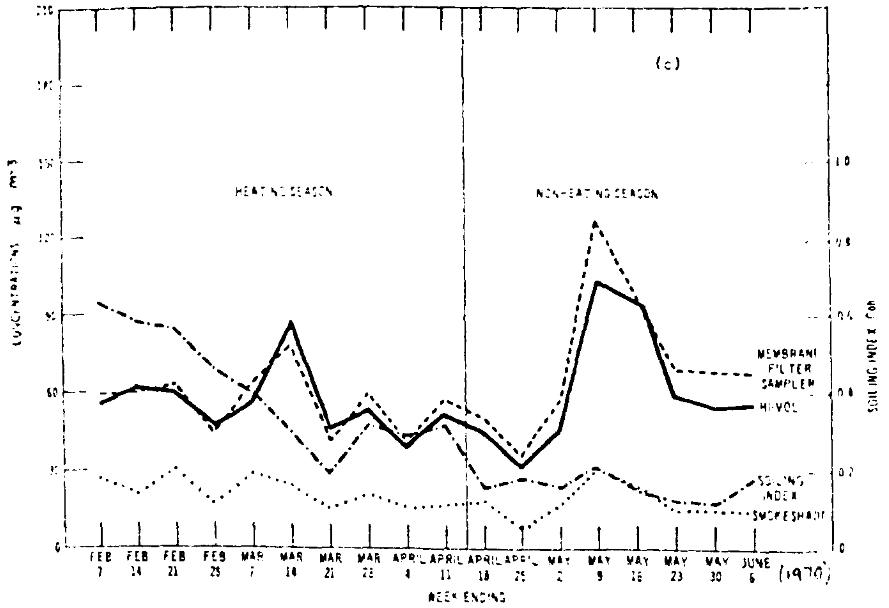


Figure 2.5 Kew Observatory average weekly particulate concentration (in 1970) as determined by a variety of techniquess.(32)

In view of the changes and the resulting poor correlations noted between reflectance and gravimetric methods, Ball and Hume (1977)(33), Kretzchmar (1975)(34), Dalagar (1975)(35), it was considered necessary to repeat the 1963 measurement and to redetermine the smoke calibration curve and the range of the corresponding gravimetric surface concentrations of suspended particles for a given darkness index of stain. Bailey and Clayton (1982)(31) did this by the simultaneous measurement of total suspended particle, total carbon concentrations and smoke shade.

The relationship between standard smoke concentration and actual gravimetric particle concentrations showed that, in general, British

Standard Smoke (BSS) concentrations are about 40% of the actual gravimetric suspended particle concentrations,(although at one site they found the results comparable). At that site, coal combustion gave a major input to particulate matter. The fact that this site was completely different from the others indicates that a single calibration curve is now inadequate in describing the relationship between Standard Smoke and gravimetric concentrations. However, they did show the Standard Smoke method gave a reasonably good correlation with the concentration of elemental carbon in the suspended particles.(31)

Yet, measurements of smoke shade and TSP carried out close to traffic, may result in the smoke shade over-estimating the TSP gravimetric concentration by factors of up to 3.(36) As will be illustrated, diesel smoke is much darker than standard smoke, leading to this over-estimate at ground level sites. However, at rooftop sites where the majority of the national smoke shade sites have been sited, vehicle-emitted particulate matter is only one of the sources of pollution. So the relationship between smoke shade and TSP gravimetric levels may vary according to the contribution to the atmospheric aerosol by vehicular sources. This will depend on the height above ground level at which the measurements are taken. For example, Clarke and Papapanayotou (1987)(37) found that average roadside smoke level of 45 µg m^{-3} was twice the urban background level as indicated by rooftop values of 18 µg m^{-3} taken near a busy city road in Leeds. Likewise, Olison (1976)(38) found the mean values of smoke in the air at a high-rise block in Stockholm were 48, 33 and 23 µg m^{-3} at heights of 10, 30 and 50 metres respectively above ground level.

The median level of smoke recorded by National Survey sites for central London was in the order of 20-30 µg m^{-3}, yet a compilation of GLC data found smoke shade levels in the range of 50-120 μg m^{-3} for a variety of urban street locations.(36) Such discrepancies may be accounted for in part by the location of the monitoring site, but also because diesel smoke is darker, weight for weight, than the standard smoke. So to aid in the interpretation of results of smoke surveys in busy streets in terms of equivalent smoke, a special calibration of the smoke filter for diesel smoke was carried out by Wallin (1965).(39) He found that because diesel smoke is darker than average urban smoke when a stain containing diesel smoke was evaluated by means of the standard calibration (1964), the calculated concentration may be over-estimated by a factor of 3 to 4 as illustrated in Figure 2.6.

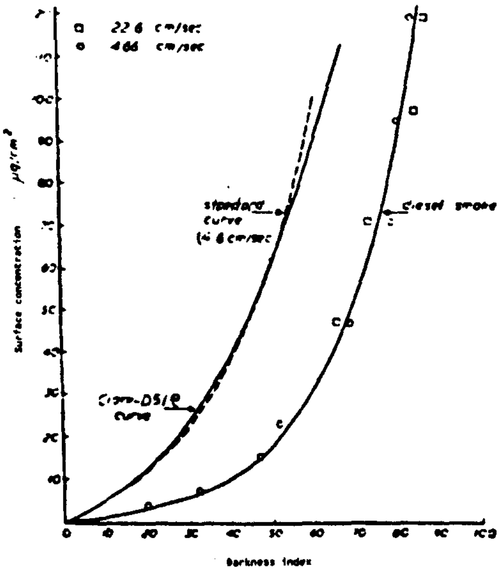


Figure 2.6 Smoke calibration curves - A comparison of the equivalent standard smoke curve and a curve derived for diesel smoke alone.(39)

Thus, the main problems in using the light reflectance method to assess total suspended particulate mass is that particulates from different sources have different light scattering/absorption/reflectance characteristics. As has been illustrated here, black staining particulate matter can result in smoke shade values higher than corresponding values obtained gravimetrically.

Another study on the relationship of the BSS to the High Volume Sampling (HVS) method was carried out by Pashel and Egner (1981) for 16 sites in America. The correlation coefficient between the two measurements varied widely from site to site confirming that the BSS to HVS relationship varies with time and location. However, on average they found that HVS concentrations are approximately 100 µg m^{-3} higher than BSS concentrations.(40) It is interesting to remember here that as stated in Sections 2.4.1 and 2.4.2, the cut-off point for sampling ambient particulate matter is approximately 45 µm and less than 15 µm aerodynamic diameter for HVS and BSS methods respectively and it is because fine and coarse particles have different production and removal mechanisms that their mass concentrations are not well correlated.(41) Thus larger sized particles are only collected by the HVS and may contribute a greater proportion to the total mass of the particulate matter collected than the smaller sized particles. However, smaller sized particles (less than 15 µm aerodynamic diameter) are usually darker than larger sized particles and although they may not contribute significantly to the mass collected they are largely responsible for the darkening of the filter sample. Also, the discrepancy between the two methods may be larger in American studies than ones carried out in the UK because the relative contribution of diesels to BSS values is smaller in many American cities(42). The importance of vehicular emissions to urban dark smoke concentrations was first realised in an analysis by Ball and Hume (1977)(33) of daily mean concentrations of dark smoke as measured by BSS method, total suspended particulate and lead in central London. Their results indicated that the vehicular contribution to the annual dark smoke concentration was in the order of 77%. This work was met with some initial incredulity for in previous years domestic sources had been considered the main contributors to ground level concentrations of dark smoke. Ball and Hume's evidence showed a very significant correlation between dark smoke and airborne lead taken on a rooftop in central London. Domestic space heating sources as significant contributors to dark smoke concentrations were dismissed because day-to-day and seasonal values of the ratio of smoke shade to lead measurements showed no temperature dependence.

Since this study, numerous other studies have likewise shown that vehicular emissions contribute the largest proportion of dark smoke levels in cities compared with other sources. For example in the Strathclyde area of Scotland, a Warren Spring Laboratory survey quote a 50-60% contribution by motor vehicles to annual average smoke levels, despite a large domestic consumption of coal in the area.(43) Other cities throughout Europe such as Paris,(44) Vienna,(45) amd Leeds(37) also report similar findings.

Thus although the BSS-method may be of little use if the concentration of total suspended particulates in the atmosphere is required, the method is useful for determining long-term changes in dark smoke and assessing the soiling potential of ambient particulate matter. Other uses for BSS levels in predicting ambient levels of total and particulate elemental carbon are given in Section 3.5.2.

2.5 The levels and sources of smoke in the UK.

In 1961, the first co-ordinated National Survey of air pollution was set up to monitor levels of sulphur dioxide and smoke using the apparatus shown in Figure 2.3. The main purpose of this survey was to assess improvements/changes in the levels of these pollutants as a result of the 1956 Clean Air Act as well as to lead to a better understanding of causes and effects of air pollution. The survey was, and still is in a modified form carried out by Warren Spring Laboratory in Stevenage, Hertfordshire, in co-operation with local authorities and such organisations. Each year the results are given in the Annual Digest of Environmental Protection and Water Statistics,(46)(47) which show the average urban concentrations of smoke and sulphur dioxide as well as the total amount of smoke and sulphur dioxide emitted from the country as a whole. As the following section will illustrate, the main source of smoke in the 1950s from both urban and rural locations was derived from coal combustion. Thus, monitoring sites were selected with a view to measuring stationary source emissions and so were often located away from traffic and near-road locations. However, as discussed in the preceding section and detailed in the section which follows, in today's urban areas, there is a greater contribution to smoke emissions by vehicular traffic than was the case thirty years ago. Thus, this siting policy means that the dark smoke concentrations now reported by the survey do not reflect the true urban smoke concentrations or the soiling potential of ambient particulate matter of near-road locations.

Despite the limitations of the light reflectance method of either over-estimating or under-estimating smoke shade mass depending on location, season, etc, the results of urban smoke concentrations measured in the Warren Spring Survey do show the changing trend in smoke levels since the survey started in 1961. Data on fuel consumption and fuel emission factors in terms of smoke/dark smoke production allow an emission inventory of UK smoke/dark smoke emissions to be established. The emissions of smoke from coal combustion have fallen by nearly 80% in the past twenty five years. Figure 2.7 shows that the average urban concentration of smoke in 1984/85 was about a tenth of that in 1962/63.(47)

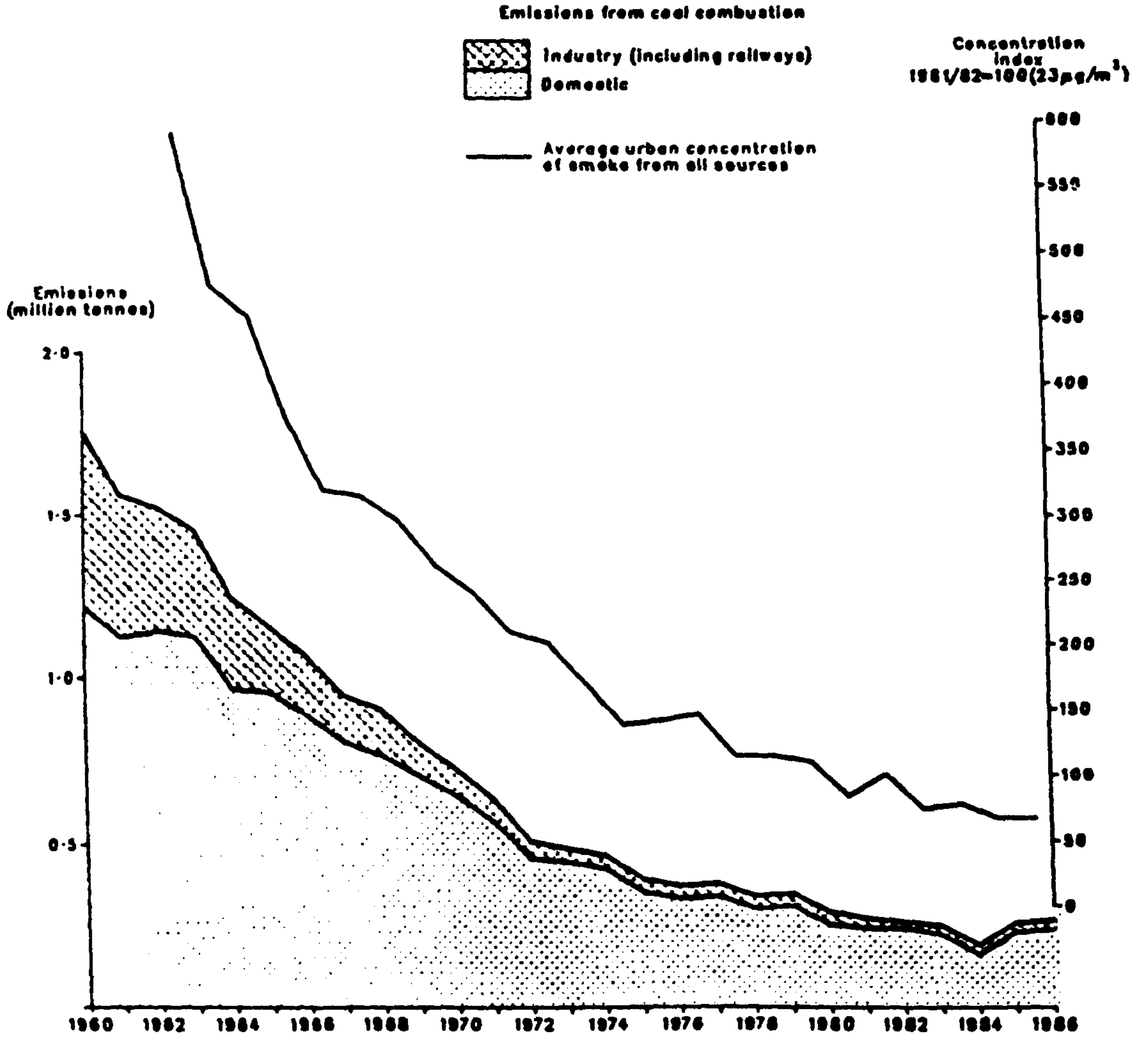


Figure 2.7 Smoke emissions from coal combustion and average urban concentrations for the UK.(47)

The decrease in coal consumption within the domestic sector has been due to the introduction of smoke control areas and moves to cleaner and more convenient supplies of energy such as gas and electricity. Various authors have examined the probable reasons why such trends occurred.(48)(49) Also since 1979 the quantity of coal used in electricity generation and hence emissions of smoke have decreased due to several reasons. For example, the increased thermal efficiency, increased efficiency of particulate removal from power station emissions, as shown in Table 2.2, as well as the reduced demand due to economic recessions as well as a larger contribution to supply from nuclear power stations.

In order to assess the relative contributions by source of urban smoke and its soiling potential it is necessary to know the type and amounts of fuel consumed within a defined area, as well as the particulate (smoke) emission factor (percentage by mass) of the fuel type and its 'blackness factor'. As described in section 2.4.2, fuels may emit particulate darker or lighter weight for weight than "standard smoke" used to calibrate the measurements of black smoke undertaken in the UK by the National Survey. Thus such factors have to be incorporated in order to permit comparisons with National Survey data. Table 2.2 gives the smoke emission factor (% by mass) and the relative soiling factor for the predominant fuel types used currently in the UK.(2) These figures were compiled by the Warren Spring Laboratory. DERV emissions are smaller and blacker particles than other emissions and consequently they have been weighted by a factor of 3. This is consistent with the results shown in Figure 2.6.

Table 2.2 The smoke emissions and relative soiling factors for fuel types predominantly used within the UK.(2)

Fuel Type	Smoke emission factor % by mass	Approx. soiling factor relative to coal	Dark Smoke Emission Factor % by mass
coal: domestic	3.5	1.0	3.5
coal: industrial	0.25	1.0	0.25
coal: power station	0.025	1.0	0.025
solid smokeless: domestic	0.56	1.0	0.56
solid smokeless: industrial	0.023	1.0	0.023
gas oil	0.025	1.55	0.039
fuel oil	0.10	0.43	0.043
motor spirit	0.15	0.43	0.065
diesel fuel	0.60	3.0	1.8

By multiplying the smoke emission factor by the quantity of a given fuel consumed the amount of smoke emitted can be calculated. Similarly, by multiplying the quantity of smoke emitted by the relative soiling factor for a given fuel, the quantity of dark smoke emitted can be derived. Alternatively, a dark smoke emission factor can be calculated by multiplying the smoke emission factor by the soiling factor. These values are included in Table 2.2. Table 2.3 illustrates the results derived by the above method for London in 1980.

Table 2.3 The quantities of smoke and dark smoke emitted (in tonnes) for London (1980) according to fuel type.(12)

Fuel Type	Amount of fuel consumed (tonnes)	Smoke Emitted (tonnes)	Dark Smoke Emitted (tonnes)
Coal:Domestic	5×10^4	1750)	1750)
Coal:industrial	2.5×10^5	625) 2375	625) 2375
Solid smokeless	3.5×10^5	1960	1960
Gas: Oil	1×10^6	250	387
Fuel: Oil	6×10^5	600	258
Petrol	2.2×10^6	3300	1419
Diesel fuel	5.2×10^5	3120	9360
	TOTAL	11605	15759
	% COAL	20.5	15
	% DIESEL	26.8	59
	% PETROL	28.4	9

Examination of the data in Table 2.3, clearly shows that diesel vehicles are the dominant source of black smoke in the London area. However, it is also possible to calculate the quantity and sources of smoke and black smoke emitted for the UK and to observe the relative contributions by fuel type to these values. In Table 2.4 the UK emissions of smoke and dark smoke are given from 1971 to 1986, these figures were derived using data from the Annual Digest of Environmental Protection and Water statistics.(46)(47) Some of the results calculated from this table are illustrated in Figures 2.8, 2.9, and 2.10. Care should be exercised on comparing yearly values with each other as climatic variations may affect the quantity of fuel consumed and hence emission levels. The

YEAR: 1971

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	15.6×10^6	546,000	546,000
coal industrial	27.2×10^6	68,000	68,000
coal power station	72.8×10^6	18,200	18,200
solid smokeless fuel	6.9×10^6	38,640	38,640
gas oil	11.8×10^6	2,950	4,572
fuel oil	45.7×10^6	45,700	19,651
motor spirit	15×10^6	22,500	9,675
derv.	5.2×10^6	31,200	93,600
Total		773,190	798,338
% coal		82	79
% diesel		4	12

YEAR: 1972

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	12.8×10^6	448,600	448,600
coal industrial	21.1×10^6	52,750	52,750
coal power station	66.7×10^6	16,675	16,675
solid smokeless fuel	6.1×10^6	34,160	34,160
gas oil	14.4×10^6	3,600	5,580
fuel oil	47.6×10^6	47,600	20,468
motor spirit	15.9×10^6	23,850	10,255
derv.	5.2×10^6	31,200	93,600
Total		658,435	682,088
% coal		79	76
% diesel		5	14

YEAR: 1973

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	12.7×10^6	444,500	444,500
coal industrial	20.1×10^6	50,250	50,250
coal power station	76.8×10^6	19,200	19,200
solid smokeless fuel	5.7×10^6	31,920	31,920
gas oil	14.3×10^6	3,575	5,541
fuel oil	46.2×10^6	46,200	19,866
motor spirit	16.9×10^6	25,350	10,900
derv.	5.7×10^6	34,200	102,600
Total		655,195	684,777
% coal		78	75
% diesel		5	15

Table 2.4 The quantities of smoke and dark smoke emitted (in tonnes) for the UK from 1971 to 1986 according to fuel type

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$12x10^6$	420,000	420,000
coal industrial	$18.7x10^6$	46,750	46,750
coal power station	$67.0x10^6$	16,750	16,750
solid smokeless fuel	$5.8x10^6$	32,480	32,480
gas oil	$12.6x10^6$	3,150	3,150
fuel oil	$43.6x10^6$	43,600	18,748
motor spirit	$16.5x10^6$	24,750	10,642
derv.	$5.5x10^6$	33,000	99,000
Total		620,480	647,520
% coal		78	75
% diesel		5	15

YEAR: 1975

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$9.9x10^6$	346,500	346,500
coal industrial	$16.9x10^6$	42,250	42,250
coal power station	$74.6x10^6$	18,650	18,650
solid smokeless fuel	$5.3x10^6$	29,680	29,680
gas oil	$12x10^6$	3,000	4,650
fuel oil	$36.2x10^6$	36,200	15,566
motor spirit	$16.1x10^6$	24,150	10,384
derv.	$5.4x10^6$	32,400	97,200
Total		532,830	564,880
% coal		76	72
% diesel		6	17

YEAR: 1976

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$9.4x10^6$	329,000	329,000
coal industrial	$15.6x10^6$	39,000	39,000
coal power station	$77.8x10^6$	19,450	19,450
solid smokeless fuel	$4.7x10^6$	26,320	26,320
gas oil	$11.8x10^6$	2,950	4,572
fuel oil	$33.9x10^6$	33,900	14,577
motor spirit	$19x10^6$	28,500	12,255
derv.	$5.6x10^6$	33,600	100,800
Total		512,720	545,974
% coal		76	71
% diesel		7	18

Table 2.4 (continued)

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$9.7x10^6$	339,500	339,500
coal industrial	$15.4x10^6$	38,500	38,500
coal power station	$80.0x10^6$	20,000	20,000
solid smokeless fuel	$4.7x10^6$	26,320	26,320
gas oil	$12.8x10^6$	3,200	4,960
fuel oil	$33x10^6$	33,000	14,190
motor spirit	$20x10^6$	30,000	12,900
derv.	$5.7x10^6$	34,200	102,600
Total		524,720	558,970
% coal		76	71
% diesel		7	18

YEAR: 1978

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$8.7x10^6$	304,500	304,500
coal industrial	$14.7x10^6$	36,750	36,750
coal power station	$80.6x10^6$	20,150	20,150
solid smokeless fuel	$4.5x10^6$	25,200	25,200
gas oil	$12.5x10^6$	3,125	4,844
fuel oil	$34x10^6$	34,000	14,620
motor spirit	$21x10^6$	31,500	13,545
derv.	$5.9x10^6$	35,400	106,200
Total		490,625	525,809
% coal		74	69
% diesel		7	20

YEAR: 1979

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	$8.9x10^6$	311,500	311,500
coal industrial	$15.0x10^6$	37,500	37,500
coal power station	$88.8x10^6$	22,000	22,000
solid smokeless fuel	$4.5x10^6$	25,200	25,200
gas oil	$12x10^6$	3,000	4,650
fuel oil	$33x10^6$	33,000	14,190
motor spirit	$21x10^6$	3,500	1,505
derv.	$6.1x10^6$	36,600	109,800
Total		472,300	526,345
% coal		79	70
% diesel		8	21

Table 2.4 (continued)

YEAR: 1980

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	7.2×10^{6}	252,000	252,000
coal industrial	13.4×10^{6}	33,500	33,500
coal power station	89.6×10^{6}	22,400	22,400
solid smokeless fuel	4.4×10^{6}	24,640	24,640
gas oil	10.7×10^{6}	2,675	4,146
fuel oil	25×10^{6}	25,000	10,750
motor spirit	21×10^{6}	31,500	13,545
derv.	5.9×10^{6}	35,400	106,200
Total		427,115	467,181
% coal		72	66
% diesel		8	23

YEAR: 1981

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	6.9×10^{6}	241,500	241,500
coal industrial	11.9×10^{6}	29,750	29,750
coal power station	87.2×10^{6}	21,800	21,800
solid smokeless fuel	40×10^{6}	22,400	22,400
gas oil	10×10^{6}	2,500	3,875
fuel oil	21×10^{6}	21,000	9,030
motor spirit	20×10^{6}	30,000	12,900
derv.	5.5×10^{6}	33,000	99,000
Total		401,950	440,255
% coal		73	67
% diesel		8	22

YEAR: 1982

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	6.7×10^{6}	234,500	234,500
coal industrial	$11,9\times10^{6}$	29,750	29,750
coal power station	80.2×10^{6}	20,050	20,050
solid smokeless fuel	4.1×10^{6}	22,960	22,960
gas oil	9.5×10^{6}	2,375	3,681
fuel oil	21×10^{6}	21,000	9,030
motor spirit	21×10^{6}	31,500	13,543
derv.	5.7×10^{6}	34,200	102,600
Total		396,335	436,114
% coal		72	65
% diesel		9	24

Table 2.4 (continued)

YEAR: 1983

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	6.2×10^6	210,000	210,000
coal industrial	11.6×10^6	29,000	29,000
coal power station	81.6×10^6	20,400	20,400
solid smokeless fuel	3.9×10^6	21,840	21,840
gas oil	9×10^6	2,250	3,487
fuel oil	17×10^6	17,000	7,310
motor spirit	21×10^6	31,500	13,543
derv.	6.2×10^6	37,200	111,600
Total		369,190	417,180
% coal		70	62
% diesel		10	27

YEAR: 1984

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	4.8×10^6	168,000	168,000
coal industrial	9.3×10^6	23,250	23,250
coal power station	53.4×10^6	13,350	13,350
solid smokeless fuel	3.2×10^6	17,920	17,920
gas oil	9.9×10^6	2,475	3,836
fuel oil	33×10^6	33,000	14,190
motor spirit	21×10^6	31,500	13,545
derv.	6.8×10^6	40,800	122,400
Total		330,295	376,491
% coal		62	54
% diesel		12	33

YEAR: 1985

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	6.5×10^6	227,500	227,500
coal industrial	11.5×10^6	28,750	28,750
coal power station	73.9×10^6	18,475	18,475
solid smokeless fuel	4.2×10^6	23,520	23,520
gas oil	8.7×10^6	2,175	3,371
fuel oil	21×10^6	21,000	9,030
motor spirit	20×10^6	30,000	12,900
derv.	7.1×10^6	42,600	127,800
Total		394,020	451,346
% coal		70	61
% diesel		11	28

Table 2.4 (continued)

YEAR : 1986

FUEL TYPE	FUEL CONSUMPTION	SMOKE EMITTED	DARK SMOKE EMITTED
Coal domestic	7.0×10^6	245,000	245,000
coal industrial	12×10^6	30,000	30,000
coal power station	32.6×10^6	20,650	20,650
solid smokeless fuel	3.5×10^6	19,600	19,600
gas oil	8.3×10^6	2,075	3,216
fuel oil	18×10^6	18,000	7,740
motor spirit	21.5×10^6	32,250	13,867
derv.	7.9×10^6	47,400	142,200
Total		414,975	482,273
% coal		71	61
% diesel		11	29

Table 2.4 (continued)

values calculated for 1984 do not follow the general trend in terms of coal smoke emissions due to the coal miners' dispute, where less coal was burnt and fuel oil was substituted in place of coal (e.g. 14 k tonnes of black smoke were derived from fuel oil in 1984, whereas in 1983 the amount produced was 7 k tonnes). Because less coal was burnt during this year, the percentage contribution from diesel emission to total black smoke rose from 27% in 1983 to 32% in 1984. The contribution from the combustion of solid smokeless fuels to the UK totals only includes that from domestic sources, as the contribution of the industrially used fuel is negligible.

Figure 2.8 shows the total mass of smoke and dark smoke emissions (in tonnes) from 1971 to 1986 from combustion sources, from results presented in Table 2.4.

Figure 2.9 indicates that from 1971 to 1986, the percentage contribution of dark smoke emitted from diesels for the entire UK appears to be increasing by just less than 1% per annum; whereas coal's contribution to UK dark smoke levels shows a very gradual trend of decreasing by about 1% per annum (with the exception of data from 1984). The figures show that DERV is responsible for 29% of national black smoke emissions in 1986 and that in urban areas where coal consumption is small the percentage of diesel contribution will be much greater than this. This is illustrated in Table 2.5. The results in Table 2.5 for dark smoke emissions in London (1980) give diesel's contribution at 60% compared with coal at 15%. Yet in 1980 the National dark smoke contribution by diesels was 23% and coal at 66% and in 1986, 28% of the dark smoke was from diesel and 61% from coal. Obviously, the National data given in Tables 2.4 and 2.5 gives emissions for the entire area of the UK and so the emissions from coal combustion have a major proportion

FIGURE 2.8 TOTAL EMISSIONS OF SMOKE AND DARK SMOKE FROM FUEL SOURCES IN THE UK (1971-1986)

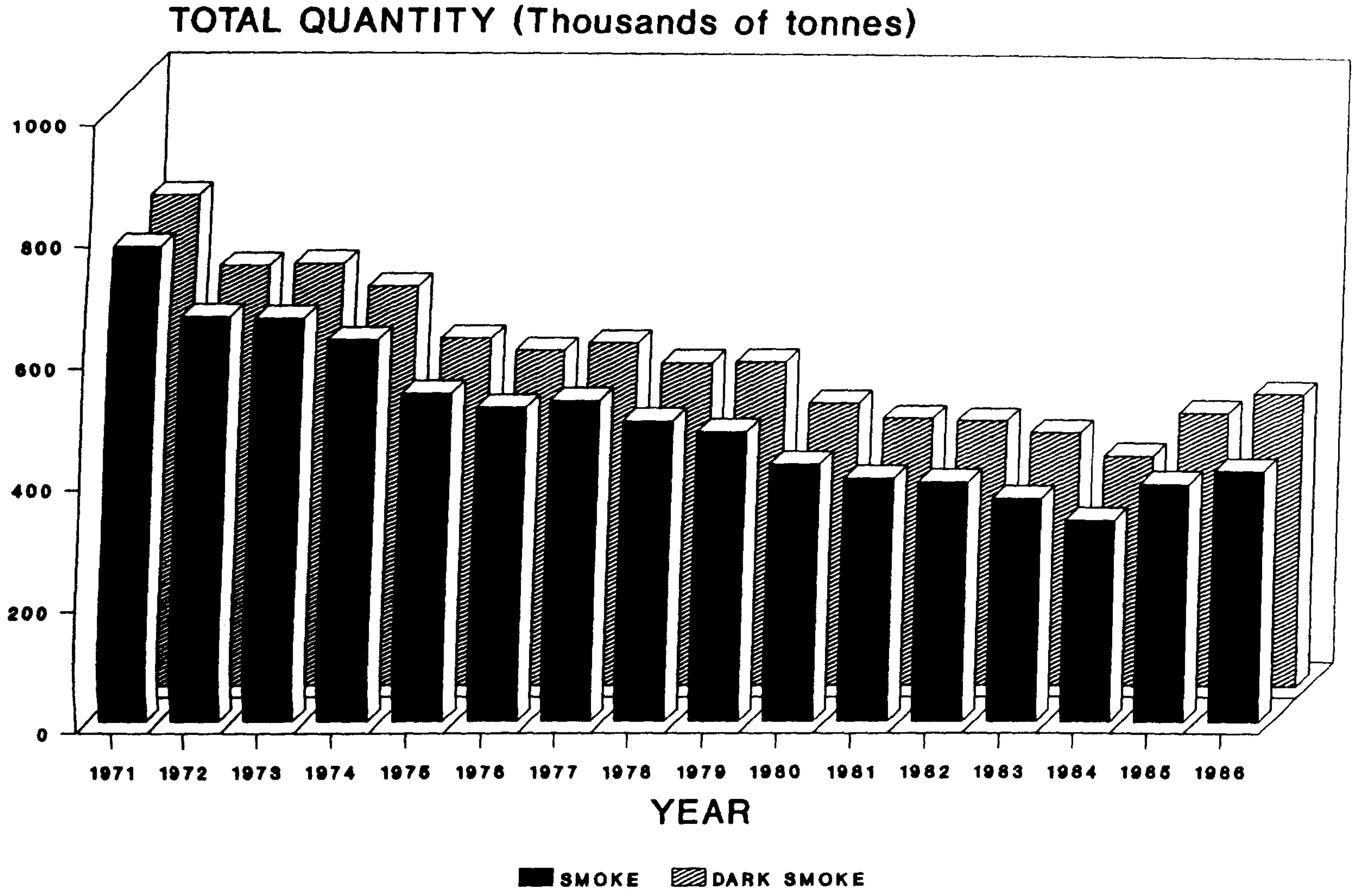
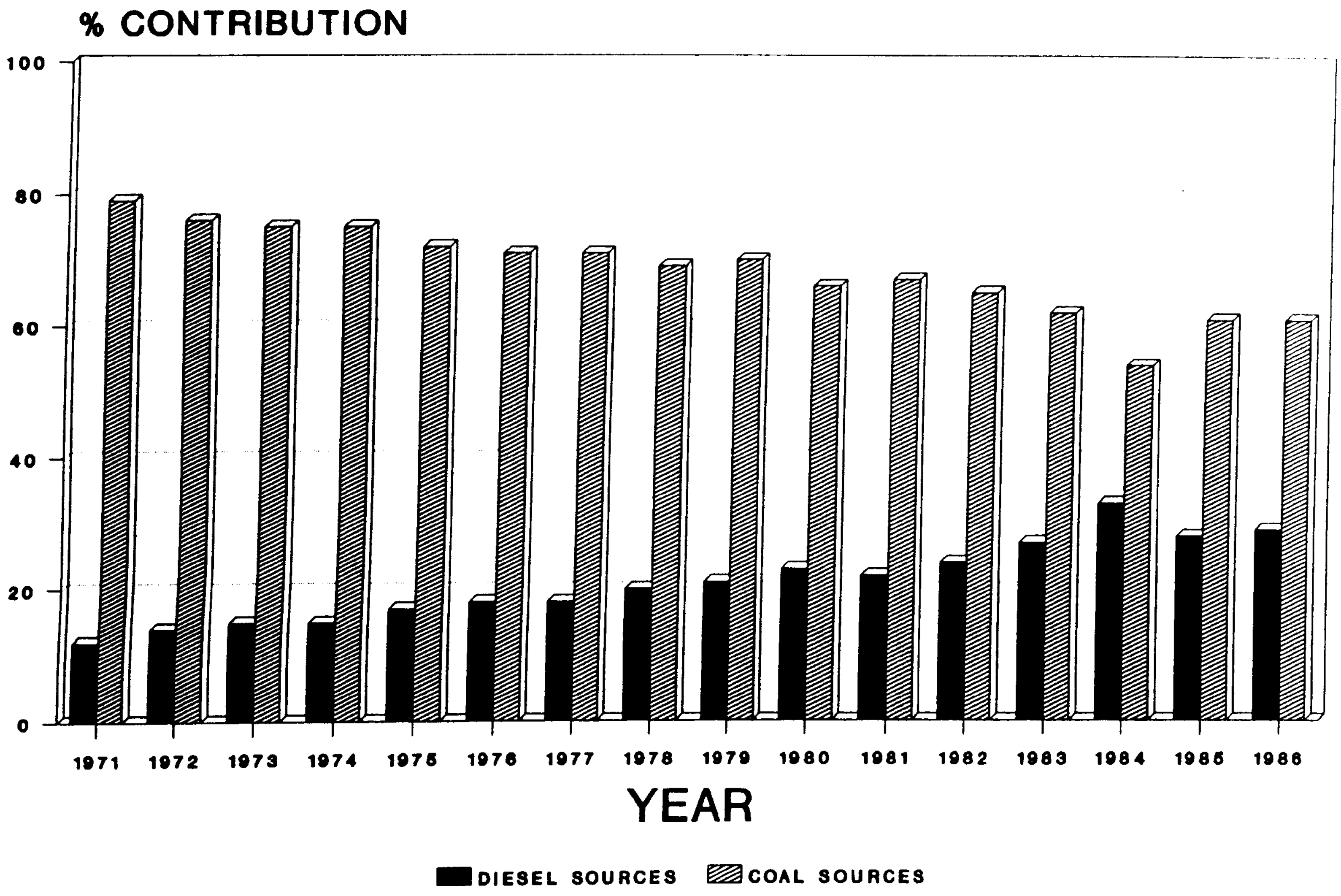


FIGURE 2.9 PERCENTAGE CONTRIBUTION OF UK DARK SMOKE MASS FROM COAL AND DIESEL COMBUSTION



of total dark smoke. The majority of diesel emissions occur within urban areas which is where over 85% of the British population live. There is clear evidence that the major source of dark smoke in urban areas is from DERV. As previously stated in 2.4.5 the siting of National Survey sites in urban areas has been traditionally located away from roadside locations, thus data from such sites may not reveal the true propensity of urban particulate matter and its soiling potential.

Table 2.5 The percentage contribution by fuel type to the total mass of dark smoke emitted for London (1980) UK (1980, 1986)

Percentage Contribution to total mass of dark smoke emitted for:

Fuel Type	London (1980)	UK (1980)	UK (1986)
Coal	15	66	61
Diesel	60	23	29
Solid Smokeless fuel	12	5	5
Gas oil	2	1	1
Fuel oil	2	2	2
Petrol	9	3	3

Emission inventories for dark smoke and smoke are still in their infancy and as Williams$^{(50)}$ notes very little work has been done in the UK to assess the validity of currently employed emission factors. He states that black smoke emission factor for a petrol driven car and a HGV DERV as 0.065% and 1.8%by weight respectively and given the consumption figure of 25 and 10 m.p.g these equate to 0.13 g km^{-1} and 4.3 g km^{-1}. However, work from the Netherlands suggests that for diesel vehicles (3.5 ton and with a DI engine) in urban locations the emission factor may be as high as 12 g km$^{-1(51)}$. More research is needed into diesel and other fuel emission factors for smoke and dark smoke if the true contribution by fuel use to dark smoke and hence soiling potential can be rigorously assessed. Indeed the type of calibration of diesel smoke as done by Wallin (1965) (39) has not subsequently been repeated. It may well be that when repeated, the figures quoted by Wallin may have to be revised. However, work has recently begun by Warren Spring Laboratory on particulate emissions from diesel lorries using a constant volume sampling technique(52) for on-road measurements and initial results show that particulate emissions from light-duty vehicles (1.6-2.5 l engine size) are in the range of 1 to 3 g per kilogramme of fuel and for 6 l engines,in the range of 19 g per kilogramme of fuel burnt.(53) Inventories for diesel vehicles are especially difficult to assess because of the vast range in their engine sizes as well as the different engine designs which can be employed.

The results in Figure 2.10(a) show the emission contributions to national airborne particulates in the Netherlands in 1985. Included is the contribution attributable from non-traffic, petrol engines and diesels over 3.5 ton and less than 3.5 ton. Figure 2.10(b) gives the national contribution of dark smoke production from fuel sources for the UK in 1985, from results presented in Table 2.4.

The relative contribution of different fuel types to the ambient particulate concentration (Dutch) and black smoke production (UK) is: in the ratio

Coal and other sources : diesel is approx. 7 : 3

for both countries on a national level. The other sources mentioned above include emissions from petrol vehicles as well as fuels used for domestic and commercial heating systems. Given that such heating

FIGURE 2.10(a)

EMISSION CONTRIBUTIONS IN 1985
TO DUTCH TSP LEVELS

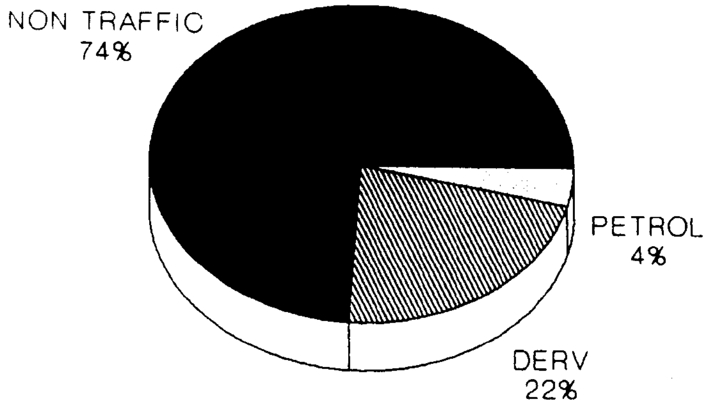
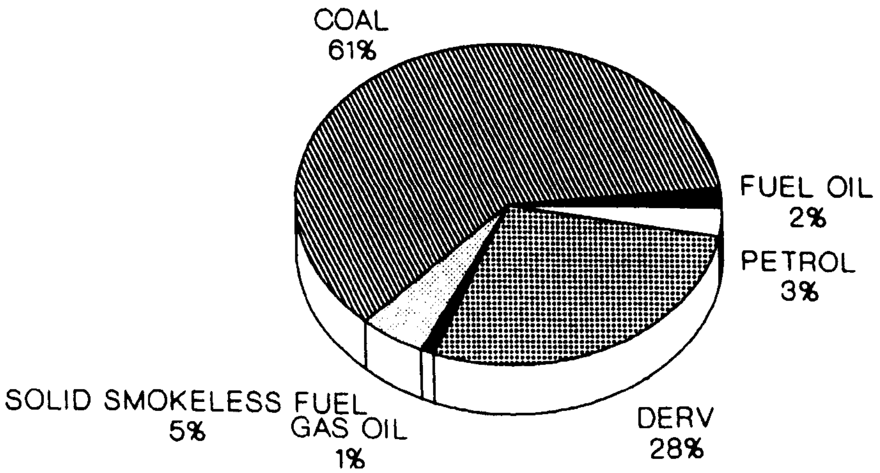


FIGURE 2.10(b)

EMISSION CONTRIBUTIONS IN 1985
TO UK DARK SMOKE LEVELS



system sources of dark smoke emissions occur predominantly within urban areas, their contributions on a national scale accounted for only 11% in 1986, while in London (1980) Table 2.5 showed that 25% of the dark smoke recorded was attributable to such sources.

Indeed, Table 2.5. showed that the relative contribution of different fuel types to black smoke production for London is in the ratio

Diesel: Coal: Solid smokeless fuel: Petrol: Gas and fuel oil (approx)
6 : 1.5 : 1.2 : 1 : 0.4

Thus, diesel black smoke production may be in the order of four times as great as that from coal in an urban area such as London.

CHAPTER THREE

AIRBORNE PARTICULATE ELEMENTAL CARBON

3.1 Carbonaceous aerosols: Introduction and Definition

The chemical and physical characterisation of carbonaceous atmospheric aerosols has begun to receive much attention in recent years. Carbonaceous particles in the atmosphere consist of two major components - graphitic carbon (alternatively referred to as black, particulate elemental i.e. PEC, or free carbon) and organic material.(54) On filtered samples, primary organic carbon shows few or no light-absorptive properties. The latter can either be directly emitted from sources (primary organics) or produced by atmospheric reactions from gaseous precursors (secondary organics). Gaseous forms of EC are only produced at extreme temperatures which are not usually achieved in conventional combustion engine processes. PEC can be produced only in a combustion process and is therefore definitely primary. Other minor sources of carbonaceous particles include carbonates and suspended soil carbon.(55) As Wolff noted there is a need for the adoption of standard terminology, for many researchers use a variety of names which are operational definitions based on their analytical methodology.(56) These names include: nonvolatile carbon, graphitic carbon, absorbing carbon, residual carbon. In 1985, Goldberg (57) proposed "that black carbon is an impure form of the element produced by the incomplete combustion of fossil fuel or biomass. It contains over 60% carbon with the major accessory elements hydrogen, oxygen, nitrogen and sulphur". Diamond and metamorphic graphites are excluded from this consideration. Because there is increasing research into the environmental effects of black carbons, a general definition that can be modified in the future as more information becomes available is essential. In this way, comparisons between the measurements recorded by different laboratories can be more easily facilitated.

3.2 The chemical and physical properties of Particulate Elemental Carbon (PEC)

3.2.1 The structure of PEC

Although not very plentiful in the earth's crust (0.1% by mass), carbon is the second most abundant element in the human body (17.5%). It occurs in all plant and animal tissues, combined with hydrogen and oxygen and in their geologic derivatives, petroleum, coal and natural gas, where it is combined mostly with hydrogen in the form of hydrocarbons. Combined with oxygen, carbon occurs as carbon dioxide in the atmosphere and dissolved in the seas and as carbonates in rocks such as limestone. In the free state, carbon occurs to a limited extent as diamond and graphite, the two allotropic forms of the element.

As shown in Figure 3.1, the principal difference between diamond and graphite is that in the former, each carbon atom has four nearest neighbours, whilst in the latter each carbon has three.

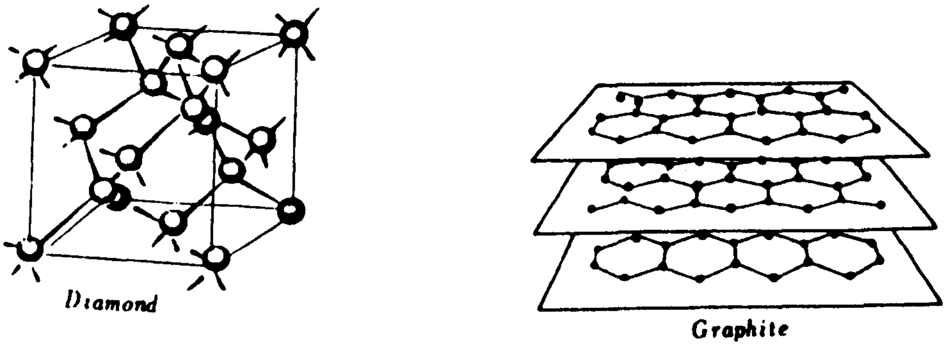


Figure 3.1 The allotropic forms of carbon.(58)

In graphite the structure consists of giant sheetlike molecules which are held together, 0.340 nm apart, by Van der Waals forces. Within the sheets each carbon atom is covalently bound by sp^2- hybrid orbitals to three neighbours 0.142 nm away, which are in turn also bound to three carbon atoms. Since each carbon has four valence electrons and only three carbons to bond to, there are more than enough electrons to establish single bonds by the use of sp^2- hybrids. The fourth electron goes into the p_z orbital perpendicular to the plane.

However, since there is no preference as to which atom the last electron should bond to (all three neighbours being equivalent), it must be considered as forming a partial π bond to all three neighbours.
The electronic configuration of graphite has been represented as a resonance hybrid of the three formulas shown at the top of Figure 3.2.

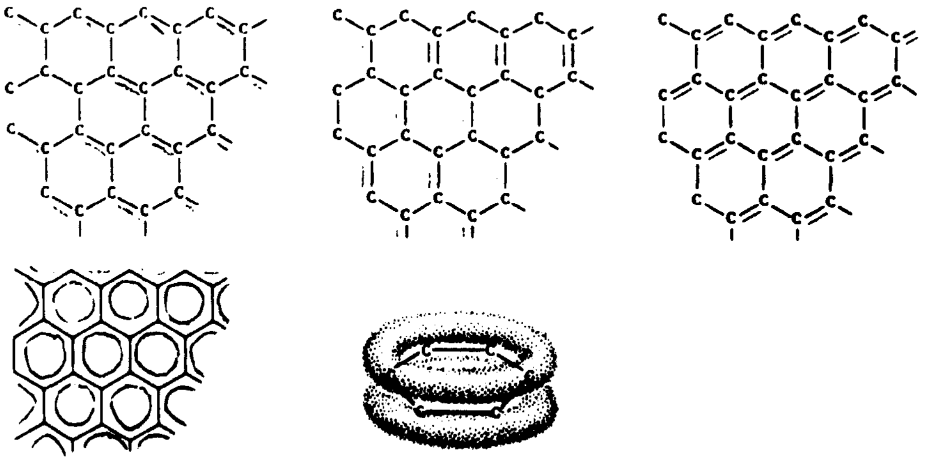


Figure 3.2 Bonding in graphite.(58)

In the lower left of Figure 3.2, an alternative representation is given in which circles stand for the so-called "π-electron system". The electrons are in molecular orbitals derived from the p_z orbitals (the

Z direction being perpendicular to the sheet). There is one electron from each carbon atom in the π system. A portion of the π system is shown in the lower right of Figure 3.2.

In addition to graphite, there are several porous forms of carbon which are similar in character. These include coke (made by heating coal in the absence of air), charcoal (made from wood in the same way) and black carbon (soot). They all have large surface areas, for example 1 cm^3 of charcoal can have a surface of 50 m^2. Since each exposed carbon atom at the surface can use its extra valence electron to bind other atoms these forms of carbon have strong adsorption properties.

The elemental carbon particles resulting from the incomplete combustion of fossil fuel have a diameter which may vary from a few nm to several hundreds nm. The results of X-ray diffraction have shown that each particle consists of a large number of crystallites of 2 to 3 nm in diameter.(59) The crystallites contain several carbon layers but in contrast to the parallel sheets of C_6 rings found in graphite, a regular stacking of the carbon sheets is not found in PEC. Instead, the sheets may be distorted and disoriented and contain some hydrogen and oxygen impurities. Such defects are probably responsible for the observed catalytic activity of elemental carbon particles and this is discussed in the next section. It is thought that the mobility of the π electrons is responsible for the light-absorption properties of PEC which is reviewed in Section 3.6.1.

3.2.2 The catalytic properties of PEC

Carbon particles can play an important role as catalyst for many chemical reactions in the atmosphere. The assessment of the impact of these carbon-catalysed reactions on air quality is difficult because the kinetics and mechanisms have not been well studied. The reaction which has been most extensively examined is the role of PEC catalysts in the oxidation of sulphur dioxide (SO_2) to sulphur trioxide (SO_3), which quickly hydrolyses to form H_2SO_4 aerosol. Chang et al (60) predict that the above catalysed reaction, in an aqueous suspension, is the dominant mechanism of sulphate formation in heavily polluted urban fogs near common SO_2 and PEC sources. Siedlewski (1965) has shown that the free electrons on carbon particles can serve as active centres for the adsorption of oxygen molecules and for the oxidation of SO_2 (61). The concentration of free electrons is related to the origin and thermal history of the carbon particles. Thus it is impractical to develop a generally applicable rate constant for the production of atmospheric soot particles. This is because these particles may arise from the combustion of different fuel types under different combustion conditions and so possess a different catalytic activity.

However, it should be remembered that if the soiling of buildings is attributable to PEC, then soiling may not be just a nuisance in terms of an aesthetic blight, but also may be involved in enhancing the rate of fabric erosion by catalytically facilitating the conversion of acidic gases such as sulphur dioxide and nitrogen oxides into sulphuric and nitric acids respectively in the presence of water (rainfall).

Work carried out by Del Monte et al (62) on the deterioration of marble surfaces exposed in an urban atmosphere found that the transformation reaction of calcite into gypsum was readily catalysed by black carbon cenospheres produced from oil burning. Photomicrographs of affected marble have shown spherical particles to be embedded in the sulphate-calcite altered layer and that unaltered calcite is free of such cenospheres. The sulphur associated with such fly-ash particles has been attributable to the source of the sulphates.

Once such acids are present on the building fabric surface they may then react for example with limestone ($CaCO_3$) and convert it into gypsum ($CaSO_4$) or calcium nitrate ($Ca(NO_3)_2$) in the cases of sulphuric and nitric acids respectively. These latter compounds are more soluble and leachable with rainfall than limestone and thus elevated erosion rates may occur. Calcium nitrate is more leachable than gypsum and considering the emissions of nitrogen oxides are increasing within the ambient atmosphere (as over 40% of the national emissions are vehicularly derived)(47), this may be a factor in explaining the fact that rates of building erosion are much the same as when ambient pollution levels of smoke and sulphur dioxide were much greater than they are now. Work carried out on the erosion rates of balustrades on St Paul's Cathedral, London, indicate that limestone was being eroded at a rate of 8 mm every 100 years during the eighteenth century and the rates today are very similar despite a dramatic decrease in the levels of SO_2 and smoke.(63) Perhaps, this is due to the 'memory effect' of stone as noted by Gibbs and/or the increasing contribution to erosion rates by the emission of nitrogen oxides and subsequent formation and effect of nitric acid on the stone surface. (64) The role of the latter has been noted by the Building Research Establishment Group (65) as an area deserving more research attention so its effects on stone may be vigorously assessed. As will be illustrated in Chapter Seven, one of the main benefits of stone cleaning as stated by such companies is that cleaning prolongs the building fabric life. Such companies' circumstantial evidence has yet to be confirmed. In that by removing soiled particles of carbon from a building's facade enhanced rates of stone erosion may be prevented and prove that Schaffer's (1932) (66) statement that soiling deposits may damage the building fabric is true and still relevant to today's forms and levels of atmospheric pollution as is illustrated in Figure 3.3.

Figure 3.3 A view of a section of the spire of The Church of St Mary the Virgin, Oxford

3.2.3 The adsorptive properties of PEC

The porous nature of the black carbons is in part responsible for their adsorption characteristics. The size of the pores is in the tenths of nanometers range. The greater the porosity the greater the ability to transfer mass. This adsorption ability has been used in industry for many years. For example, activated carbon has been used to remove odorous fumes resulting from industrial processes. However, it should also be noted that elemental carbon particles resulting from incomplete combustion of fossil fuels are chemically and catalytically active and can be effective carriers for toxic air pollutants through their adsorptive capability. The potential health effects of this phenomenon are reviewed in Section 3.6.3. Carbon atoms located at active sites show strong tendencies to react with other molecules because of their residual valencies.

During particle formation, interactions between flue gas, water, air, etc and carbon particles occur, resulting in the incorporation of hydrogen, oxygen and nitrogen into the structure.(60) As Mattson and Mark(67) note: it is the surface chemical properties which may be of greater importance in determining the adsorptive capabilities of a given black carbon. They note the principal factors involved are (1) the nature of the starting material; (2) the chemical characteristics of the environment in which the carbon was formed and (3) the time and temperature of the reactions yielding the carbon. The types and amounts of minerals in the starting materials affects the absorbtivity of the final product.(67) Also black carbons may possess acidic or basic characters usually governed by their mode of formation. Exposure of black carbon to oxygen at temperatures between 200 and 400°C yields an acidic type, while treatment at high temperatures in carbon dioxide or in vacuo followed by exposure to oxygen produces a basic form.

3.2.4 The shape, size and chemical composition of PEC

Three characteristic of the environmental black carbons are often used to try and identify their sources and the distance travelled from the source to the site of deposition. They are their surface morphologies, shapes and size distribution.

Various types of black carbon are produced in the combustion of organic materials. Four distinct types (although not necessarily source specific) have been identified by Medalia and Rivin.(68) The smallest particles are formed through coagulation from the gas phase and have been designated as "aciniform carbon". This is defined as "clustered like grapes". They are (near) spherical with mean diameters around 20-30 nm and adhere to each other to form straight or branched chains.

A second form includes cenospheres - hard, shiny, porous or hollow carbon spheres which are usually 10-100 µm in diameter. They form when liquid drops undergo carbonization without major changes in shape. These are produced from coal and oil burning.

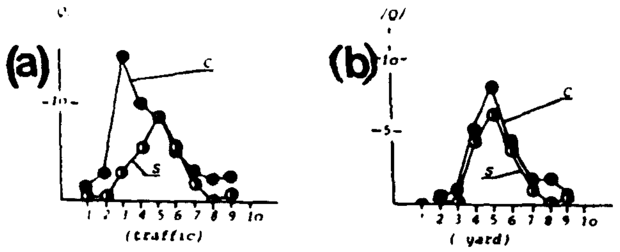
The third form includes the charcoals or chars, small fragments of carbonized woods or coals - ranging in size from microns to fractions of meters. They can maintain the structures of plant, tree or animal parts from which they originated.

Finally there are "carbonaceous microgels" which are formed from microscopic entities in which spheroidal carbon particles with colloidal dimensions are embedded in organic materials. Figure 2.2. illustrates results of some microscopic examination of soot particles as described above.(13)

Recent developments of electrical aerosol analyzers, cascade impactors and of scanning electron microscopic techniques have provided a basis for in-depth studies on the size distributions of black carbon in ambient and source samples.

The small particle mode (those < 1 µm) may comprise black carbons formed through a condensation process with gas phase moieties. Larger particle modes may be produced as a result of the union between two or more discrete assemblages. Their sources can be the cenospheres and chars from fossil fuel and wood burning, as well as particles that have grown by the accumulation of other particles.(57)

Whitby has found multimodal distributions of black carbons issuing from a variety of combustion sources such as flames, diesel engines and motorway traffic.(69) Also, Wilson demonstrated size distributions recorded in a group of cars driving along a highway exhibited three distinct modes each of which can be attributed to certain processes of particle production.(70) Subsequent work carried out in Vienna, using a low pressure impactor showed that automotive traffic produces large amounts of nucleation mode material in the size range below 0.1 µm.(71) Most of this material was soot and other organic carbon compounds. After ageing, i.e. coagulation and dilution in the urban atmosphere, the nucleation mode material contributes to the accumulation mode; an accumulation mode of carbon was found at 0.5 µm. There is a "coarse mode" at several microns that is attributed to the precipitation of fine particles on the walls of exhaust systems and a subsequent entrainment in the issuing gases. The authors also noted that soot material was indicated by the optical appearance of the aerosol deposits. Whereas the deposits of the coarse particles are greyish, those of the accumulation mode exhibit a black colour, which even deepens in the nucleation mode size range. This agrees with the findings reported in Section 2.4.3, that it is the smaller sized particles that are the most responsible for the soiling of filter samplers and that these arrive predominantly from sources of carbon-based fuel combustion. Evidently, carbon is a main constituent of the nucleation mode produced by the traffic. This is supported by comparative studies where the in-traffic aerosol was measured along a road and where another impactor was operated in a back yard. These results are illustrated in Figure 3.4(a) and 3.4(b)(71).



Stage numbers: 1:≈0,021µm; 2:≈0,042µm; 3:≈0,087µm; 4:≈0,18µm; 5:≈0,35µm; 6:≈0,71µm; 7:≈1,4µm; 8:≈2,8µm; 9:≈5,7µm; 10:≈11,3µm.

/Q/: quantity of mass, elemental carbon or sulfate, µg/m³ per stage

M: mass distributions, C: carbon distributions, S: sulfate distributions

Figure 3.4 The size distributions of ambient carbon and sulphate particulate as sampled from (a) in-traffic and (b) backyard.(71)

The carbon distribution in traffic exhibits a peak at 0.08 µm aerodynamic equivalent diameter (a.e.d) and is present as a bump at the position of the accumulation mode. Whereas at the remote site, the nucleation mode disappears and an accumulation mode remains in the carbon distribution. This result which is found in all other comparative measurements is again evidence that nucleation mode material is directly produced by the traffic and that there is a rapid decay of the nucleation mode by coagulation and dilution. The authors suppose that the accumulation mode of the carbon distribution is mainly a coagulation product of the nucleation mode material.(71)

Work has also been carried out on particulate carbon emissions and their size distribution from diesel engines under a variety of engine conditions.(72) This work notes that the production of diesel particulates increases with engine load, due to the increase of fuel/air ratio and the lack of adequate oxygen for complete combustion as mentioned in Section 2.3.3. The spread of particle sizes increased as the load increased. The mass median diameter for all loads showed little variation with an average of 0.52 µm. The concentration of particles in the size range 0.4-1.0 µm decreased at higher loads but that of intermediate particles (2-9 µm) showed only a moderate variation. However, the concentrations of both fine (< 0.4 µm) and coarser (>10 µm) particles increased markedly with engine load. These studies suggest that agglomeration is the main mechanism responsible for the increased particle size distribution as the load is increased.

The size of PEC particles emitted into the atmosphere affects their dispersion within the ambient environment. However, the chemical association of such particles is also a factor which may influence the extent of its dispersion. Thus, the ash, tar and associated volatile organic molecules such as polycyclic aromatic hydrocarbon compounds, that may be produced with the different black carbons appear to be characteristic of their modes of formation but also may influence their adhesive properties. For example, if a particle of elemental carbon is coated with a sticky co-generated adhesive compound, its soiling propensity may be enhanced in that, if such a particle is deposited on to a surface its removal may be more difficult to achieve than had it not been coated with an adhesive compound. Likewise if it was coated with a water soluble compound its removal from a surface may be facilitated, with the compound and particle being removed by rainfall.

Table 3.1 reports the composition of some black carbons. The furnace black sample produces a relatively pure source of PEC, whilst other sources produce a soot which is less than 50% PEC, the rest often being organic matter. It is interesting to note the comparatively high percentage of PEC in diesel soot and the value recorded in urban dust. Values of PEC recorded experimentally in this project for air samples and soiled material samples are given, and further discussed in Chapter Six.

Clearly, the physical, chemical, adsorptive and catalytic behaviours of carbon particles depend very much on their crystalline structure, surface composition and electronic properties. Indeed the initial chemical composition and process of formation for PEC determines whether the PEC is hygrophobic or hygroscopic as it is when coated with H_2SO_4. Factors such as these also govern the life cycle of the particles once they have been emitted into the atmosphere and are discussed in Section 3.3.

Table 3.1 The composition of some black carbons(68)

Sample	% elemental carbon	% ash	Weight loss (N_2,910°C)	% extractable in Methylene chloride + toluene	% extractable in Water
Furnace black	98	0.27	1.5	0.13	0.90
Chimney soot from wood-burning fireplace	0.024	21.8	48.0	15.8	14.2
Blended chimney soots from domestic coal fires	0.36	24.6	52.4	35.6	19.0
Soot from "soot box" of domestic oil furnace	0.83	53.8	43.7	0.64	50.7
Soot from small diesel engine	51	2.2	49.2	51.1	3.6
Urban dust	0.47	64.6	36.2	2.9	27.0

3.3 The atmospheric cycle of PEC

It is necessary to evaluate the presence and life-cycle of particulate elemental carbon (PEC) in the atmosphere so that attempts to understand and predict its impact on the environment can be made. Charlson and Ogren(73) state these effects can be organized into four categories:

1 Effects which are functions of CONCENTRATION, such as the atmospheric heating rate due to absorption of sunlight;

2 Effects which are functions of DOSAGE or a product of concentration and time of exposure. For example the effect on health by the bodily accumulation of carbon;

3 Effects depending on a COLUMN BURDEN, such as the influence on

visibility along a sight path;

4 Effects depending on a FLUX DENSITY such as the rate at which carbon is deposited on to surfaces.

Under atmospheric conditions, PEC is essentially inert, as its chemical properties are largely determined by the nature of graphite, the surface characteristics and co-existing substances. Graphite is inert at ordinary temperatures, hygrophobic and insoluble in any solvent. For example, extreme conditions such as temperatures of over 600°C are required to oxidise graphite in air. So given that chemical removal mechanisms are non-existent, physical removal mechanisms such as that by wet or dry deposition are the only modifications and removal processes that exist for PEC within the atmosphere.

3.3.1 Dry deposition of particulate matter from the atmosphere

Aerosol particles may contact the ground or other surfaces and be deposited in the absence of precipitation. This is usually known as dry deposition. Dry deposition can occur by gravitational sedimentation, inertial impaction or Brownian diffusion. Size is an important factor in determining the removal mechanism and its rates. Particles less than 0.1 to 0.2 μm do not move in response to gravitation or electrostatic forces, but are controlled by Brownian motion. Diffusion processes control the deposition rates of these small particles. The deposition of particles larger than 1 μm is determined by aerodynamic processes including sedimentation to the ground. By using Stokes' drag law for viscous flow, the terminal velocity of such particulates can be calculated, and it increases with the square of the particle diameter. For example, unit-density spheres of 0.1 and 1 μm in diameter, the terminal velocities are 0.0004 cm sec^{-1} and 0.0035 cm

sec^{-1} respectively as is indicated in Figure 2.1.

The effect of sedimentation on particulate matter less than 1 µm is negligible, and turbulent diffusion controls their transport to the surface. Indeed, at very low wind speeds and stable conditions, lack of turbulence can effectively impede the deposition of such particulate matter. Thus, because of the relative inefficiency of such processes leading to the dry deposition of fine particulates, transport over large distances is possible. As is described in Section 3.6.2, significant transport of particulate matter on the macroscale, of more than several thousand kilometres may occur. For example, a study by Rahn (1971) strongly suggested that PEC and the associated springtime sulphate haze observed in the Artic originated from sources in Eurasia, and that the mean transport time from the sources to Point Barrow in Alaska was in the order of 20 days.(74)

However, because of the small size and near-surface sources of vehicular PEC emissions it has been suggested that dry deposition is a more important removal mechanism for them than for particles emitted from elevated stacks. This, and the fact that there are larger concentrations in urban areas, indicates that urban dry deposition fluxes are probably larger than in rural areas. Heintzeberg and Winkler(75) suggest that coagulation near the source rapidly decreases the number, concentration and increases the mean size, so that the residence time of PEC in an urban atmosphere is in the order of hours compared with that in the upper troposphere of several days. This is because Brownian motion is more pronounced in smaller sized particles which increases the occurrence of collisions with other particles and the opportunity to form agglomerates.

3.3.2 Wet deposition of particulate matter from the atmosphere

Aerosols can be removed from the atmosphere by rain or snow. This process is termed wet deposition. Two basic processes are involved. Firstly, 'rainout', the result of the aerosol serving as a condensation nucleus for water vapour or being captured in the formation of cloud droplets. The second process is called 'washout' and is the removal of aerosols by falling raindrops. Several physical processes act together and contribute to rainout. Particulates larger than 1 μm can serve as condensation nuclei for the formation of cloud droplets. Submicron particulates may significantly increase their size through water condensation in convective clouds.

Removal rate mechanisms indicate that washout is generally very effective for particulates larger than 1 μm. Inertial capture is ineffective for smaller particles. Particles above 0.1 μm in diameter are practically unaffected by falling rain. For smaller particulates, the removal rate increases because of Brownian diffusion. The total efficiency of wet deposition has been largely studied for sulphate aerosols. The majority of the sulphate mass within the atmosphere is in particles of diameter of 0.1 - 1 μm.(76)

Precipitation scavenging is likely to be the predominant removal for PEC under most conditions, although the exact way in which PEC is incorporated into rain depends upon the size and hygroscopicity of the PEC - containing particles as was mentioned in 3.2.4. Thus, for example, accumulation-mode PEC (0.1 - 1 μm diameter particles) coated with hygroscopic substances, removal may be achieved via the nucleation of cloud droplets which ultimately falls as rain. The dominant removal mode for PEC less than 0.1 μm diameter is by diffusion to cloud and rain droplets. Both these mechanisms are effective so that the atmospheric residence time is in the order of days for such particles and is similar to that of soluble submicron sulphate particles. However, accumulation-mode PEC being hygrophobic has a longer residence time because the processes of nucleation scavenging and diffusion to hydrometeors are less effective in these circumstances.(77) The abundance of PEC in rainwater is thus dependent upon not only the amount of PEC in the air, but also upon the degree to which PEC is coated with hygroscopic substances; the presence of the latter may also depend upon the abundance of such natural or anthropogenic sources already present in the atmosphere, or emitted simultaneously with the PEC. Indeed, source characteristics is one of the four main factors responsible for the cycling of PEC through the atmosphere, the other three being aerosol mechanics, chemical properties of PEC and meteorological factors.(73) With respect to the source characteristics of PEC, as was shown in Section 2.3.3 naturally or anthropogenically produced sources of PEC almost all involve combustion; be it gas phase reactions in which hydrocarbons are dehydrogenated or the pyrolysis of a droplet or particle of a carbon containing material such as the soot produced by oil burners or diesel engines. Plus, as was shown in Table 3.1 some sources produce relatively pure PEC whilst others produce a soot which is less than 50% PEC. Table 3.3 will also illustrate that source factors govern the mass of PEC emitted into the atmosphere. The amount of PEC produced per unit of fuel burnt varies with the type of fuel, as well as the operating conditions, for example, a badly-tuned engine will burn fuel less efficiently and thus more incomplete combustion occurs.

3.3.3 Measurement of wet and dry deposition fluxes of PEC

The measurement of the wet removal flux may be obtained by the chemical analysis of the insoluble material in precipitation samples. An estimate of the dry deposition flux may be obtained by exposing the clean surface to the atmosphere but not to precipitation. This surface is then washed and the resulting solution analysed in the same way as the precipitation samples. In this way an estimate of the contribution to the precipitation samples can be obtained. Ogren et al (77) did exactly this for a 17 day period near Seattle, America. They found the contribution of the dry deposition measurement was only 4% of the total deposition (9 mg m^{-2} h^{-1}) for the site studied. However, the site had a comparatively low PEC concentration in air of 0.5 µg m^{-3}, compared with levels often observed in urban areas now typically range from 2-16 µg m^{-3} (as will be illustrated in Table 3.6) and thus the dry deposition fluxes may be greater in urban areas than those observed by Ogren for Seattle.

It is also worth noting that Ogren et al report that PEC demonstrated a strong affinity for the walls of some of the sample containers used in this research. For example measurements on conventional polyethylene buckets and stainless steel beakers indicated that about half of the PEC was retained on the walls of such containers, even after vigorous scrubbing with distilled water and surfactant. However, with glass containers less than 5% of PEC was retained by the surface.(77) Thus illustrating the fact that certain surface properties and textures exhibit different abilities in the retention of PEC. For example, a smooth surface has less aerodynamic resistance to that of a rough one which may cause turbulence to the airflow around the surface and thereby cause the deposition of particles within that air stream. The surface also exerts a strong influence on micrometeorological conditions around it, for example thermophoresis causes the darkening of surfaces above heating appliances due to the warm air circulation. Other examples of the ability of different materials to retain particulate matter on their surfaces are given in Section 4.1.2 and results from this research appear in Chapter Six.

The role of rainfall in PEC transport at surfaces has been partially measured within this experimental research and is given in Chapter Six. It appears to indicate that rainfall increases the reflectance of a surface after a rainfall event. This may be because coarser particles are removed with the action of rainfall and thus a cleansing process occurs. However, the rainfall may deposit PEC on to surfaces and thus some soiling is occurring but is masked because the removal of the larger particles produces an overall increase in the previous reflectance level recorded.

The fact that PEC can demonstrate strong affinities for certain surfaces is due to the chemical nature of the surface of PEC, which is often coated with condensed hydrocarbons(78) and as previously mentioned, these hydrocarbons adhere strongly to vessels made from or coated with similar materials. The hydrocarbons are attached to PEC which is vehicularly derived and this may increase the propensity of such particles in building soiling, especially given that even the use of a surfactant on Ogren's soiled containers could only remove 50% of the PEC.(77) The role of rainfall alone in removing soiled particles which are vehicularly derived from a building's surface may be limited.

3.4 Area emission identification of PEC sources

3.4.1 Introduction

Carbon particles emitted from many source types are chemically indistinguishable. Furthermore, primary aerosol carbon emissions to the atmosphere arise from more than fifty classes of mobile and stationary sources.(79) An assessment of the contribution of the different classes of emission sources to recorded air quality can be attempted by four routes:

(i) chemical element balance receptor models;

(ii) emission inventories;

(iii) emission inventories and dispersion models;

(iv) use of tracers.

It is difficult to obtain unambiguous separation between sources contributing to the carbon content of an ambient sample by the multivariate statistical methods used in chemical element balance studies. Emission inventories may suffer because some of the more important sources may be overlooked and uncertainties exist in estimating the dispersion characteristics from the various sources.

Using information on the level of source activity, total aerosol emission rate, particle size and chemical composition, an estimate of the mass emission rate of total carbonaceous and particulate elemental carbon for the Metropolitan Los Angeles area was carried out by Cass et al.(79) They found that 46 metric tons of fine aerosol carbon was emitted daily in this area, and 33% of that material was present as PEC.

Figure 3.5 shows the percentage contribution by source of the total 15 metric tons per day of PEC emitted in the area.

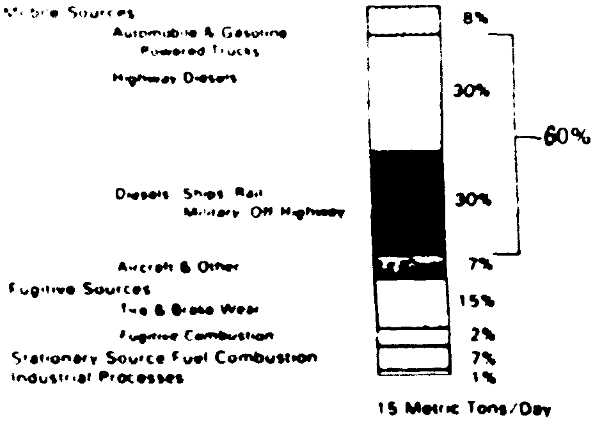


Figure 3.5 <u>Sources of non-volatile particulate carbon, greater Los Angeles Jan-Feb. 1980.</u>(79)

It is seen that the elemental carbon emissions (in particle size less than 10 μm in diameter) for this area, was dominated by internal combustion engines burning light and middle distillate fuel oils (diesels and jet aircraft). Indeed, diesel engines consumed less than 5% of the fuel burnt within the air basin, but accounted for as much as the 60% of the estimated PEC emissions. As Wolff (1981)(56) notes despite all combustion sources emitting PEC, the most important sources appear to be motor vehicles in urban areas and wood combustion where this is the predominant source of fuel used, as is illustrated in the following sections.

3.4.2 Vehicular Sources of PEC

Diesel exhaust particulates are usually defined as any material collected on a filter at a temperature below 52°C excluding condensed water.(80) Diesel particulates consist predominantly of combustion generated soot and adorbed or condensed hydrocarbons. Smaller amounts of sulphates and fuel additives may also be present. Figure 3.6 illustrates the typical composition of a diesel particulate.(80)

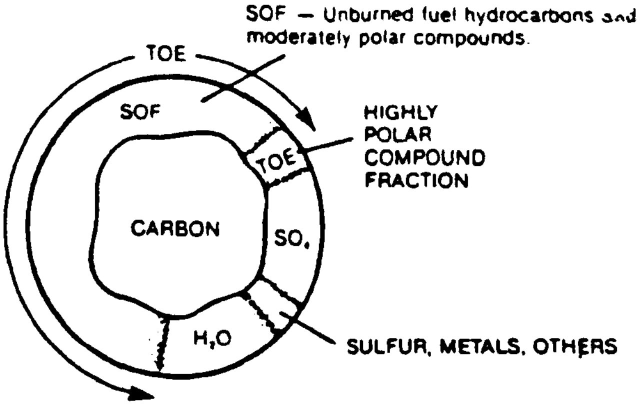


Figure 3.6 DIESEL PARTICULATE COMPOSITION(80)

DEFINITIONS

TOTAL PARTICULATE MASS (TPM) - All material collected at 52° ± 3°C according to US EPA procedures.

SOLVENT EXTRACTABLE FRACTION (SEF) - Material removable by various organic and inorganic solvents.

COMBINED WATER - Water associated with sulfates and measured by drying TPM over drierite.

SOLVENT EXTRACTABLE FRACTIONS

SOLUBLE ORGANIC FRACTION (SOF) - SEF removed by SOXHLET EXTRACTION with METHYLENE CHLORIDE.

TOTAL ORGANIC EXTRACT (TOE) - SEF removed by SOXHLET EXTRACTION with TOLUENE: ETHANOL.

WATER SOLUBLE SULFATES (SULFATES) - SEF removed by WATER and analysed by ION CHROMATOGRAPHY.

Diesel exhaust particulates consist of a solid fraction where the carbon/hydrogen molar ratio varies from 8:1 to 11:1, a soluble organic fraction, sulphates and trace elements.(81) Most of the particles are due to the incomplete combustion of fuel hydrocarbons, though some are contributed by the lubricating oil and other fuel carbon components. The particles themselves are carbonaceous solid chain aggregates on which organic compounds are adsorbed. Diesel particulates consist of over 90% by mass of particles with a size less than 1 μm.(82) However, upon sampling diesel particulates on a filter paper, particle agglomeration occurs and the particle sizes are generally larger than 1 μm. Electron microscopy examination of such filter papers, typically gives a mean particle size of 2-3 μm.(83)

3.4.3. Sources of PEC from domestic wood burning

Residential firewood use is concentrated in the urbanized areas of the northeast and north central states of the United States. In some cities, it can account for a substantial amount of the particulate matter in the winter atmosphere. Thus, in the Denver, Colarado area, about 20-30% of the aerosols are attributed to this activity and 50% in Portland, Oregon.

The carbon emissions from domestic fireplaces have been studied by Muhlbaier and Williams (1982)(84). They attribute the higher production of charcoal from softwoods as a consequence of their high content of lignin that previously had been shown to promote charcoal formation. This evidence is presented in Table 3.2.

Table 3.2 Carbon emissions from the combustion of wood in domestic fireplaces.(84)

Type	Organic C	Elemental C g kg^{-1} wood	Remainder
Softwood	2.8 ± 1.5 (45%)	1.3 ± 0.5 (21%)	2.1 ± 0.6 (34%)
Hardwood	4.7 ± 3.4 (47%)	0.39 ± 0.34 (4%)	4.9 ± 4.2 (49%)
Synthetic log	1.7 ± 1.1 (24%)	3.5 ± 3.3 (49%)	2.0 ± 1.2 (28%)

Another study has shown residential wood combustion contributes about 75% of the black carbon in aerosols from Elvenum, Norway, although this burning only accounts for 3% of the energy production.(85)
Much less is known about the EC emissions from other combustion sources. Although they appear to be less significant than vehicular and wood burning emissions, this is a field which requires additional work. However, the results of air emission inventory for PEC from combustion derived sources for London (1980) and the UK (1971-1986) are given in the following section.

3.4.4 Emission Inventories of PEC for London and UK

As shown in Section 2.4.3 the size of particles most responsible for the blackening of filters sampling the ambient aerosol are less than 2 µm in diameter and that the majority of such particles are derived from the incomplete combustion of fossil fuels. The unburnt fuel is cracked to produce carbon and hydrogen and the carbon forms a basic constituent of the resulting smoke. Airborne particulate elemental carbon (PEC) is particularly important in the context of the darkness of the smoke, as will be shown in this section.

To approach the problems of identifying PEC sources in the urban aerosol, a PEC inventory for the area of concern can be calculated from annual consumption of fuel use and their PEC emission factors. In column 3 of Table 3.3, the different amounts of PEC emitted per kilogramme of fuel consumed for a range of fuels, is given.(86) By multiplying this factor by the amount of fuel consumed, the mass of PEC emitted can be calculated. Similarly, by adding the total amount of PEC produced by each fuel within the area of concern and dividing by the amount produced by each fuel type, the percentage contribution of the mass of PEC produced can be derived; as is shown in Table 3.3 for London in 1980.

Table 3.3 Mass of Particulate Elemental Carbon (PEC) emissions (in tonnes) according to fuel use for London (1980)

Fuel type	Amount of fuel consumed (10^3 tonnes)	PEC emission factor (86) (% by mass)	Amount of PEC emitted (tonnes)	% of PEC Total by fuel Type
Coal: domestic	50	0.0001	0.05	0.004%
Coal: industrial	250	0.0001	0.25	0.02%
Solid smokeless fuel	350	0.0001	0.35	0.03%
Gas oil	1000	0.01	0.1	0.009%
Fuel oil	600	0.002	12	1%
Petrol	2200	0.002	44	4%
Diesel	520	0.2	1040	94.8%
		TOTAL:	1096.75	

Likewise Table 3.4 gives the total and mass of PEC for the UK according to fuel usage for 1971 to 1986. The data was derived using the annual amounts of fuel consumed in UK given in Table 2.4 and the emission factors for PEC in Table 3.3. The total emissions of PEC and the estimated relative contribution of derv during this period for the UK is given in Figure 3.7. However, the mass emitted from power stations has not been included here as the mass of PEC emitted into the atmosphere is very small. The disparity between the two bar lines has comparatively lessened since 1982 due mainly to the increased contribution from diesel sources. The percentage contribution of PEC mass emissions from fuel type during this period is given in Table 3.5 and illustrated in Figure 3.8. The percentage contributions from coal and solid smokeless fuels are not shown in Figure 3.8 as their contribution to the total was less than 1%.

These estimates show that diesel emissions make the major contribution (80-95%) to PEC at both urban and national level whereas their contribution to dark smoke was substantial only at the urban level. Less than 5% of the total mass of smoke emitted for the UK in 1985 was PEC and for London (1980) PEC accounted for 9% of the total smoke emitted. However, this comparison does not take account of the darkness of PEC.

Table 3.3 and Table 2.2 reported that diesel fuel has PEC emission factor of 2.0 g PEC $(\text{kg fuel})^{-1}$ and a smoke emission factor of 6 g smoke $(\text{kg fuel})^{-1}$, thus diesel smoke maybe comprised of 33% PEC. However, it should be remembered that these figures are only approximate, and the value of 33% PEC quoted may well be highly speculative. As shown in Figure 3.6 and Section 3.1, apart from PEC there is very little other combustion-derived material in diesel exhaust which contributes to its

TABLE 3.4

TOTAL AND MASS EMISSION OF PARTICULATE ELEMENTAL CARBON ACCORDING TO FUEL TYPE USE (IN TONNES) FOR THE UK FROM 1971 to 1986

Fuel Type	1971	1972	1973	1974	1975
Coal: domestic	15.6	12.8	12.7	12	9.9
industrial	20.8	16.0	16.0	14.9	12.9
Solid smokeless fuel	11.9	10.5	9.9	9.7	8.8
gas oil	1180	1440	1430	1260	1200
fuel oil	914	952	924	872	720
motor spirit	300	318	338	330	360
diesel fuel	10,400	10,400	11,400	11,000	10,800
TOTAL	12,842	13,149	14,130	13,498	13,111

Fuel Type	1976	1977	1978	1979	1980
Coal: domestic	9.4	9.7	8.7	8.9	7.2
industrial	12.2	12.2	11.6	12.1	10.4
Solid smokeless fuel	8	7.8	7.6	7.7	6.3
gas oil	1180	1280	1250	1200	1070
fuel oil	678	660	680	660	500
motor spirit	380	400	420	420	420
diesel fuel	11,200	11,400	11,800	12,200	11,800
TOTAL	13,467	13,769	14,177	14,508	13,813

Fuel Type	1981	1982	1983	1984	1985	1986
Coal: domestic	6.9	6.7	6.2	4.8	6.5	7.0
industrial	9.4	9.6	9.5	8.0	9.3	10.0
Solid smokeless fuel	6	6	5.8	5	6	5.5
gas oil	1000	950	900	990	870	830
fuel oil	420	420	340	660	420	360
motor spirit	400	500	420	420	400	430
diesel fuel	11,000	11,400	12,400	13,600	14,200	15,800
TOTAL	12,842	13,292	14,081	15,687	15,911	17,442

Figure 3.7 **CONTRIBUTION OF DIESEL TO TOTAL MASS EMISSIONS OF EC FROM FUEL SOURCES FOR UK**

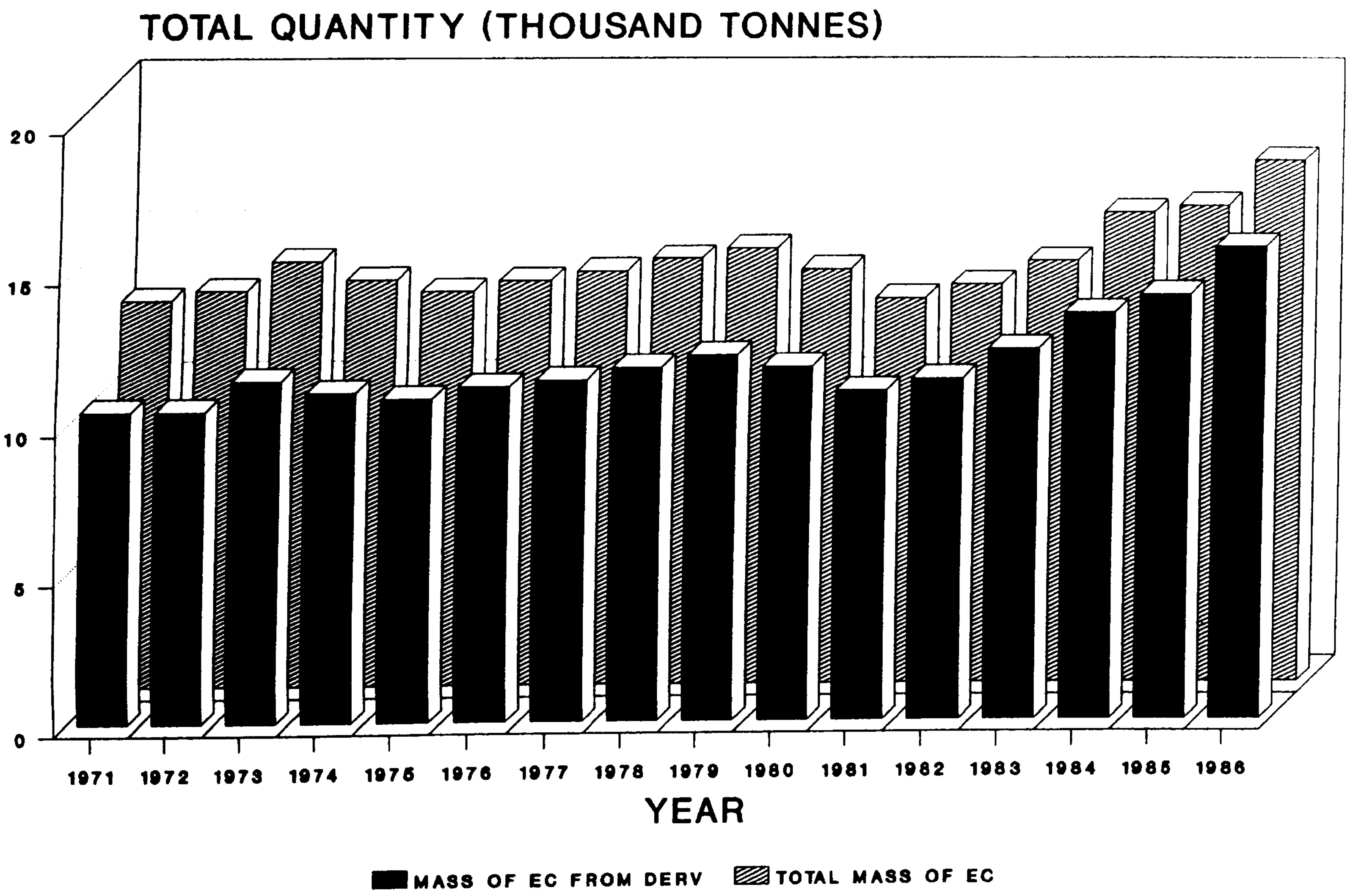


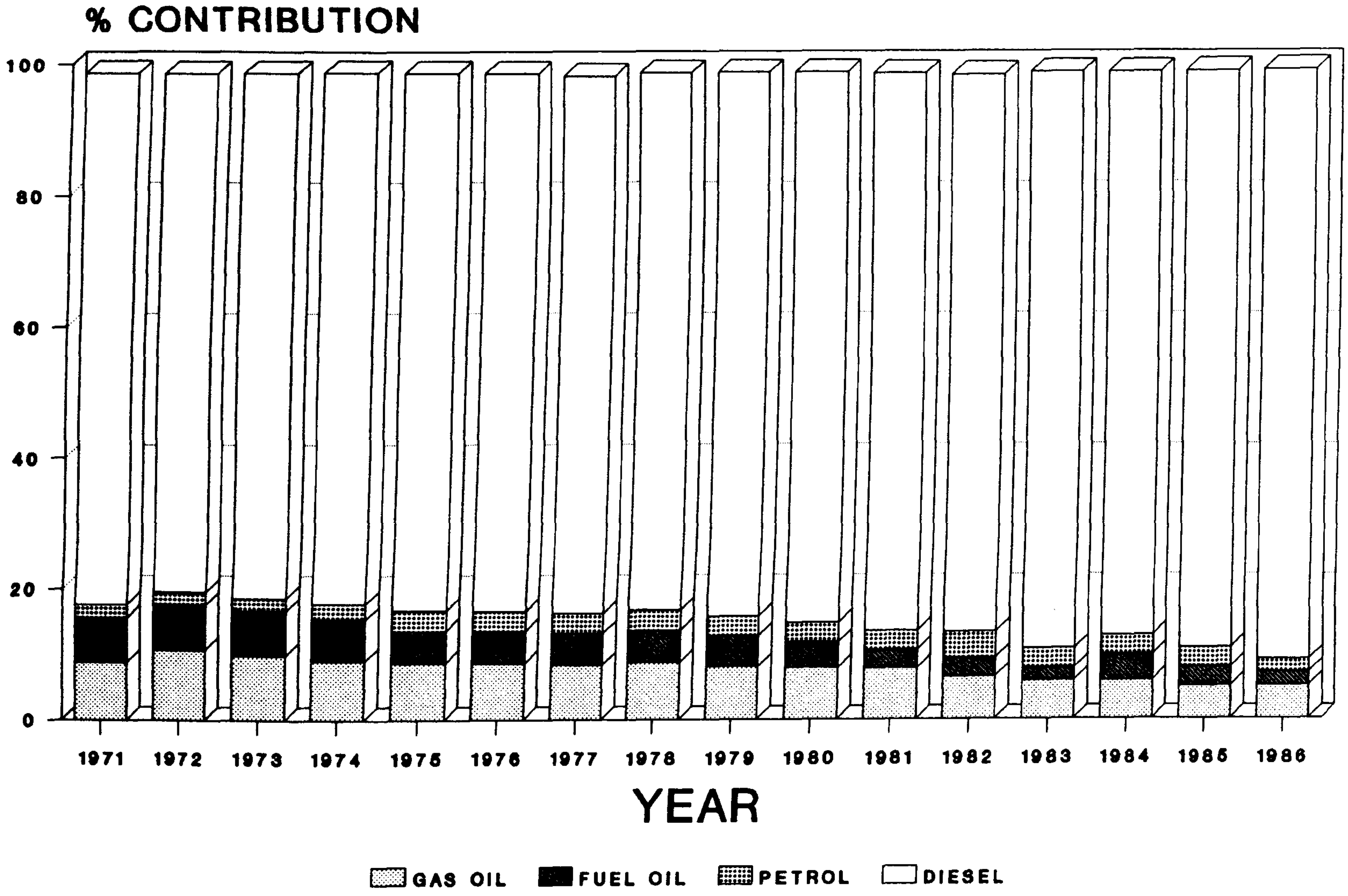
Table 3.5: The percentage contribution by fuel type to the total mass of particulate elemental carbon emitted in the UK from 1971 to 1986 *

Annual percentage contribution by fuel type to the total mass of particulate elemental carbon emitted for the UK *

Fuel Type	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Coal: industrial	0.1	0.1	0.09	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.03	0.04	0.04
domestic	0.1	0.1	0.1	0.1	0.1	0.1	0.08	0.08	0.08	0.07	0.07	0.07	0.06	0.05	0.05	0.05
Solid smokeless fuel	0.09	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.03	0.04	0.03
gas oil	9	11	10	9	9	9	9	9	8	8	8	7	6	6	5	5
fuel oil	7	7	6	6	5	5	5	5	5	4	3	3	2	4	3	2
motor spirit	2	2	2	2	3	3	3	3	3	3	3	4	3	3	3	2
diesel fuel	81	79	81	81	82	83	82	83	84	85	85	85	88	86	89	90

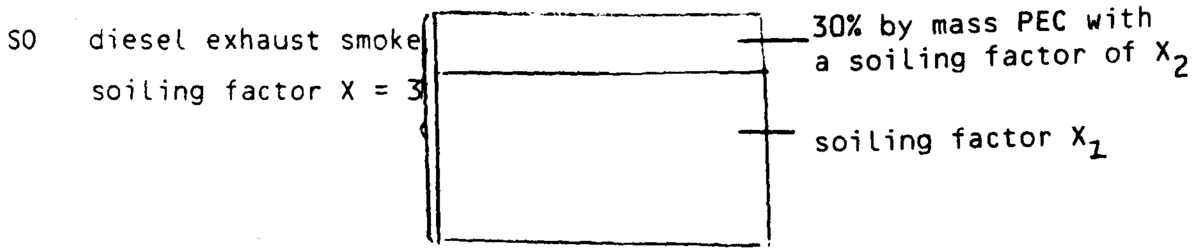
* due to rounding off of figures totals may not equal 100 exactly.

Figure 3.8 **PERCENTAGE OF EC MASS EMISSIONS BY FUEL SOURCE FOR UK (1971 to 1986)***



* The percentage contributions from coal and solid smokeless fuels are not shown in Figure 3.8 as their contribution to the total was 1%

light absorptive soiling properties.



Thus given that the overall soiling factor of diesel smoke is: X = 3, then $\frac{1}{3} X_2 + \frac{2}{3} X_1 = 3$. If the darkness is caused entirely by PEC i.e. $X_2 \gg X_1$, so $X_1 \simeq 0$ then X_2, the soiling factor for the PEC in diesel equals 9. It is on the basis of these estimates that a model for the soiling of materials was developed on the premis that all soiling was caused by PEC. These models are introduced in Chapter Four.

3.5.1 Ambient concentrations of PEC

Ambient concentrations of PEC reported from the literature are given in Table 3.6. Because the various researchers use different analytical techniques, some caution must be exercised when comparing the concentrations. Despite these differences, several general points can be made. Generally levels of particulate elemental carbon in urban areas are in the range 2 to 10 μg m^{-3}, in rural areas around 1 μg m^{-3} and falling to 0.2 μg m^{-3} in remote continental areas. Marine areas bordering continents generally exhibit concentrations in the range of 0.1 - 0.3 μg m^{-3}, with a steady gradient of decreasing concentrations towards the remote oceans.

Table 3.6 Ambient concentrations of particulate elemental carbon (in µg m^{-3}) reported for a variety of locations

Remote areas	Reference Number	Ambient concentration of PEC (in µg m^{-3})
Arizona and Colorado, America.	56	0.2
Pt. Barrow (Spring) Alaska.	56	0.3
Puget Island, W.A. America	56	0.7
South Dakota, America	56	1.1
Senonches, France	90	1.2
Cities		
New York City, America	56	4.2 - 13.3
Portland, America	56	10
Washington D.C. America	56	6.5
Los Angeles, America	56	3.1 - 4.1
Denver, America	56	5.4
Hamburg, FRG	75	2.4
" (smog) FRG	75	24
Paris, France	90	7.9
Chicago, America	90	4.6
Orleans, France	90	2.9
Clermont, France	90	2.4
Norfolk, America	90	3.0
Strasbourg, France	90	2.9
Leeds, England	37	6
Clemson, America, urban	90	3.3
" America, residential	90	1.7

Finally, the contribution of elemental carbon from diesel sources alone may be further elucidated in the future by the use of a tracer. Many emission tracer substances exist such as lead and bromine from petrol powered vehicles, Vanadium for residual oil etc. Unfortunately, no unique tracer already present in diesel fuel or produced during combustion so far exists. However, recently a tracer substance has been found for diesel and initial field experiments indicate that the marking method has been successful. The rare earth element Dysprosium has proven useful for this purpose. It can be detected by neutron activation analysis in quantities of nanograms and it does not occur naturally. An organic, diesel soluble Dysprosium compound is added to the fuel. During the combustion process the Dysprosium is oxidized and attaches to the formed soot particles.(87) Hopefully, this line of research will ultimately aid in the quantification of the rates of EC emission from diesel vehicles into the ambient atmosphere, plus its distribution and residence time within the atmosphere and assess the contribution of diesel exhaust responsible for environmental effects such as soiling and Arctic haze phenomenon etc. Recent research carried out in Vienna (88) on direct apportionment of diesel vehicles using Dyprosium as a marker for all the diesel fuel used in the area found that the mass concentration of diesel particles in the atmosphere varied between 5 to 23 $\mu g\ m^{-3}$. The mass fraction of diesel particles of the total aerosol mass varied between 12 and 33%, with higher values found in remoter areas suggesting diesel particulates are easily diffused. The concentrations of diesel particles settling to the ground were 0.012-0.07 $g\ g^{-1}$ collected dust. These results also agreed with similar results of the estimates of diesel particle concentration as deduced from emission inventories, or by using lead concentrations as an indicator for vehicle emissions. Thus the emission inventories given in Chapters Two and Three, as well as the models in Section 3.5.4 may well be more accurate than previously expected.

3.5.2 Relationship between ambient Particulate Elemental Carbon and Smoke Shade Levels

An evaluation of B.S.S. method by Edwards et al (1983)(89) concluded that reflectance as measured in this method is controlled by the optical absorption coefficient of the aerosol, which in turn is usually controlled by sub- μm PEC; BSS may be used as an estimator for the mass concentration of PEC. They found a good correlation between BSS (range of 0-200 $\mu g\ m^{-3}$) and sub- μm PEC of:

$$\mathrm{PEC}\ (\mu g\ m^{-3}) = (0.13 \pm 0.03)\ \mathrm{BSS}\ (\mu g\ m^{-3}) - (0.1 \pm 2.4)$$
$$(r^2 = 0.68\ n = 31)$$

This is consistent with the observation that in urban areas, PEC usually accounts for 10-20% of the fine gravimetric aerosol mass in London where smoke levels range from 20-70 $\mu g\ m^{-3}$ this would indicate PEC concentration of 2-9 $\mu g\ m^{-3}$. Clarke et al(37) has measured an average value of 6 $\mu g\ m^{-3}$ at a streetside location in Leeds.

Other authors have also tried to relate levels of ambient black smoke ($\mu g\ m^{-3}$) with total carbon concentration of particles in the atmosphere. Bailey and Clayton(31) found:

$$\text{Total carbon } (\mu g\ m^{-3}) = 0.42\ (\text{smoke}) + 4.34$$

for the range of smoke 0-200 $\mu g\ m^{-3}$. Assuming PEC is one third of total carbon, this implies that the PEC concentration is about 14% of the smoke value. This result is in agreement with the calculations determined by Edwards,(89) whose correlation indicated that 50 μg of smoke corresponded to 6 ± 2 μg of PEC. This result was determined using the OECD calibration curve, the corresponding British Standard value is 42.5 μg smoke. The PEC is thus 14 ± 4% of the smoke. The above two equations will be employed to predict levels of total/elemental carbon during the experimental programmes described in Chapters 5 as well as being compared to levels of PEC recorded in the experimental programme.

3.5.3 Relationship between ambient PEC and Lead Levels

The dependence of PEC concentration on the population of cities has been implied in previous studies. The elemental carbon and lead content of fine particles from American and French cities of comparable size and industry has been investigated.(90) Leaded petrol is widely used in Europe so the concentration of lead in the atmosphere of European cities was expected to be higher than similar cities in the U.S. Each country showed a roughly linear relationship between lead and EC, although the correlation was much greater for the French samples (r^2 = 0.88) than those for the U.S. (r^2 = 0.47).

The results also showed that both lead and PEC concentrations in each country are semi-logarithmically related to population. Data such as this can provide a basis from which to estimate the anticipated changes in the concentrations of lead and EC in the two countries, for as concluded by Ohta and Okita(91) the projected shift toward diesel powered passenger vehicles should result in an increase in particulate carbon, especially in urban areas. In addition, the trend toward reduced use of leaded petrol in both Europe and U.S. should continue to decrease the lead content of urban and rural aerosol.

Further, it might be expected that the dispersion and dry deposition behaviour of PEC may be similar to that of lead. Both have strong sources in vehicular exhaust (be it that lead is from petrol engine and EC predominantly from diesel engines) and similar size distributions. For example, Slinn(92) reported an average dry deposition velocity for lead of 0.31 cm s^{-1}, which is at least an order of magnitude greater than that anticipated for sub-0.2 μm diameter particles. This work further suggests that such theoretical estimates are too low, or that the lead particles sampled were dominated by large particles and hence had larger settling velocities. Clearly, additional measurements on atmospheric residence for PEC are required, as with the demise of lead in petrol due in the next decade, new work on lead and its related models may be of limited value.

3.5.4 Modelling Airborne PEC

The dispersion of vehicle emitted Pb aerosol in the atmosphere has received considerable attention, with the theoretical foundations set by Chamberlain et al.(93) If we assume:

(i) PEC emissions from diesel-engined vehicles and Pb emissions from petrol engined vehicles have the same dispersion characteristics after emission;

(ii) both emissions have the same dependence on driving mode, and

(iii) transportation is the only source of PEC and Pb:

then

$$\frac{C_{EC}}{C_{Pb}} = \frac{Q_{EC}}{Q_{Pb}}$$

$$\text{Now} \quad Q_{EC} = (2\ \text{g EC kg}^{-1})\ \text{fuel} \times (\text{mass of diesel fuel consumed kg year}^{-1})$$

$$\text{and} \quad Q_{Pb} = \frac{(\text{level of Pb in petrol, g l}^{-1}) \times (\text{mass of petrol consumed kg yr}^{-1})}{(\text{density of petrol, kg l}^{-1})}$$

Assuming the density of petrol is 0.7 kg l^{-1}
and the current level of lead in petrol is 0.15 g l^{-1}

$$C_{EC} = \frac{C_{Pb} \times 10 \times \text{ mass of diesel fuel consumed (kg year}^{-1})}{\text{mass of petrol consumed (kg year}^{-1})}$$

For example:

In the UK in 1985:

the mass of diesel fuel consumed was 7.1 x 10^{9}kg

the mass of petrol consumed was 2.04 x 10^{10}kg

So $$Q_{EC} = 2x7.1x10^{9}g = 14.2x10^{6}kg$$

$$Q_{Pb} = \frac{0.15x2.04x10^{10}g}{0.7} = 4.38x10^{6}kg$$

$$\frac{C_{EC}}{C_{Pb}} = \frac{14.2}{4.38} = 3.48 \triangleq 3.5$$

On a UK national level, the level of lead in air is equal to 0.1 $\mu g\ m^{-3}$ so the level of EC in air is expected to be approximately 0.35 $\mu g\ m^{-3}$. This ratio of 3.5:1 agrees well with that quoted by Cass et al.(79)

Likewise for London in 1980:

The mass of diesel fuel consumed was $5.2x10^{8}$kg

The mass of petrol consumed was $2.2x10^{9}$kg

So

$$Q_{EC} = 2x5.2x10^{8}x10^{3}g = 10.4x10^{8}g \text{ EC}$$

$$Q_{Pb} = \frac{0.4x2.2x10^{9}x10^{3}g}{0.7} = 9.4x10^{8}g \text{ Pb}$$

$$\frac{C_{EC}}{C_{Pb}} = \frac{10.4}{4.7} = 2.2$$

In London, since the phase-down of lead in petrol, the level of lead in the air is now in the range of 0.15 $\mu g\ m^{-3}$ However, in 1980 the level was approximately 0.5 $\mu g\ m^{-3}$, thus levels of EC would be expected to have been approximately 0.6 $\mu g\ m^{-3}$.

Alternatively,

Chamberlain's dispersion model, in its simplified form presented by Hamilton et al.,(94) can be applied as follows:

For area sources of vehicle emitted pollutants under class D atmospheric stability conditions:

$$C_{EC} = 94\ Q_{EC} \quad \text{(rural sites)}$$

$$C_{EC} = 26\ Q_{EC} \quad \text{(urban sites)}$$

Where C is in $\mu g\ m^{-3}$ and Q_{EC} is in $\mu g\ m^{-2}\ s^{-1}$

Using the previous figures.

For the UK in 1985

The emission of EC in that year was 14.2×10^9g

The area of the UK is $2.44 \times 10^{11} m^2$.

So $$Q = \frac{14.2 \times 10^9}{2.44 \times 10^{11} \times 365 \times 24 \times 3600}$$

$$= 0.0018\ \mu g\ m^{-2}\ s^{-1}$$

$$C_{EC} = 94Q$$

$$C_{EC} = 0.17\ \mu g\ m^{-3}$$

For London in 1980

The emission of EC in that year was $10.4 \times 10^8 g$

The area of London is $2.3 \times 10^8\ m^2$

$$\text{So} \qquad Q = \frac{10.4 \times 10^8\ g}{2.3 \times 10^8 \times 365 \times 24 \times 3600\ m^{-2}\ s^{-1}}$$

$$= 0.14\ \mu g\ m^{-2}\ s^{-1}$$

$$C_{EC} = 26Q$$

$$C_{EC} = 3.6\ \mu g\ m^{-3}$$

In table 3.6 the levels of ambient PEC recorded for a variety of locations were given; comparisons of the levels predicted here for London using the two models agree well with those levels of PEC predicted from experimentally recorded levels of smoke. The levels predicted for the U.K. may slightly underestimate the national level. Until more measurements are made, one can only predict, by the use of models, what the ambient levels may be (as illustrated above). However, considering the basic assumptions, the model may be used to predict ambient levels of EC quite accurately.

3.6. Some of the possible environmental effects of PEC emissions

The potential importance of PEC has been increasingly recognised and received attention in the past few years. This is because of its role in atmospheric optics and chemistry, as well as its constitution of a significant fraction of the respirable particulate fraction. In addition because PEC absorbs light it may have some potential for altering climate by affecting the surface-atmosphere heat balance.

3.6.1 Visibility degradation

The degradation of visibility is one of the most easily perceived effects of air pollution. There are several factors which influence how far one can see through the atmosphere, such as the optical properties of the atmosphere, characteristics of the objects observed, the amount and distribution of light and the properties of the human eye. The ability to see through the atmosphere depends on the presence of suspended particles and gases, which have the ability to scatter and absorb light, causing the appearance of haze, a decrease in contrast, and a change in the perceived colour of distant objects. Visibility can be defined as the greatest horizontal distance at which a suitable object can be seen and recognised with the unaided eye.

Visibility can be impaired by the effects which gas molecules and particles have on visible radiation: absorption and scattering of light. The absorption of certain wavelengths of light by gas molecules and particles is sometimes responsible for atmospheric colourations.

Light scattering refers to the deflection of the direction of travel of light by airborne material and is considered the most important phenomenon responsible for impairment of visibility. Visibility is decreased when there is a significant scattering. The scattering by particulate matter of sizes comparable to the wavelength of visible light (known as Mie scattering) is mostly responsible for visibility reduction within the atmosphere. The average wavelength of light is about 0.52 μm. Thus, particles in the range 0.1 to 1 μm in radius are the most effective, per unit mass in reducing visibility.

Given that diesel particulates consist of over 90% by mass of particles with a size less than 1 μm,(95) the role of diesel particulates in visibility degradation has been assessed by several authors.(96)(97)(98) The light attenuation by an exhaust plume is given by the Beer Lambert relation:

$$I/I_o = \exp(-b_{ext}\, x)$$

with I_o and I the initial and transmitted light intensities respectively, b_{ext} the light extinction coefficient (in reciprocal meters) for the wavelength of light used and x the pathlength (in meters). Because the gases in diesel exhaust do not significantly absorb or scatter light, the total extinction coefficient is described as:

$$b_{ext} = b_{scat} + b_{abs}$$

where b_{scat} and b_{abs} are the light scattering and absorption coefficient for the particulate matter in the exhaust. If the mass concentration (M in g m^{-3}) of the particulate material is known, the optical constant can be converted to mass-specific optical coefficients, $\frac{b}{M}$ (in $m^2\ g^{-1}$).

It has been estimated that light absorption by black carbon particles is responsible for as much as 17% of the total extinction coefficient in the winter time in downtown Los Angeles.(98) The disproportionately large influence of black carbon upon light extinction, also reflected in findings from the Denver winter haze study, is partly because black carbon is more effective than nonabsorbing aerosol particles (such as sulphates and nitrates) in attenuating light.(99) Indeed, on a unit mass basis, elemental carbon is the most efficient visibility reducing particulate.

The effect of diesel vehicle PEC on visibility in California was estimated for 1980 and projected for the early 1990s.(100) An emission budget model indicated that heavy-duty diesel vehicles contributed to nearly half of statewide PEC emissions in 1980 and about 5-15% of light extinction. Because of increased diesel usage due to both overall traffic growth and partial conversion of the vehicle fleet to diesels (10% of light duty, 20% of medium-duty and 60% of currently petrol heavy-duty) visibility in California is projected to decrease significantly (about 9-35%) from 1980 to the early 1990s if no pollution control procedures are adopted. Indeed, with the present trend towards the use of fuels rich in carbon emissions (i.e. wood, especially in U.S.A, and diesel fuels), it is expected that the impairment of visibility by PEC will continue to receive further attention. An example of the potential safety and economic costs caused by impaired visibility is illustrated by the operations carried out in a road traffic tunnel in Chapter Five.

To conclude this section on the effects of pollutants and visibility, Seinfeld(101) notes:

(1) Scattering by particles causes 60-95% of visibility reduction;

(2) Sulphate is almost always the most important scattering material, followed by organic carbon. Nitrate may be important in some locations;

(3) Absorption by soot particles causes 5-40% of visibility reduction;

(4) Nitrogen dioxide appears to cause little visibility reduction.

3.6.2 Climatic effects

As mentioned in Section 3.3.1, concern over the possible climatic effects PEC may cause has been generated. This is because PEC is a very effective absorber of visible radiation and can lead to significant heating effects, depending primarily on its distribution in time and space. The impact of such highly absorbing particles on a regional or global scale has not been assessed so far but could be especially important over regions like the polar icecaps with a high surface albedo. Rosen et al (1984)(102) have observed substantial concentrations of graphitic carbon particles at ground level and at altitude over the Western Arctic and that the concentrations of these particles appear to be sufficient to lead to significant heating effects during spring time over the high surface albedo polar icecap.

To conclude, significant graphitic concentrations have been observed at remote locations in the Northern hemisphere. If one ignores the possible contribution of natural burning processes (such as forest fires), which are expected to be small during winter and spring in the Northern hemisphere and the Arctic haze is at its maximum, then this graphitic component can be attributed largely to anthropogenic combustion processes. The source and the climatic effects of these highly absorbing species are uncertain and still await more systematic measurements and careful modelling.

3.6.3 Health effects

There are a large number of organic and inorganic compounds accompanying the formation of black carbons in fossil fuel and wood burning, many of which may be associated directly with the carbon particles. A major concern involves the observation that many of these compounds are carcinogenic. This was first noted over 200 years ago by Sir Percival Pott who indicated a relationship between the high incidence of scrotal cancers among chimney sweeps and their exposure to soots. There are two possible sources of polycyclic aromatic compounds (PAC) in the soluble organic fraction of diesel particulates. The first is from the combustion reactions, the other is unburnt fuel. Many of the PAC produced during combustion condense upon the combustion particulate after they cool.(103) The greater proportion of these particles occur in the less than 3.5 μm size class which is respirable. Over 90% of the total amount of benzo (a) pyrene is found in particles less than 0.2 μm in diameter. There is concern about the health effects of such particles, because such sized matter can be firmly lodged in the lung's alveoli and are less effectively removed via cilia action from the body than are the larger sized particles. Thus, such particles lodged in the lungs may exert carcinogenic and mutagenic activity.

Stober (1987)(104) in a review of the existing literature on the health hazards from the PACs originating from diesel exhaust exposure states there is very weak and suspect epidemiological evidence that exposure to airborne diesel soot constitutes a health hazard to occupationally exposed workers and that the cigarette smoking habits of such workers is the main influence of such reported cancer statistics. Recent attention has focussed on the nitrogen containing PAH (PANH) and sulphur containing PAH (PASH). PANH have been suggested as the important precursors for the direct acting mutagenic nitro-PAH (NPAH) which have been identified in diesel exhaust,(105) and it is known that some PANH themselves are carcinogenic and/or mutagenic. It is known that different pollutants exert a particular observed effect on certain organs of the body, for example exposure to acidic gases such as sulphur dioxide causes primarily bronchial irritation, cadmium in the body exerts its effect on bones as in 'itai-itai' disease. Such pollutants exert their effects predominantly on a 'target organ'. There is increasing evidence that exposure to diesel particulate containing PAH, PANHs affects the bladder. A recent study on workers occupationally exposed to diesel particulate, was observed to have an elevated rate of bladder cancer as compared with the general population.(106) Thus, previous studies which have examined the incidences of lung cancer with exposed workers(107) have not shown a related correlation, because the lungs may not be the specific target organ concerned with respect to diesel exhaust.

However, it is not yet justifiable to state that diesel exhaust particulates alone pose a real health risk for the population at large, especially considering the numerous other sources of PACs which also contribute to ambient urban levels. Such sources include wood and coal burning, industrial processes, etc. It should be remembered that most humans spend over 90% of their time in an enclosed environment and thus it is the concentration of such compounds within this area that represent a more substantial risk to health than those levels recorded at street level. This has been illustrated by the increasing concern on the detrimental health effects of people who have been exposed to passive smoke as a result of inhaling the smoke from cigarette smokers. Such forms of enclosed exposure to pollutants are currently deemed to have a greater potential effect on health than those which may result from mainly open-air exposure to diesel particulates and other fossil fuel derived sources.

4. The methods and models used to assess the soiling process

4.1.1 Problems in assessing material damage by particulate matter

There is much qualitative evidence that air pollutants cause damage to building materials and equipment.(108) The air quality control approach to this problem is to curtail the level of such pollutants to concentrations that cause little risk. This methodology assumes that quantitative data between pollutant exposure and material damage are known. However, this is usually not the case, especially with respect to building materials.

Airborne particulates that deposit on a surface may cause soiling. If the particulate matter contains reactive components or enhances damage by other environmental factors such as the presence of moisture and acidic air pollutants, the particulate matter may directly or indirectly cause material degradation. Furthermore, even if the soiling matter does not cause any physical damage, the cleaning of a surface soiled by particulate matter may cause damage through removal of some of the top surface of the material. Such an example may be the sand blasting soiled stone buildings if carried out by unskilled operators. It is also possible that large particles carried by strong wind currents could cause surface erosion as was mentioned in Section 2.2. However, the deposition of such particles is a transient effect, as these sand-derived particles are easily removed with subsequent rainfall.(7)

It is also important to realize that different materials react in specific ways and that the damage is cumulative, for materials have no regenerative capacity. This produces a relation between pollutant concentration and rate of deterioration with no time threshold effects. Thus, the pollutant concentrations to most usefully consider are long-term averages. Episodes of unusually high concentration are not of such great importance as they may be when considering human health.

A lot of the evidence on direct damage such as corrosion or erosion to materials caused by particulate matter is circumstantial or relates to specific situations where chemically reactive particulate matter is involved. One of the main problems is that particulate matter, especially emanating from combustion sources, often co-exists with acidic gases such as the sulphur and nitrogen oxides. Thus, assessing the damage attributable to the particulate matter alone may be difficult because it may react synergistically or participate as a catalyst in other chemical reactions. So damage functions for particulate matter may be difficult to evaluate. A damage function can be defined as a mathematical expression of the quantitative relationship between some measure of material damage and levels of air pollutants and other environmental factors.(109) There have been a number of damage functions for the joint effect of sulphur dioxide and moisture on a number of materials especially metals,(110) but there are few damage functions for material damage from particulate matter. This reflects the poor state of understanding of the specific role of particulate matter in material damage.

4.1.2 Damage functions for particulate matter based on wet and dry deposition experimentation

There are few damage functions available that have experimentally related the soiling of materials to concentrations of particulate matter. One of the most quoted was derived from a study by Beloin and Haynie (1975).(111) Here samples of six different materials (painted siding, concrete block, brick, limestone, asphalt shingles and window glass) were exposed vertically (except the shingles which were exposed on a roof) for two years at five locations which covered a range of TSP concentrations from 60 to 250 $\mu g\ m^{-3}$. Surface reflectance was used as a measure of soiling and was carried out every three months during the first year and every six months for the second year. For all materials (except asphalt shingles), the regression relationship showed that the change in reflectance was proportional to the square root of the amount of particulate matter. For asphalt shingles, the change in reflectance was proportional to the dose. Figure 4.1 illustrates how the result of such analysis for acrylic emulsion paint can be predicted.(112) The results of the linear regression for soiling of acrylic emulsion house paint from this work is:

$$Y = B\sqrt{TSP \times t} + A$$

where Y = measured percent reflectance; B = slope of linear regression; TSP = Average TSP concentration ($\mu g\ m^{-s}$); A = intercept of linear regression and t = exposure time (months). For acrylic emulsion paint, the initial reflectance value for calculating reflectance change was 92.5%, the value for A was 90/79 and B was -0.413.

Assuming that a 35% loss in absolute reflectance triggers repainting a householder would theoretically repaint every 2.1 years at a TSP level of 260 $\mu g\ m^{-3}$ and every 7.2 years at a TSP level of 75 $\mu g\ m^{-3}$. Murray et al (1985) in a study of material damage in California, found that the average repainting cycle was approximately every seven years. TSP concentrations in this study area ranged between 55 and 115 $\mu g\ m^{-3}$.(113) Thus, the data from California appears to agree quite well with the soiling function prediction, assuming a 35% reduction in reflectance is a reasonable criterion for painting.

However, as is more fully explained in Chapters Seven and Eight the frequency of cleaning is strongly dependent on an individual's acceptable soiling level as well as particulate level and time. Thus, consideration should be given to socio-economic factors that control ability and motivation to maintain clean surfaces when attempting to relate maintenance cycles to physical soiling behaviour.

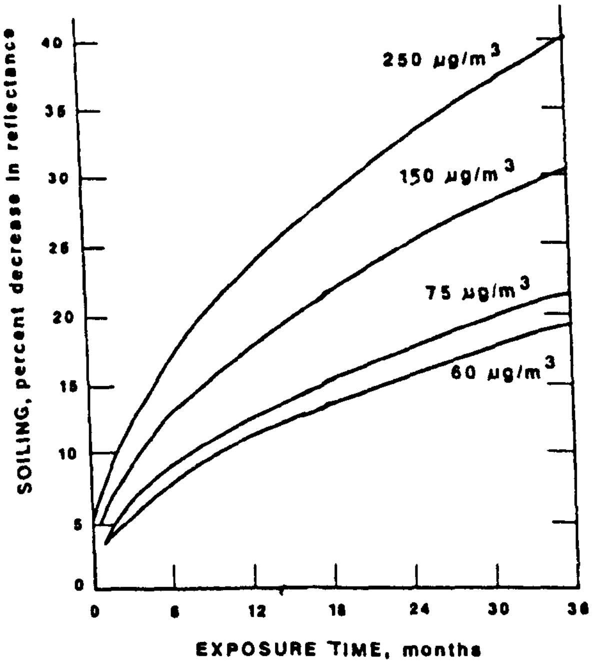


Figure 4.1 Damage function for soiling of acrylic emulsion paint. (112)

Soiling functions for white painted wood and other materials exposed for up to 18 months in this research are given for a variety of nine sites in London where smoke levels as recorded by the British Standard Method ranged from about 7 to 50 μg m^{-3} are given in Chapter Six. However, as can be seen from the variety of Figures 6.10/12/14 in Chapter Six, and in Appendix C, the damage functions for paint soiling as measured as percent decrease in reflectance with time do not follow the same trend as given in Figure 4.1. Such discrepancies are more fully examined and discussed in Chapter Six. Unfortunately, there has subsequently been only one other study since the Beloin and Haynie (apart from this) which has exposed materials for periods of up to two years; this was by Martin et al (1986) in Melbourne, Australia.(114) Some complementary studies, described in Section 4.1.3 are based on dry deposition exposure regimes. Thus, little knowledge has been recently gained on the effects and rates of particulate soiling and/or removal from a surface from such studies. These dry deposition studies are not strictly applicable to 'real world' situations, where the action of rainfall is present and may well exert an effect on a soiled surface.

In the Australian study, concrete and aluminium both painted and unpainted and glass were exposed horizontally at six sites around Metropolitan Melbourne. The assessment carried out during a 2 year period involved measuring the darkening effect of grime after subjecting the specimens to a standard cleaning procedure. Sites were characterized in terms of freefall dust, water soluble dust, rainfall and suspended particulates.(114) The effect of discolouration or darkening of the soiled surface was measured by a tristimulus light reflectance meter and reported in terms of a light darkness coordinate(L).(115)

The difference between the L values for the 'washed and as received' specimens was considered to indicate 'removable grime' (ΔL_R) and the difference between the L values for the 'washed' and 'original' specimens to indicate 'fixed grime' (ΔL_F). Results of the measurements of removal and fixed grime for white painted concrete for the horizontal and vertical specimens after 12 and 24 months exposure at the six different sites are given in Table 4.1. The total dustfall and percentage solubles for the first 12 months of the study are given in Table 4.2

Table 4.1 Grime on White Painted Concrete (CPW)(114)

Site		ΔL_R		ΔL_F	
		12 months	24 months	12 months	24 months
1	Horizontal	1.9	2.8	3.9	4.4
	Vertical	1.3	1.4	1.5	3.1
2	Horizontal	1.1	1.3	1.4	1.1
	Vertical	0.7	0.5	0.7	0.7
3	Horizontal	1.6	1.4	1.4	2.2
	Vertical	0.9	0.7	0.7	1.5
4	Horizontal	1.7	2.0	0.9	1.6
	Vertical	1.0	1.1	0.1	0.8
5	Horizontal	1.0	D	2.6	D
	Vertical	1.1	D	0.1	D
6	Horizontal	4.9	7.3	7.7	10.8
	Vertical	1.0	8.4	6.9	8.6

Note: Mean L for originals = 95.4

ΔL_R = Δ L Attributed to removable grime

ΔL_F = Δ L Attributed to fixed grime

D = Specimen damaged

Table 4.2 Total Dustfall and Percentage Solubles For the First 12 Months(114)

	Site 1	2	3	4	5	6
Total dust	308.3	42.9	49.0	41.3	45.0	234.8
Total solubles	15.5	10.8	9.4	12.5	13.0	26.3
% solubles	5.0	25	19	29	29	11

Note: Dustfall units are g m^{-2}

From such results, it was concluded that grime deposition is accumulative. For in 80% of cases ΔL_F is greater at 24 months than at 12 months. This indicates that rain does not completely clean specimens. Although, it would remove loose dust and because of this it was considered that the fixed grime ΔL_F is a better indicator of performance of specimens and severity of sites than total grime or removable grime ΔL_R.(114) It was also noted that fixed grime is generally (but not always) much greater on horizontal than on vertical surfaces. As is shown in Table 4.3 the ratio of $\Delta L_F/\Delta L_R$ for white painted concrete for both horizontal and vertical surfaces at the sites for 12 months generally shows horizontal surfaces have a higher ratio than vertical surfaces. However, this trend is less pronounced for 24 months:

Table 4.3 The ratio of $\Delta L_F/\Delta L_R$ for white painted concrete for horizontal and vertical surfaces.(114)

Site		12 months	24 months
1	Horizontal	2.05	1.57
	Vertical	1.15	2.21
2	Horizontal	1.27	0.84
	Vertical	1	1.4
3	Horizontal	0.87	1.57
	Vertical	0.77	2.14
4	Horizontal	0.52	0.8
	Vertical	0.1	0.72
6	Horizontal	1.57	1.47
	Vertical	6.9	1.02

ΔL_F = Δ L attributed to fixed grime
ΔL_R = Δ L attributed to removable grime.

A comparison of the relative behaviour of the different specimens is given in Figure 4.2 in terms of ΔL_F summed for all sites (except Site 5 which was damaged.) The ranking of different specimens is similar for both horizontal and vertical and 12 and 24 months exposure.

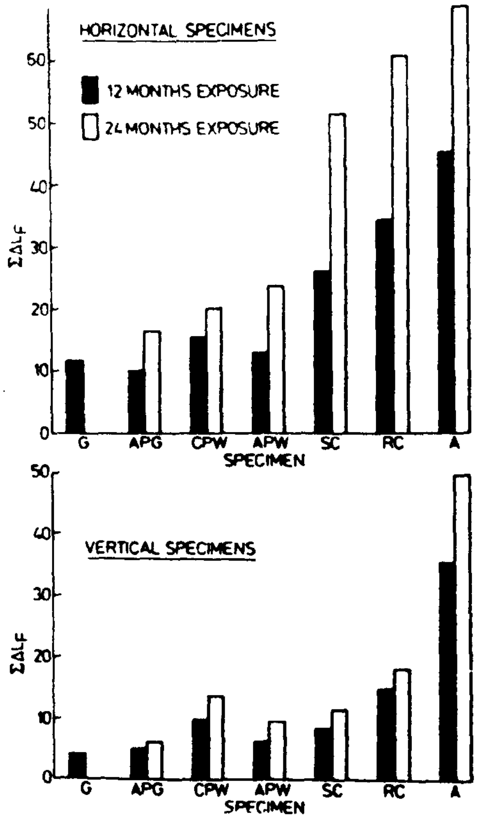


Figure 4.2 Grime on different specimens summed for five sites ($\Sigma\Delta L_F$) for both 12 and 24 months exposure.(114)

where G = glass APG = grey painted aluminium
CPW = white painted concrete
APW = white painted aluminium SC = smooth concrete
RC = rough concrete A = aluminium

From Figure 4.2, it can be seen that aluminium retains the most grime followed by the concrete surfaces, then generally the painted surfaces which differ little from glass. The difference between the rough and smooth concrete is attributed to a greater mass of grime being retained on the roughened surface. The relative retention of grime for the horizontal compared to the vertical exposures is much higher for the concrete surfaces than for the other specimens. Painting concrete markedly reduces grime retention on horizontal surfaces (by about 70%

reduction), but has no such effect on vertical surfaces. Yet, painting aluminium reduces grime collection on both horizontal and vertical surfaces by about 70%. The authors' explanation for such observations was postulated in terms of the glass and painted surfaces being relatively inert to grime, whilst the concrete and aluminium are relatively active. Such activity involves reaction between the water soluble components of the dustfall and the surface, and the reactions of attachment occur where the surfaces are wet after draining of free water from the surface. Because horizontal surfaces remain wet for longer periods after rain or dew deposition than the vertical surfaces, more reaction of attachment can occur. Aluminium is more reactive than concrete and the vertical surface would be subjected to dew deposition more often than the vertically displayed concrete sample.

A visual comparison with the data given in Figure 4.2 can be made with the data collected in this research project in the different soiling characteristics of the various materials exposed both horizontally and vertically and is given in Figures 6.10/12/14 and Appendix C. However, detailed comparisons are not strictly applicable between these two sets of data due to the different measuring techniques employed and the different materials used.

4.1.3 Damage investigations from particulate matter based on dry deposition studies

Work carried out in London measured the changes in reflectance caused by dust deposits on a microscope slide exposed to dry conditions only. This work has shown some evidence that the build-up of dust on such a surface does not continue indefinitely and that some cleansing mechanism can actually cause a reduction in loading with time.(116) Two methods were used to monitor changes in surface appearance. The first was a diffusion system 45° 'gloss meter' which can measure the change in surface reflection caused by the deposited dust. The other technique observed the fractional area covered by the deposited particulate matter using an optical microscope fitted with a calibrated graticule. Figure 4.3 shows the variation in deposited dust, expressed as a percentage of the area covered per day, for a series of clean slides exposed over a period of several days, and the accumulated build-up of dust on a single slide over the same period.

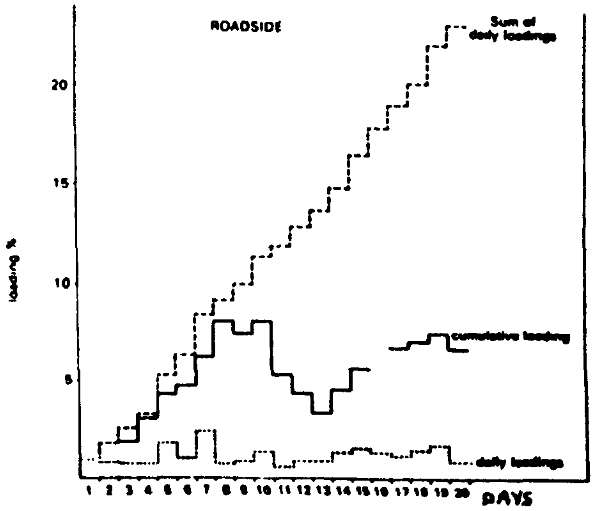


Figure 4.3 Percentage area covered for a clean slide (daily loading) and for a dirty slide (cumulative loading) on successive days.(116)

These above results show that for surface loadings of up to 5-10%, the cumulative loading is fairly close to the sum of the individual daily loadings. However, between the seventh and ninth day the cumulative loading actually declined, after which an increase was noted again. This could not be explained by rain washing the surface(117) for the samples were exposed only in dry weather, but could possibly be due to the scouring and cleansing action of dust particles blowing over the surface, as was first suggested by Blacktin in 1934.(118)

In Brooks and Schwar's study (1987)(116) slides were also exposed with their surface horizontal at a roadsite site, 3m above ground level, where 50,000 vehicles day^{-1} pass on average and also at a rooftop site, 30m above this road. This was to differentiate between soiling rates with height and any differences in rate during the day and at other times. Thus slides were put out during two periods in the day, one from 10.00h to 16.00h (daytime) and the other from 16.00h to 10.00h (night time). Table 4.4 shows the reduction in gloss (as measured by a gloss meter) for slides exposed at the roadside and rooftop sites.

Table 4.4 <u>Percentage Reduction in Gloss Reading per 6h Based on Daily Measurements.</u>(116)

Location	Daytime				Night-time			
	n	Mean	Range	SD	n	Mean	Range	SD
Roadside	20	1.9	0.0-5.8	1.3	14	1.6	0.4-3.0	0.8
Rooftop	20	1.5	0.0-4.2	1.2	13	1.4	0.4-3.3	1.0

n - Number of samples SD - standard deviation

However, Table 4.5 summarises the measurements made of the percentage area of a slide covered by deposited dust particles greater than about 5 μm in diameter.

Table 4.5 Percentage Area of Slide Covered per 6h Based on Daily Measurements.(116)

Location	Daytime				Night-time			
	n	Mean	Range	SD	n	Mean	Range	SD
Roadside	20	0.90	0.36-2.05	0.45	17	0.56	0.22-1.10	0.26
Rooftop	21	0.17	0.04-0.80	0.16	15	0.13	0.06-0.27	0.06

n - Number of samples SD - standard deviation

Here, the rooftop percentage-area covered rates are a factor of 4 to 5 less than for the roadside. This is a much greater difference than was found for gloss rate reductions as shown in Table 4.4. As the authors note that this would seem to suggest some essential difference between rooftop and roadside soiling characteristics. Further information on this was gained from the examination of the measured size distribution of the dust particles exposed daily at the roadside site and illustrated in Figure 4.4.

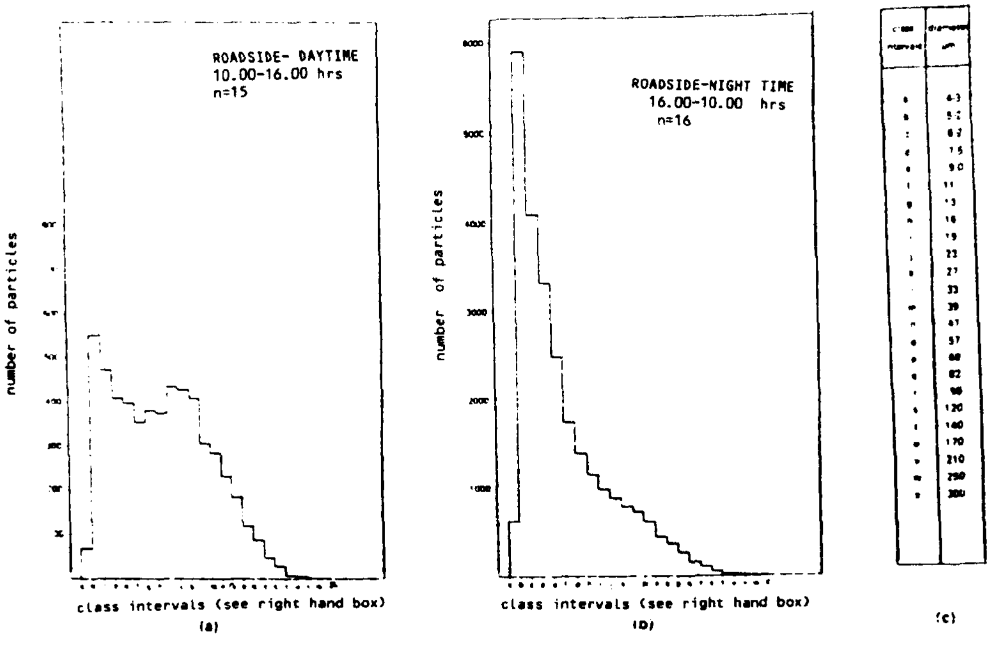


Figure 4.4 Size distribution of dust particles having a diameter greater than about 5 µm collected on slides exposed at a roadside site.
(a) Daytime, (b) night-time and (c) size intervals.
(Note non-linear scale for class intervals.)(116)

These distributions represent the sum of particles counted on all of the slides for the given size intervals. The roadside daytime data exhibits a bimodal distribution which is not apparent for the rooftop site exposed either during the day or night-time or for the roadside site during the night. It is clear that many large particles are deposited on the slides exposed during the daytime than at other times or on the rooftop site. Figure 4.5 represents the proportion by the different sized particles, greater than about 5 µm in diameter, that contribute to the total area of the slide covered. Thus, for daytime dusts, 50% of the covered area is accounted for by particles of greater than about 20 µm at the rooftop site and greater than about 50 µm at the roadside site.

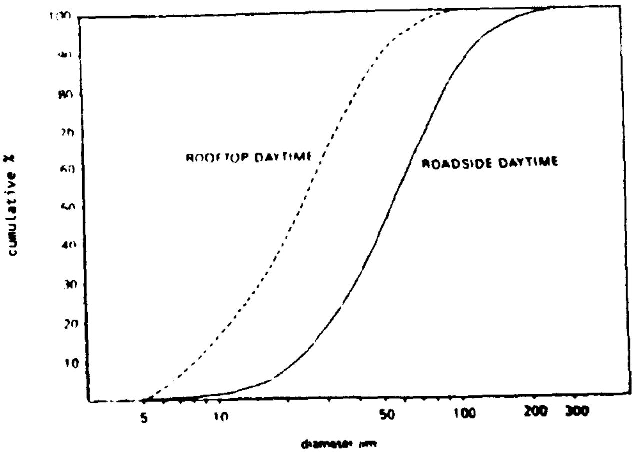


Figure 4.5 Contribution to area covered by particles of different diameters collected on slides exposed at a roadside and rooftop site.(116)

This study examined the size distribution within the coarse particles mode only and does not report any results of the contribution of particles less than 5 µm in size. However, as was noted in Section 2.4.3, it is the fine particulate mode that is most responsible for reflectance effects, hence as shown in Table 4.6, there are similar gloss readings at rooftop and roadside sites although daytime roadside site has the greatest percentage decrease for the sites, suggesting vehicular pollution may be an important contributing factor responsible for this decrease. However, the coarse particulate mode,(i.e. from resuspended surface dust) is an additional roadside contribution, which affects the percentage coverage (elevating that value) but not the reflectance.

Table 4.6 A comparison of the percentage reduction in gloss and area covered readings for a roadside and rooftop site in central London.(116)

Site and time of sampling		% reduction in gloss readings	% area of slide covered	Ratio % reduction in gloss reading: % Area readings
Roadside	Daytime	1.9	0.9	2
	Night-time	1.6	0.56	3
Rooftop	Daytime	1.5	0.17	9
	Night-time	1.4	0.13	11

The results of Brooks and Schwar(116) confirm the findings of Haynie(119) who also exposed glass slides in different locations. One was exposed vertically close to a road with a traffic flow of 13,000 vehicles per day and another horizontally at a 70° angle on a window sill about 20 metres away from the same road. These slides were left for a month and then examined microscopically to deduce the number and sizes of the particles present on the slides. Haynie found that a few very large particles deposited by gravitational settling can dominate both particle volume and cross-sectional area measurements. In considering surface coverage as soiling, 99% of the volume and 63% of the soiling on the glass on the window sill was caused by 39 particles with a diameter of greater than 10 μm. For the vertically placed slide near the road, where gravity does not contribute to deposition, large particles were also dominant. Here, particles with diameters greater than 10 μm account for 90% of the volume and 32% of the soiling. Finally, Haynie found that the total soiling was significantly greater on the glass near the road than the glass on the window sill, 0.138 $mm^2\ mm^{-2}$ compared to 0.070 $mm^2\ mm^{-2}$, which was consistent with the presumption that the ambient concentration of particles is greatest near the primary source.(119)

From the examination of the light and electromicrographs of the exposed slides, Haynie notes the presence of particles of tyre rubber present in both the roadside site and on the window sill site. Although fewer were present on the latter with most of the irregular shape particles being crystalline earth materials. Figure 4.6 shows a composite of low magnification micrographs of the particles deposited on a window sill. The differences between the particles at the top and the bottom are shown, because the action of rainfall tended to wash the very large particles to the bottom. For because the glass was at an angle of about 70°, gravitational settling was partly responsible for the deposition of these larger particles.

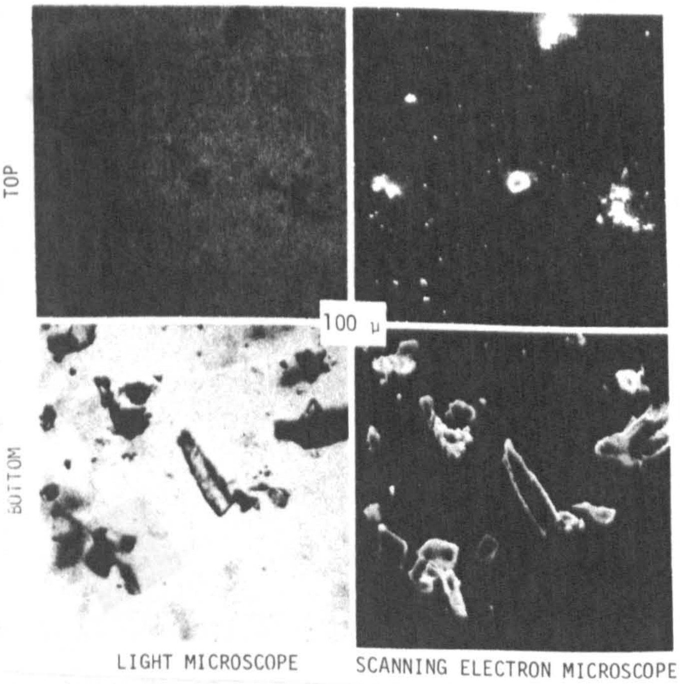


Figure 4.6 Particles deposited on glass at 70° to the horizontal on a window sill.(119)

This would appear to suggest that despite the larger particles such as those from rubber tyre abrasion depositing on to such surfaces, their duration on such a surface may be transient, for such particles are subjected to a greater gravitational influence than are smaller sized particles and they may be water soluble such as some soil-derived particles. Also they might have a less adhesive particle surface than other smaller particles such as those emanating from combustion sources. Thus their contribution to soiling which is a long-term process may be more limited than other smaller sized particles. Haynie also examined particles from a window which had not been washed manually for over ten years and only exposed to blowing rain. It was found that the particles present were similar to those deposited on the window sill slide, indicating that particles larger than 10 µm adhere to vertical surfaces and thus contribute significantly to soiling. Unfortunately, no indication of the previous meteorological conditions in terms of rainfall and wind action are given. Thus, if conditions were such that the presence of rainfall and wind had been negligible prior to the samples being removed for analysis, one may reasonably expect that the larger sized particles will be dominant on such exposed surfaces. For although such particles may be present, this is no indication that they are permanently attached to such surfaces and thereby contribute to soiling. Perhaps, there is a problem with terminology here and the terms dustiness and soiling have been misused by Haynie. As will be shown more fully in Chapter Six, the fluctuation in reflectance of exposed materials in the open environment and the re-soiling rates of such materials may be very dramatic following a period where the materials have been naturally cleansed by rainfall. This may suggest that the action of rainfall preferentially removes the large sized particles and thus an increase in reflectance of the materials is noted.

However, the rapid re-soiling occurs again within a short time period (in the order of a few days) which may be due to the greater proportion of larger sized particles being predominantly deposited on to the surface rather than the small sized ones. There is never a full recovery to the original reflectance level of the materials during their exposure, so undoubtedly some particles remain permanently attached to the surface. As will be shown in Figures 6.20/21, the presence of particles visible to the naked eye is generally more discernable with surfaces that have not recently been subjected to rainfall. However, after a rainfall event, a more obvious grey-oily sheen is apparent on the surface, with less particles visible to the eye.

Finally, another study by Coe and Lindberg (1987)(120) examined particles deposited on leaves and inert surfaces during dry periods for determination of particle morphology and size. All the surfaces were examined using scanning electron microscopy (SEM) and five areas of high particle density were selected. Then photographs were taken of each of these areas at different magnifications of X 300 so particles greater than 1 µm could be seen, one at X 500 to include submicrometer sized particles (0.05 µm). The particles were counted and classified into class sizes ranging from 1 µm to 10 µm and thus from this data, the frequency distribution could be calculated. Results from the size distribution data suggested that the deposited particle mass was dominated by particles larger than 10 µm in diameter, despite the fact that nearly 40% of the 3800 plus particles analysed were less than 2 µm in diameter.(120) These results are consistent with the findings of Haynie(117) and Brooks and Schwar(116) that 50% or more of the deposited mass is attributable to particles in the order of 10 µm and larger, and that particle sedimentation may be an important dry deposition process. However, it should be remembered here the findings reported in Section 2.4.3, that it is the fine particulate mode that is most responsible for reflectance effects. Thus, despite the deposited particle mass being dominated by particles greater than 10 µm in diameter, this should not imply that such particles are also responsible for the soiling/reflectance change of the surface on to which they have been deposited (being usually temporarily).

4.2.1 Lanting's Models

As mentioned in Section 4.1.1, damage functions for the soiling by particulate matter based on experimental data are scant and to date only two authors have derived mathematical models by which to predict rates of soiling.

Lanting reviewed two models which, although based on completely different physical principles for describing the soiling process, gave similar values for decrease in reflectance with time when appropriate input data was used. Both models assume that soiling is caused, in its entirety, by particulate elemental carbon.(121)

The first model was formulated assuming:

(a) the fraction X of substrate area covered by particulates would increase with time according to the equation

$$x = 1 - \exp(-kt) \qquad \text{Equation (1)}$$

(b) soiling potential k is described by:

$$K = \frac{3\,C\,V_d}{4\,r\,\gamma} \qquad \text{Equation (2)}$$

(c) Change in reflectance can be modelled by:

$$R = R_o\,(1-X) + R_p\,(X) \qquad \text{Equation (3)}$$

where t = time (year)

γ = density of the particles (g cm^{-3})

C = concentration of PEC (μg m^{-3})

V_d = deposition velocity (cm s^{-1})

r = radius of the projected area of the particle (μm)

R = Reflectance of the soiled surface (%)

R_o = Initial reflectance of the surface (%)

R_p = Reflectance of the settled particles (%)

The basic assumption in this model is that the change in reflectance is between uncovered area and covered area. The depth of coverage in the covered area is assumed to be immaterial; monolayer coverage gives a final value of R_p. The basis of equations 1 and 2 will be described in Section 4.2.3.

The second model assumed that the exposed area was covered at a uniform rate and that reflection was determined by absorption, which in turn was determined by layer thickness. This resulted in the equation:

$$R = R_o \exp\ (-\ 2\ A\ C\ V_d\ t) \qquad \text{Equation (4)}$$

where A = Specific absorptivity (m^2 kg^{-1})

Lanting's first model is similar to Haynie's model (Section 4.2.2). Haynie used the symbol X for fractional coverage.(112) Lanting used an alternative notation, AC, but X has been used instead in the above summary of Lanting's work to facilitate comparisons. Lanting also used AC instead of K (equations 1 and 2) in his original paper.

Lanting used the following input data which is in general agreement with the values quoted and used in this research.

where the symbols have the following meaning

$C = 2\ \mu g\ m^{-3}$

$V_d = 2 \times 10^{-4}\ m\ s^{-1}$

$\rho = 2000\ kg\ m^{-3}$

$r = 0.025\ \mu m$

$A = 1 \times 10^{4}\ m^{2}\ kg^{-1}$

By substituting into equations 1 - 4 and using a value of t x 1 year, both models give a value for R/R_o of approximately 0.8. Similarly, equation 1 gives a soiling constant for K of 0.17 yr^{-1} and in equation 2 a value of 0.19 yr^{-1} is derived.

4.2.2 Haynie's Model

Haynie assumed that reduction in reflectance was directly related to the fraction of substrate covered. To this extent, the principle is the same as that employed in Lanting's first model and equations (1), (2) and (3) are used in Haynie's theory. However, while Lanting considered that only PEC contributed to soiling, Haynie assumed that all particulates deposited from the atmosphere would contribute and that differences in contribution arose from particle size and deposition velocity, not composition and related optical properties.

Lanting used single value input parameters in his models. Haynie considered the size spectrum of particulate matter and evaluated K in equation (2) as

$$K = \sum_i \frac{3\, C_i\, U_i}{4\, \Upsilon_i\, \rho_i} \qquad \text{(where i is an interval of the size spectrum)}$$

Haynie's results for several surfaces and windspeeds are shown in Figure 4.7(112) and resulting values for reflectance in Figure 4.8.(112)

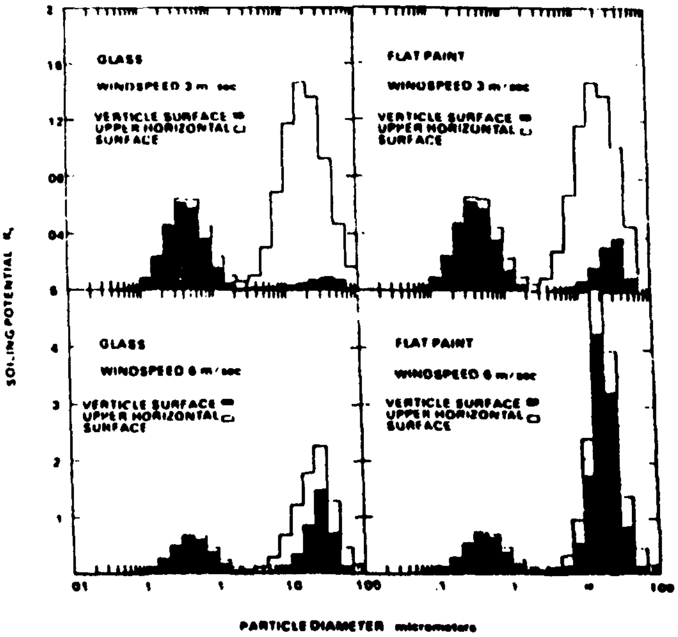


Figure 4.7 <u>Soiling function as a function of particle diameter for different surfaces and windspeeds.</u> (112)

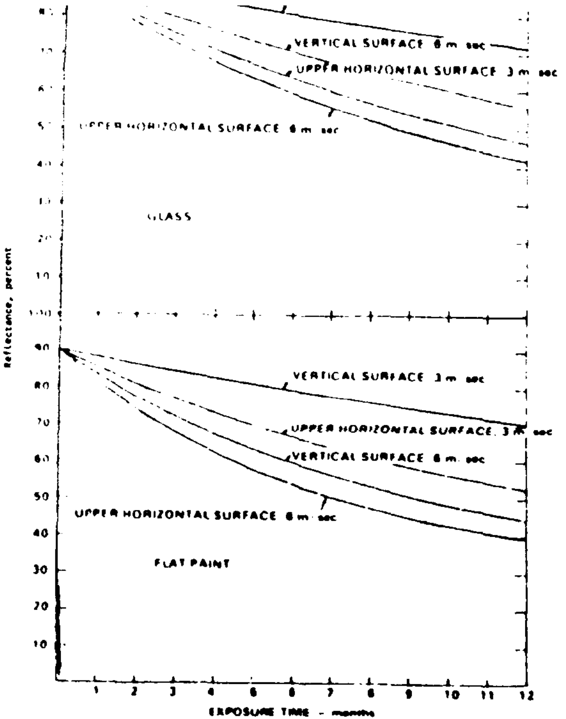


Figure 4.8 Reflectance change with time for different surfaces and windspeeds: substrate reflectance (Ro)=90%, particle reflectance (Rp)=30%.(112)

4.2.3 A generalised model for soiling

The two model principles reviewed predicted an exponential decay in reflectance. Models have been based on (a) loss of reflectance is proportional to area covered or (b) loss of reflectance is proportional to the thickness of the deposit.

Situation (a) is shown in Figure 4.9. The total deposition rate on surface = $A_o . J$ ($\mu g\ s^{-1}$), while the deposition rate to an uncovered surface $\frac{dm}{dt} = (A_o - A)\ J$ ($\mu g\ s^{-1}$)

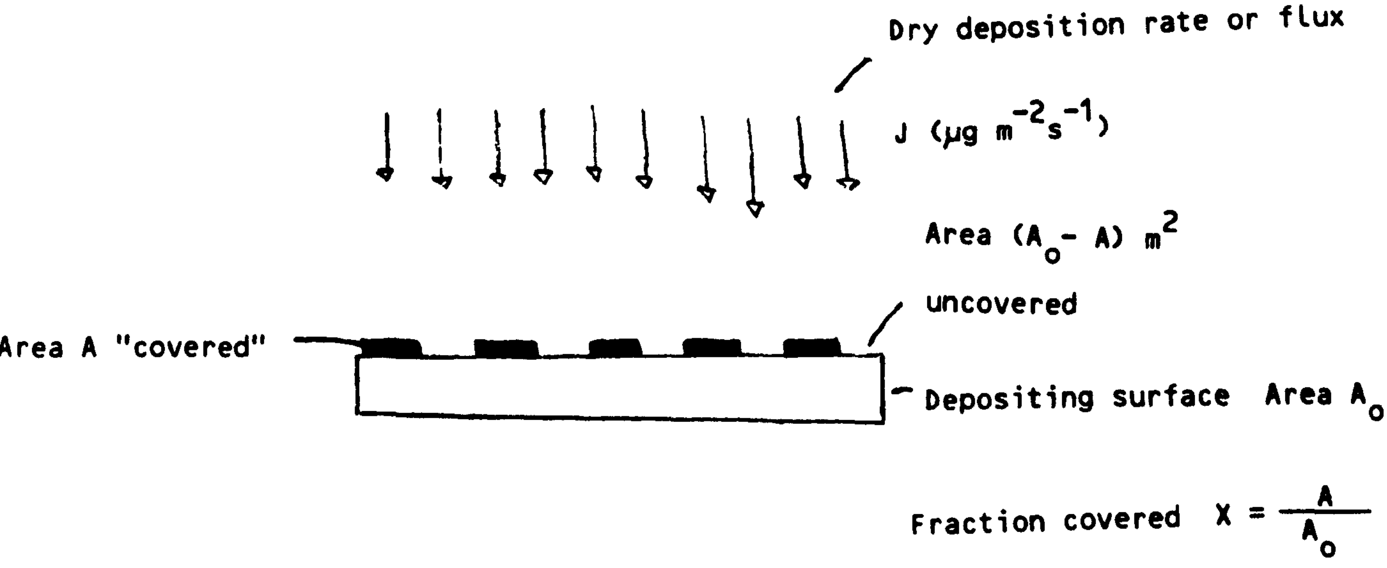


Figure 4.9 Particulate Deposition and Surface Coverage

This mass can be related to additional surface area covered, as follows:

Mass (M) is produced by (n) particles, of (r) radius and (ρ) density, where

$$M = n \frac{4}{3} \pi r^3 \rho$$

These particles have a total cross-sectional area of

$$A = n . \pi r^2$$

$$M = \frac{4}{3} A r \rho$$

$$\frac{dM}{dt} = \left(\frac{4}{3} r \rho \right) \frac{dA}{dt}$$

Dry deposition rate ($\mu g\ m^{-2}\ s^{-1}$) is related to airborne concentration C ($\mu g\ m^{-3}$) and dry deposition velocity V_d ($m\ s^{-1}$) by the equation

$$J = C V_d$$

$$\frac{dM}{dt} = (A_o - A) \quad C V_d$$

$$\frac{4}{3} r\rho \frac{dA}{dt} = (A_o - A) \quad C V_d$$

$$\frac{dA}{dt} = (A_o - A) \frac{(3 C V)}{(4 r\rho)} = K \quad (A_o - A)$$

$$\text{where } K = \frac{3 C V}{4 r\rho}$$

$$\int_0^{A} \frac{dA}{A_o - A} = K \int_0^{t} dt$$

$$\frac{A - A}{A_o} = e^{-kt}$$

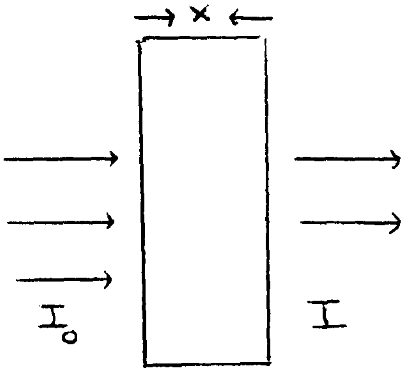
The fraction covered, $X = \frac{A}{A_o}$

$$1 - X = e^{-kt}$$

$$X = 1 - e^{-kt}$$

With (b), the model assumes the loss of reflectance is proportional to the thickness of the deposit

absorption

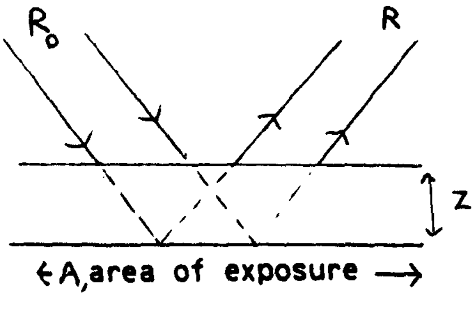


$I = I_o e^{-\mu x}$

where μ (m^{-1}) is linear absorption coefficient

mass absorption coefficient, $\alpha = \frac{\mu}{\rho}$ (units $m^2\ kg^{-1}$)

So $I = I_o e^{-\rho \alpha x}$



Z = thickness of deposit

$R = R_o\ e^{-\rho \alpha 2 Z}$

With this model, deposition rate = A C V_d (kg s^{-1}) over area A (m^2)

mass deposited in time t = A C V_d t (kg)

This is contained within volume A Z, density ρ

$$\frac{A\ C\ V_d\ t}{A\ Z} = \rho, \text{ so } \rho Z = C\ V_d\ t$$

So $$R = R_o\ e^{-2\alpha C\ V_d\ t}$$

$$= R_o\ e^{-kt} \qquad \text{where } k = 2\alpha C\ V_d$$

So in general soiling can be described as:

$$R = R_p + (R_o - R_p)\ e^{-kt}$$

where K is the soiling potential A value of K as derived by Lanting's models gave a figure between 0.17 and 0.25 year^{-1} for an environment where the ambient level of PEC was 2 µg m^{-3}. Haynie's model gives a value of K of 0.25 yr^{-1} using a value for TSP of 30 µg m^{-3}, for a level of 50 µg m^{-3} TSP the value of K is equal to 0.4 yr^{-1}. The experimental values of K recorded for a variety of locations are given in Chapters Five and Six and compared with the predictive theoretical models of Haynie and Lanting. Using the ascribed formula of Haynie and Lanting, the rates of soiling can be calculated for a range of hypothetical TSP/EC levels. These rates are presented in Table 4.7 and illustrated in Figure 4.10. A value of $R_p = 0$ was assumed. The graphs show the theoretical exponential decay in soiling, with the results of Lanting predicting more rapid soiling rates than Haynie. The levels of EC used here have been derived using the relationships described in Section 3.5.2 and may slightly overestimate the level of EC; however, allowing for this margin of error, the soiling rates predicted by Lanting are greater than those of Haynie.

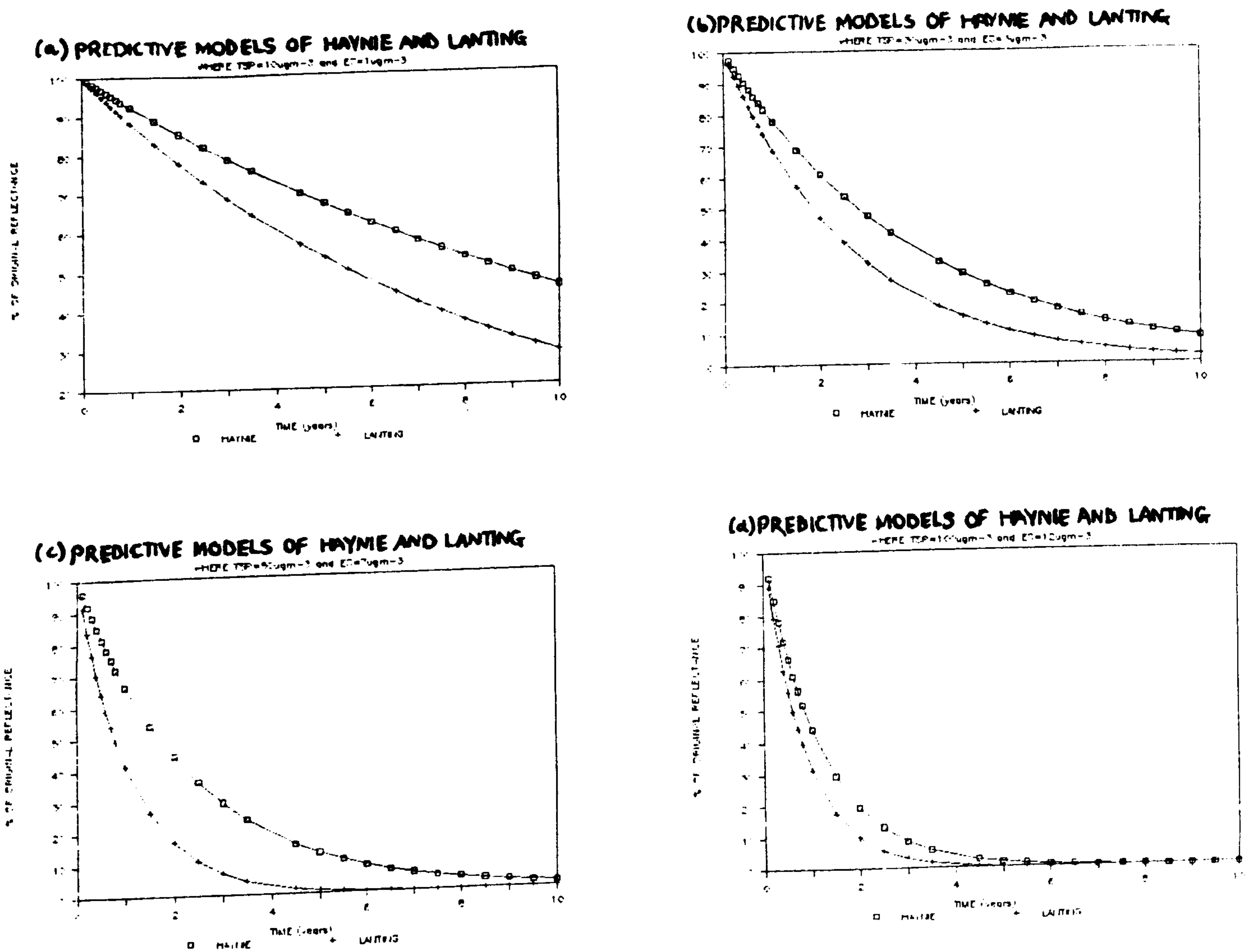


Figure 4.10(a)-(d) A comparison between the predicted soiling constants of Haynie and Lanting for a variety of TSP and EC levels.

(a) TSP = 10 μg m^{-3} EC = 1 μg m^{-3} (b) TSP = 30 μg m^{-3} EC = 3 μg m^{-3}
(c) TSP = 50 μg m^{-3} EC = 7 μg m^{-3} (d) TSP = 100 μg m^{-3} EC = 12 μg m^{-3}

Table 4.7 A comparison between the predicted soiling constants of Haynie and Lanting for a variety of TSP/EC levels.

TSP level ($\mu g\ m^{-3}$)	EC level ($\mu g\ m^{-3}$)	Haynie's soiling constant (yr^{-1})	Lanting's soiling constant (yr^{-1})	% of original reflectance 2 years exposure	
				Haynie	Lanting
10	1	0.08	0.126	88	80
30	3	0.25	0.378	62	49
50	7	0.41	0.882	45	19
100	12	0.82	1.162	21	11

However, it should be remembered that in practice, the deposition of aerosols from the ambient atmosphere on to materials including building materials is a complex phenomenon and predictive models must of necessity simplify the situation. An indication of the nature of the deposit formed on the surface of the material is provided by laboratory experiments and/or experiments involving deposition on to glass substrates. As illustrated in Figure 4.11.(122)

Depositing atoms form networks of islands separated by valleys before a uniform thickness of deposit is eventually formed. This contradicts the simple models in that Haynie's and Lanting's first model assume random deposition; whilst Lanting's second model assumes a uniform thickness at all stages. In addition the situation in the ambient atmosphere involving materials with irregular surfaces will be even more complex than Figure 4.11 suggests. Likewise, meteorological conditions such as rainfall have not been in the models of Haynie and Lanting. Yet as is shown in Section 4.3 the rain runoff from a building facade may alter the degree of soiling upon that material surface. Also, from the experimental data given in Chapters Five and Six, meteorological conditions are deemed to be an important factor in helping to explain the fluctuation levels between soiling and dustiness levels on materials fully exposed within the ambient environment.

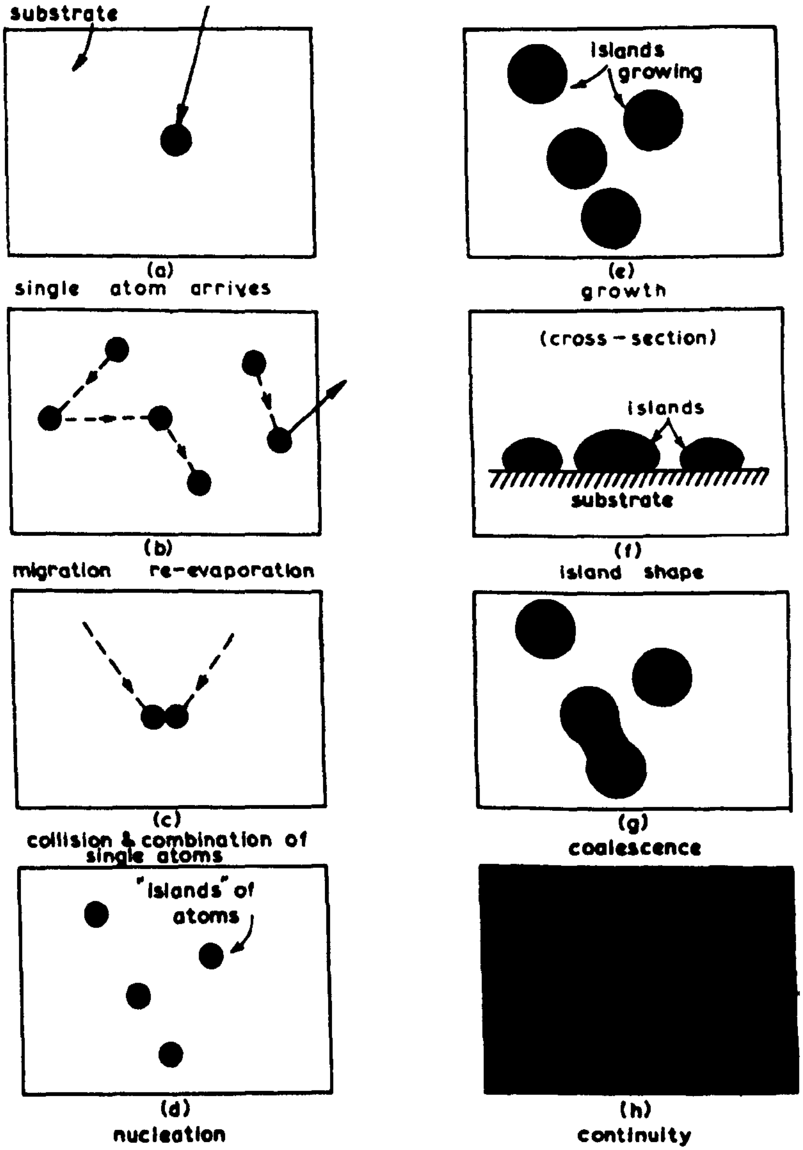


Figure 4.11 Formation stages of a thin film(122)

4.3 The role of rainfall on building facades

An understanding of how rain strikes an external wall surface and the action of subsequent runoff streams of rain can provide information on how soiling patters arise on facades. It may also aid in the detection of decaying areas, for as Ashurst and Dimes(123) note, if it was not for the action of water on building stone, very little decay would occur. Water is involved in such destructive mechanisms as corrosion, leaching and efflorescence, biological decay and freezing. Because the movement of water over exterior surfaces results in washing or in deposit of dirt in concentrated locations, it may appear as a disfigurement of the building's appearance or in more serious conditions a complete breakdown of materials. Thus when considering the design of building constituents such as walls and windows, the prevention of rain penetration and the control of water migration over the building surfaces to prevent changes in appearance and water absorption into wall materials should be considered and adapted to minimise such effects.

Driving rain may be defined as rain carried along by wind at an angle to the vertical so that it strikes vertical surfaces of buildings. Most rainstorms have wind associated with them, so there is increased exposure for windward facing surfaces. Rain deposit and its migration over building facades will be affected by exposure to driving rain and its directional variation with time. When wind hits a rectangular building, either freestanding or much taller than its neighbours, the airflow divides at about two-thirds of the building height. Some flows up the face and over the roof, whilst some flows sideways and round the upper windward corners; the rest flows downward to form a vortex in front of the building and sweep round the lower windward corners. These flows described by Wise (1965) are illustrated schematically in Figure 4.12.(124)

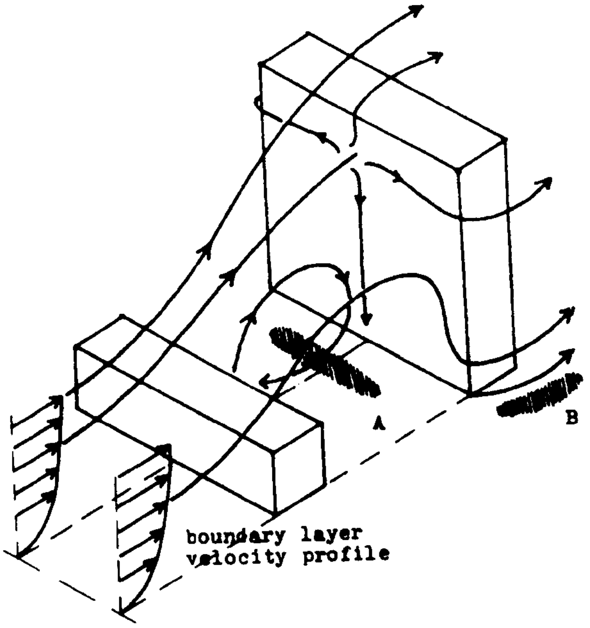


Figure 4.12 Typical flow pattern round a high rectangular building with a low rectangular building to windward. Velocities in Zones A and B may be twice that of free wind at the same height and three to four times that in streets sheltered by low buildings.(124)

Falling raindrops are deflected by the general airflow and then further deflected by the air currents passing over and round buildings. It is thought that drops carried in the flow may be unable to follow the change in direction and, instead, strike the building face, producing concentrated wetting at windward edges, thus accounting for the wetting of windward corners, parapets and protruding cornices and projections such as columns and sills. Figure 4.13(125) shows the general airflow and rainfield patterns for a vertical projection from a building face.

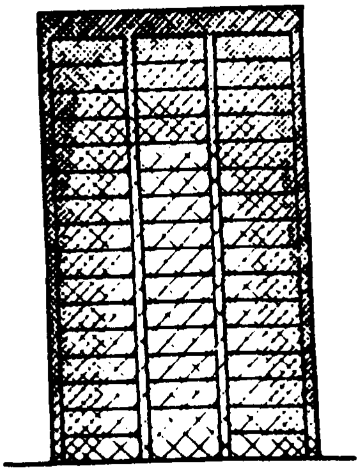
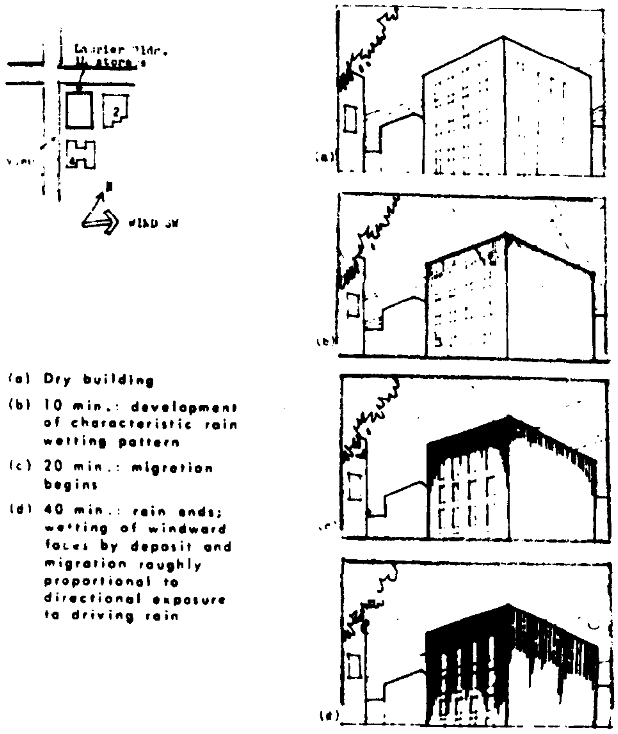


Figure 4.13 Typical wetting pattern on the face of a multi-storey building subjected to wind-driven rain.(125)

The deposit of rain on a building face is not uniform. Owing to the deflection of air and rain, rain deposit is usually several times greater at the top and sides of an exposed building face than it is over the remainder of the wall. The location of concentrated rain deposit on the building face should remain constant over the course of the rainstorm provided that the wind direction and speed do not vary greatly. So that at the start of a typical rainstorm only the top and sides of the windward face will be wetted, but the nature of the wall material will determine what happens as the storm progresses. Water deposited on the building surfaces will tend to be absorbed initially by porous material such as stone, brick or concrete, but as soon as the rate of deposit exceeds the rate of absorption the water will continue to migrate down the wall. On non-porous material such as metal and glass, water will begin to flow down the wall almost immediately after it has been deposited.

Surface saturation of porous materials is usually apparent by a change in the colour of the material. It can show the progressive wetting and the paths of concentrated flow on building faces. Observations of this type are illustrated in Figure 4.14(126) which shows a time-lapse sequence for a building of precast exposed-aggregate concrete panels. The pattern of intense wetting shows rain deposits concentrated at the top of the building, although the entire windward face and portions of the other walls must also have received some rain.(126)



(a) Dry building
(b) 10 min.: development of characteristic rain wetting pattern
(c) 20 min.: migration begins
(d) 40 min.: rain ends; wetting of windward faces by deposit and migration roughly proportional to directional exposure to driving rain

Figure 4.14 Laurier building, Ottawa, during a forty minute moderate rainfall.(126)

Thus, it may be expected that buildings are more soiled on the lower reaches of the building than at the top; because any of the particles that have been deposited at the top may be removed by the action of rain runoff which is greatest there. Such particles may then be deposited lower down the facade. However, it is interesting to note that many buildings which have either been recently built or cleaned exhibit a very strong soiling pattern where the bottom reaches are more greatly soiled than the top; more than perhaps might be due to rain runoff alone. Indeed looking at older buildings which are over fifty years old and have never been cleaned, they seem to soil more uniformly down the facade than modern or cleaned buildings. Circumstantial evidence gained from interviewing stone cleaning companies generally indicates that soiling is much greater nowadays at the bottom than was the case in the previous thirty years plus and that the deposit is stickier and more difficult to remove than in the height of the coal burning days. This may in part be due to the change in fuel usage and its emission distribution characteristics. For example, the smoke from coal burnt domestically within our cities was evolved from chimneys often 20-30 metres above ground level. However, in urban areas where coal is not commonly used, the greatest proportion of smoke evolved into the ambient atmosphere comes from DERV (as shown in Chapter Two) whose point of emissions (exhaust pipes) is less than one metre above ground level. It may be that because emissions from diesel vehicles are known to be sticky that any particles colliding with a building facade are more firmly adhered to it than other sources of (often larger) particles in the urban environment; thus the bottom is more heavily soiled than the top. The extra traffic on the road now as compared to thirty years ago, may also mean that more tyre, brake and road debris is generated and although only usually temporarily suspended in the atmosphere due to its comparatively large particle size may also impact upon a facade but usually only the bottom section due to its limited suspension. This circumstantial evidence is highlighted in Figure 4.15 which shows a building situated in Dock Road, Liverpool. The traffic outside the building includes many diesel vehicles as the local bus garage is located nearby. The immediate area is also served by many taxis, as well as lorries going to and from the docks. This photograph was taken only four years after it had been cleaned.(127)

Figure 4.15 The soiling pattern which emerged after four years of the building being cleaned, located in Dock Road, Liverpool.

Finally, the facade geometry of buildings is largely responsible for the local concentration of runoff, concentrations that lead to the characteristic marking patterns frequently observed on building surfaces. There is usually a fairly even accumulation of dirt on vertical surfaces except where some feature causes a concentration that tends to produce a lighter, cleaner streak across the general pattern. This has been referred to as "white washing". Near or on horizontal surfaces which tend to have a greater dirt accumulation, runoff can carry the dirt to adjacent vertical surfaces to produce dark dirty streaks across the general pattern. On any building there will probably be combinations of dirt accumulation, dirt-washing and white-washing as illustrated in Figure 4.16.(126) As Beijer(128) notes it takes a few years before an interested observer clearly sees that a soiling pattern is emerging; indeed it is the contrast between the dirt and white-washing areas which highlights this pattern and it is the streaked patterns which may make the soiling more apparent and objectionable to the public's perception of the building facade.

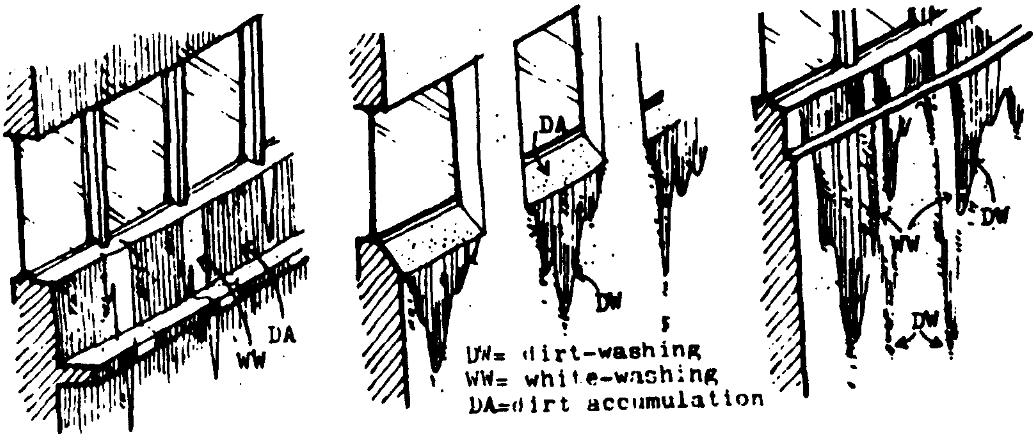


Figure 4.16 Some characteristic marking patterns.(126)

Figures 4.17(a) and (b) show such examples as illustrated above in Figure 4.16. These photographs were taken of a housing estate in Edinburgh which was built seventeen years ago in 1971. Figure 4.17(b) shows the action of water dripping from a leaking pipe down the facade and illustrates the degree of soiling that has taken place since the building was built. This serves as a useful reminder that modern-day buildings are also being soiled, though fortunately (as yet) not as fast as was reported in the 1930s as illustrated in Figure 4.18 of a building in Manchester.(129) Indeed it is interesting to compare Figure 4.15 and Figure 4.18 and the different zonation patterns of soiling with time, although a strict comparison may not be valid because the individual microclimate and the pollution characteristics near each building cannot be assessed.

4.4 Summary

Having reviewed the existing two theoretical models used to predict soiling rates within the ambient environment and assessed the role of rainfall in its contribution to the soiling/cleaning of building facades (a fact which neither of the two models take truly into account), it was decided to test the two theories by three experimental programmes:

(1) measuring soiling rates in a road traffic tunnel where the action of rainfall is absent. This is described in Chapter Five;

(2) measuring soiling rates daily in a suburban location so any changes in soiling rates can be analysed in terms of the amount of daily rainfall;

(3) measuring soiling rates at nine sites within metropolitan London on an approximate monthly basis. The results of the latter two experimental programmes are given in Chapter Six.

Figure 4.17(a) An example of dirt washing on a 17-year old Edinburgh housing estate

Figure 4.17(b) An example of white-washing (by the action of a leaky pipe) on a 17-year old Edinburgh housing estate

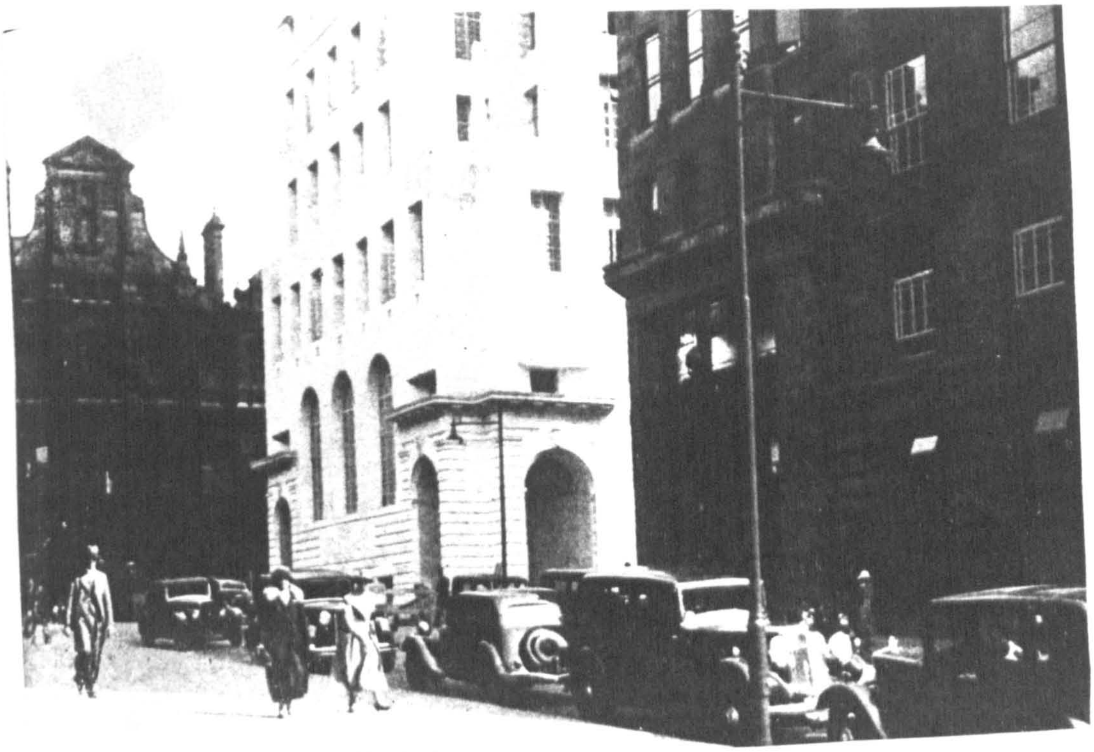


Figure 4.18 Buildings in Manchester: A building in King Street photographed just after completion in 1935. Compare it with its neighbours - those on the immediate right in similar stone were completed only in 1927 and 1929.(129)

CHAPTER FIVE

5. Measurement of soiling rates in a road traffic tunnel

5.1 Introduction and Objectives of experimental programme

As was discussed in the previous chapter, the role of precipitation is deemed to be important in the removal and re-deposition of particulate matter on soiled building facades. Indeed the preliminary results from the nine-site exposure programme described in Chapter Six, suggested that meteorological conditions especially rainfall may be an important factor in explaining the observed fluctuation in reflectance levels recorded.(130) To further assess the role of rainfall and its effect on reflectance levels on exposed materials, it was decided to expose two of the materials, wood and tile as used in the nine-site programme, in a road-traffic tunnel where rainfall is absent. Furthermore, this programme permits a soiling constant to be calculated where smoke levels are higher than in most urban locations. It is also of interest because the source of particulate matter is largely vehicularly derived. Ambient levels of smoke, total suspended particulate matter and elemental carbon were sampled and compared with the relationships reported in Sections 2.4.4 and 3.5.2. The concentration of total carbon was also measured for the material deposited on the exposed surfaces and compared with ambient levels. The theoretical soiling rates predicted by the models of Haynie(112) and Lanting(121) were also calculated for the tunnel location and compared with the experimentally recorded results. The economic and other implications of soiling in tunnels were also evaluated.

5.1.1 Description and location of tunnel site

The Hatfield tunnel, part of the A1(M) in Hertfordshire, was chosen to carry out the investigation. Figure 5.1 shows its geographical location. The tunnel was opened in December 1986, it is 1.1 km long and has a 7-day average of over 26,700 vehicles per day using it. Table 5.1 shows a typical week's number of vehicles using the tunnel. Furthermore, electronic road sensors can record the length of vehicles and their speed which show that approximately 15% of the traffic is from larger vans and heavy goods vehicles which are predominantly using diesel fuel.

Table 5.1 Vehicle numbers using the southbound bore of the Hatfield tunnel for the week 18-24/1/88.(131)

	Mon 18/1	Tue 19/1	Wed 20/1	Thu 21/1	Fri 22/1	Sat 23/1	Sun 24/1
No. of vehs. per day	29,754	30,375	30,977	31,306	30,565	16,786	17,170

Average number of vehicles on working weekdays = 30,595

Average number of vehicles for the entire week = 26,704

5.1.2 Ambient levels of smoke, total suspended particulate matterand elemental carbon in the tunnel

A continuous monitoring programme of the aforementioned pollutants was not possible due to security and access reasons. However, as shown in Table 5.2 some measurements were taken; unfortunately they were taken at various times during the exposure period and comparisons between the measurements are not strictly valid.

Figure 5.1 Geographical location of the Hatfield tunnel and views from within it

Table 5.2 Ambient levels of smoke, total suspended particles (in $\mu g\ m^{-3}$) and percentage total carbon measured within Hatfield tunnel

Smoke Shade Results ($\mu g\ m^{-3}$)	Total Suspended Particulates ($\mu g\ m^{-3}$)	% Total Carbon
347	208	45.3
158	186	44.5
171	230	44.2
249		
128		
374		
129		
273		
238		
396		
335		
259		
210		
186		
average 246.7	208	44.6
S.D. ± 89	22	0.6

TSP levels were recorded over an 8 hour period (10.00 - 18.00 hours) and as experimentally described in Section 2.4.2.1. In addition samples of total particulate matter present in the ambient atmosphere were collected using an electrostatic precipitator for 8 hours and then analysed using a Perkin-Elmer 240C elemental analyser. Experimental details are further given in Appendix B.

The smoke shade levels were measured using the British Smoke Shade apparatus as described in Section 2.4.1; however, the apparatus was fitted into an eight-port sampling device. This has a timing motor which was selected for a number of predetermined periods (in this case 8 x 24 hour periods), the sampling lines are automatically changed by switching on the valve changeover motor. The motor moves the upper slotted disc through 45° which connects the air intake in sequence to a number of standard daily instruments for the predetermined period.

The average smoke level of 246 $\mu g\ m^{-3}$ was based on a 24 hour sample carried out over 14 days. Unfortunately only 3 TSP levels could be measured during the sampling period and only then from 10.00-18.00 hours, thus missing the morning rush hour peak traffic flow and only partially capturing the late evening rush hour. The averaged results indicate that the TSP level is slightly lower than those of the dark smoke. This is consistent with the findings presented in Section 2.4.4. Diesel derived vehicular smoke is darker than that of the British standard smoke, so here the smoke shade technique may overestimate the total particulate level. However, further analysis of the data is not valid because of the different temporal variations in sampling as imposed by the Tunnel authorities.

However, further comparisons of the smoke shade levels with that of total carbon are possible. The analysis of the ambient sample collected using the electrostatic precipitator gave an average percentage of total carbon of 44.6% of the sample analysed and an average ash content of 29%. An example of the results obtained using the elemental analyser is given in Table 5.3. As stated in Section 3.5.2 the results of Bailey and Clayton (1982)(31) suggest that levels of ambient elemental carbon (in $\mu g\ m^{-3}$) can be predicted using the smoke shade values. It has been assumed here that their relationship for smoke concentrations in the range of 0-200 $\mu g\ m^{-3}$, is still applicable for a level of 247 $\mu g\ m^{-3}$.

$$\text{Total Carbon} = 0.42\ (\text{smoke}) + 4.34 \quad (\text{in } \mu g\ m^{-3}).^{(31)}$$

The experimentally observed 45% total carbon was close to the Bailey and Clayton value of 42%. Thus, for the tunnel location, the concentration of total carbon would be equal to:

$$\begin{aligned} \text{Total carbon} &= 0.42\ (247) + 4.34 \\ &= 108\ \mu g\ m^{-3}. \end{aligned}$$

Assuming that elemental carbon is the third of total carbon, the concentration of elemental carbon is around 36 $\mu g\ m^{-3}$, according to the Bailey and Clayton model.

The work of Edwards et al (1983)(89) also showed that 50 μg of smoke corresponded to 6 ± 2 μg of elemental carbon. This calculation was derived using the OECD calibration curve, thus the corresponding British Standard value is 42.5 $\mu g\ m^{-3}$ smoke using the equation given in Section 3.5.2 and the elemental carbon is thus 14 ± 4% of the smoke. So the 247 $\mu g\ m^{-3}$ average smoke level for the tunnel corresponds to an elemental carbon concentration in the range of 24 - 44 $\mu g\ m^{-3}$. These levels cover the predicted Bailey and Clayton level of 36 $\mu g\ m^{-3}$ for the tunnel.

Dividing the percentage of total carbon by three gives a percentage of elemental carbon of 14.8%. Taking 14.8% of the average observed TSP level gives a value of 30.5 $\mu g\ m^{-3}$ for the ambient concentration of elemental carbon within the tunnel. This experimental work is in very close agreement with the theoretically derived values of Bailey and Clayton(39) and of Edwards et al.(89) This experimentally derived value of elemental carbon concentration ($\mu g\ m^{-3}$) has been used to derive the Lanting soiling constant for the tunnel, whose theory was shown in Section 4.2.1. Likewise, the value of TSP for the tunnel has been used to deduce Haynie's soiling constant for this location. The predictions of these models are compared with experimental data in Section 5.2.

Table 5.3 <u>An example of the results obtained analysing a sample of the deposited matter collected using an electrostatic precipitator to collect an ambient sample within the Hatfield Tunnel</u>

COMPOSITION %	AS RECEIVED	MOISTURE CORRECTION	DRY ASH FREE
NITROGEN	0.94	0.94	1.30
CARBON	44.23	44.23	60.81
HYDROGEN	4.85	4.85	6.67
ASH	27.27	27.27	
MOISTURE		0.00	
TOTAL	77.29	77.29	68.78

5.1.3 Experimental details for soiling measurements

A piece of wood painted with white gloss (40cm x 30cm) with a white ceramic tile (15cm x 15cm) mounted in the middle of the wood was exposed on top of an emergency display panel in the exit bore of the southbound section of the Hatfield tunnel, for a total period of 222 days. The materials were displayed 3 metres above ground level and 5 metres from the nearest of the three traffic lanes, (the slow lane). Measurements of the tile and wood reflectance were taken using an Eel Reflectometer at approximately weekly intervals during the exposure period and are given in Table 5.4 and Figure 5.2. Measurements of ambient atmospheric levels were taken but a continuous monitoring programme was not permissible due to safety and operational difficulties as laid down by Hertfordshire Council and the Police Constabulary. However, as shown in Table 5.2 a total of 14 smoke shade measurements, 5 TSP levels and 3 electrostatic precipitator samples were obtained. These latter samples and samples taken from the soiled materials surfaces were subsequently analysed for total carbon using the Perkin-Elmer 240C elemental analyser. The results of these analyses are given in Table 6.6, Section 6.4. Experimental details on the electrostatic precipitator and the elemental analyser are given in Appendix B.

5.1.4 The Reflectance measurements for wood and tile during the exposure period

The measurements in Table 5.4 below give the percentage of the materials original reflectance with time and these are graphically displayed in Figure 5.2.

Table 5.4 The percentage of original reflectance of wood and tile samples exposed in the Hatfield tunnel with time

Days of Exposure in Hatfield tunnel	Percentage of original reflectance WOOD	TILE
1	100	100
7	97	97
13	93	92
20	93	86
27	82	77
35	85	80
42	83	76
50	75	74
71	68	63
75	64	59
82	63	56
89	54	57
97	56	57
103	54	52
117	52	50
139	43	51
145	42	58
152	40	51
174	51	54
180	50	46
188	49	41
201	43	39
208	42	41
215	34	41
222	32	38

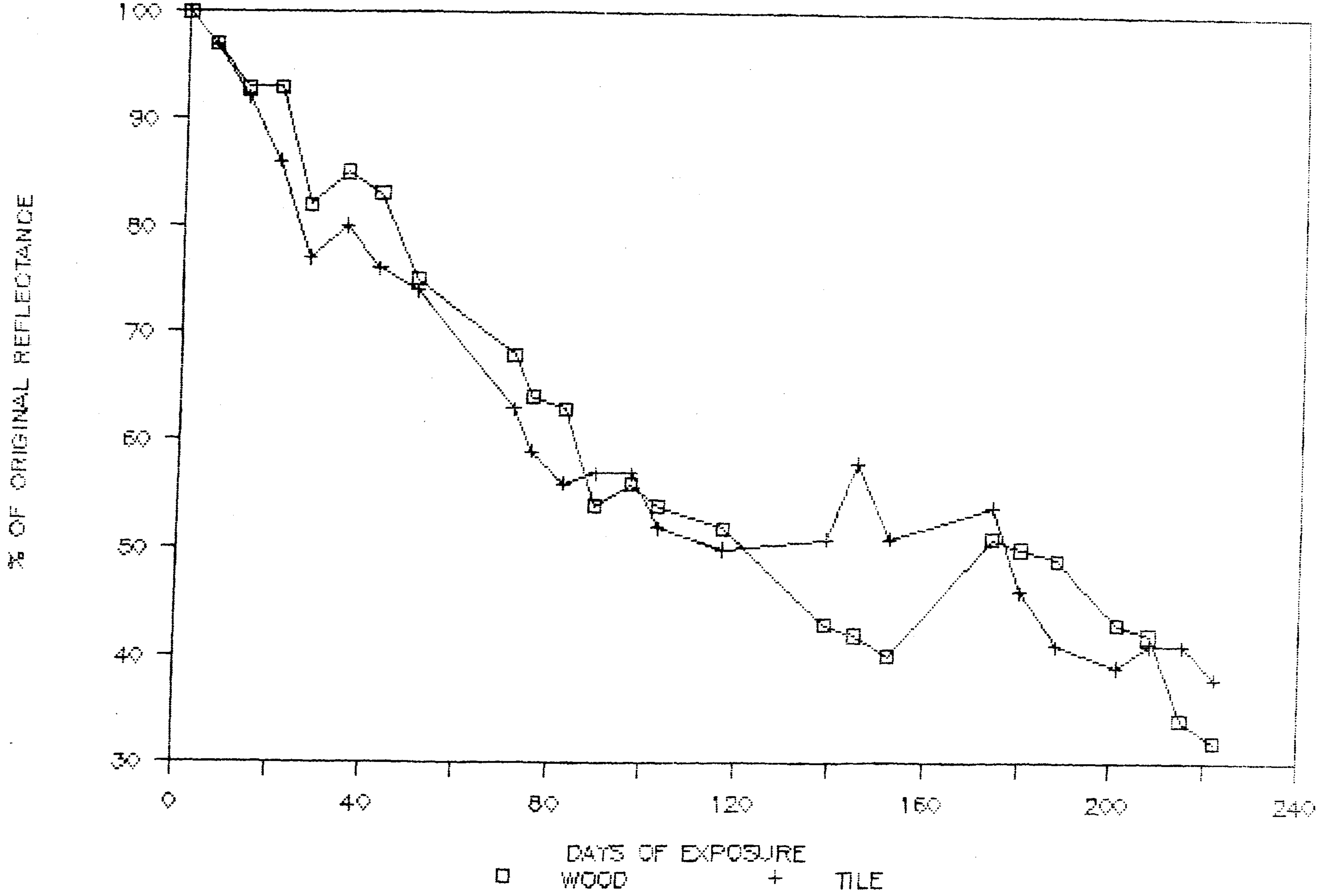


Figure 5.2 <u>The change in reflectance for materials exposed in the Hatfield tunnel with time</u>

5.2 Models for soiling in the Tunnel

5.2.1 Exponential models

Following an examination of Figure 5.2, some initial tentative observations were made:

(i) the absence of rainfall within the tunnel may be responsible for the nearly constant decline in reflectance for both materials during the exposure period. The increase in reflectance noted from days 152 to 174 may in part be due to the removal of the materials from the tunnel due to maintenance cleaning operations. Thus the handling and removing of the materials from the tunnel for the one day may have removed some of the deposited matter and thus altered the reflectance;

(ii) the decrease in reflectance for the exposed materials seemed to be following an exponential decrease rather than a linear one;

(iii) the decrease in reflectance for both wood and tile tended to follow a similar trend.

Thus, further calculations were carried out to investigate if any of the initial observations could be quantified.

The results of percentage reflectance for both materials was expressed as a rate of change of reflectance and are given in Table 5.4. Thus, at the beginning of day 1, the percentage for both materials was 100%, however after day 7 both recorded a 97% of original reflectance, thus there had been a decrease of 3% over the 6 day period. Because there had been a decrease in reflectance a negative figure was given, thus the gradient would equal -3/6 which equals -0.5% in reflectance per day. This was carried out for all data and results are given in Table 5.5.

Table 5.5 The percentage change in reflectance per day for tile and wood sample with time

Gradient Tile	Gradient Wood	Exposure time (year)
-0.50	-0.50	0.019178
-0.80	-0.60	0.035616
-0.85	0.00	0.054795
-1.28	-1.50	0.073973
0.30	0.30	0.095890
-0.57	-0.28	0.115068
-0.25	-1.00	0.136986
-0.52	-0.30	0.194521
-1.00	-1.00	0.205479
-0.42	-0.14	0.224657
0.14	-1.28	0.243836
0.00	0.22	0.265753
-0.83	-0.30	0.282192
-0.14	-0.14	0.320548
0.04	-0.40	0.380822
1.16	-0.16	0.397260
-1.00	-0.28	0.416438
0.13	2.00	0.476712
-1.33	-0.16	0.493151
-0.62	-0.12	0.515068
-0.15	-0.46	0.550685
0.28	-0.14	0.569863
0.00	-1.14	0.589041
-0.42	-0.28	0.608219

These above results are graphically shown in Figures 5.3 and 5.4.

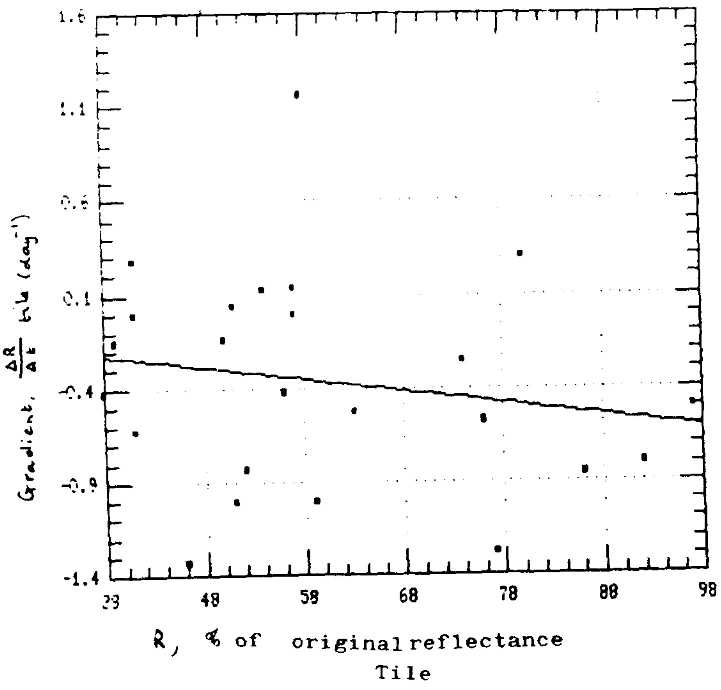


Figure 5.3 Linear model for tile: a plot of gradient per day against % of original reflectance

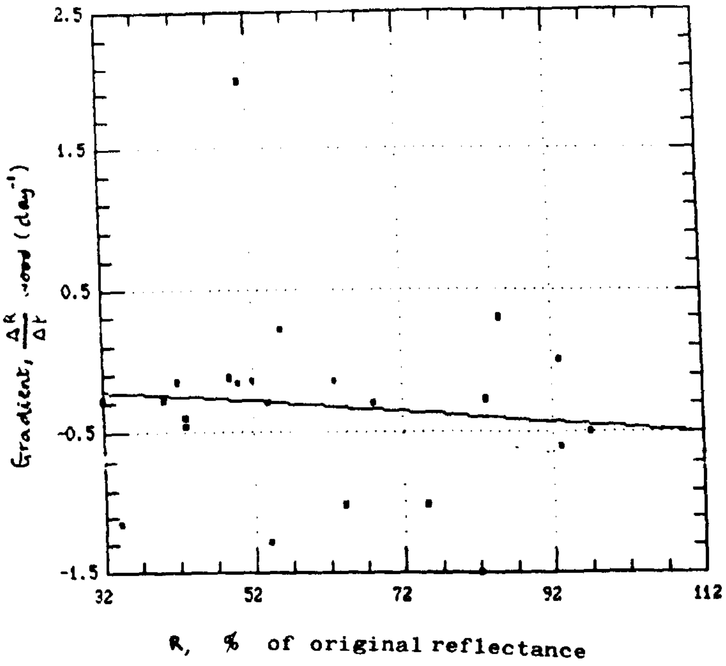


Figure 5.4 Linear model for wood: a plot of gradient per day against % of original reflectance

Although the correlation coefficients between the rate of change of reflectance and reflectance are weak (R = -0.19 for tile and R = -0.10 for wood), it was assumed that a straight line was the best suited curve to fit the data sets displayed in Figures 5.3 and 5.4. This permits the change in reflectance to be modelled by the equation:

$$R = R_o e^{-Kt} \qquad \text{where } R_o = 100\%$$

$$\frac{dR}{dt} = - K R_o e^{-Kt} = KR$$

These are the lines shown in Figures 5.3 and 5.4.

Also,

$$\frac{R}{R_o} = e^{-Kt}$$

$$- \ln \frac{(R \quad)}{(R_o)} = Kt$$

This allows for a more convenient visual presentation of the results.

The value of K (year^{-1}) can be calculated by plotting the $-\ln (R/R_o)$ against time (year). K will be equal to the slope of the best fitted straight line emanating at the origin. As can be seen from Figure 5.5, a straight line with a slope equal to $K = 1.87 \text{year}^{-1}$ has been fitted by eye for tile. The same approach for wood is shown in Figure 5.6 and a K value of 1.92 year^{-1} was found.

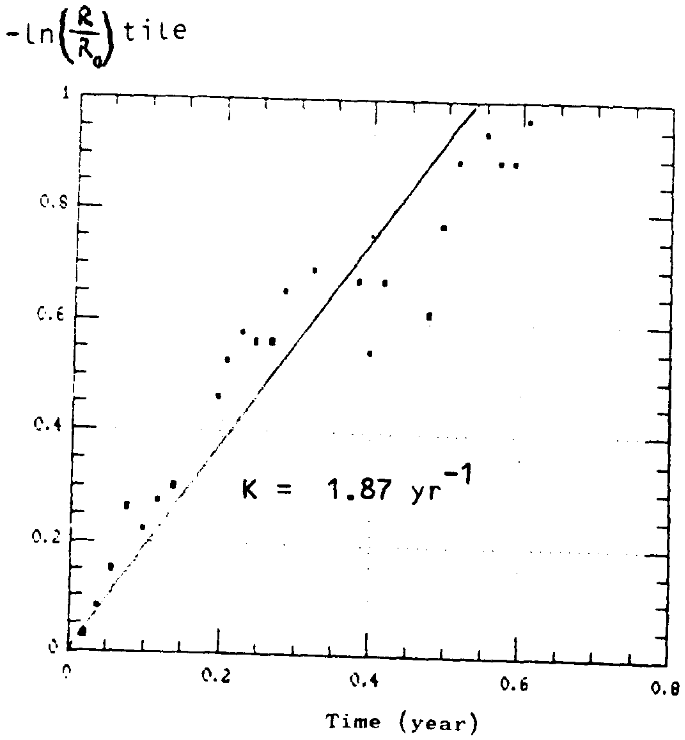


Figure 5.5 A plot of -ln of $\left(\frac{R}{R_a}\right)$ with time

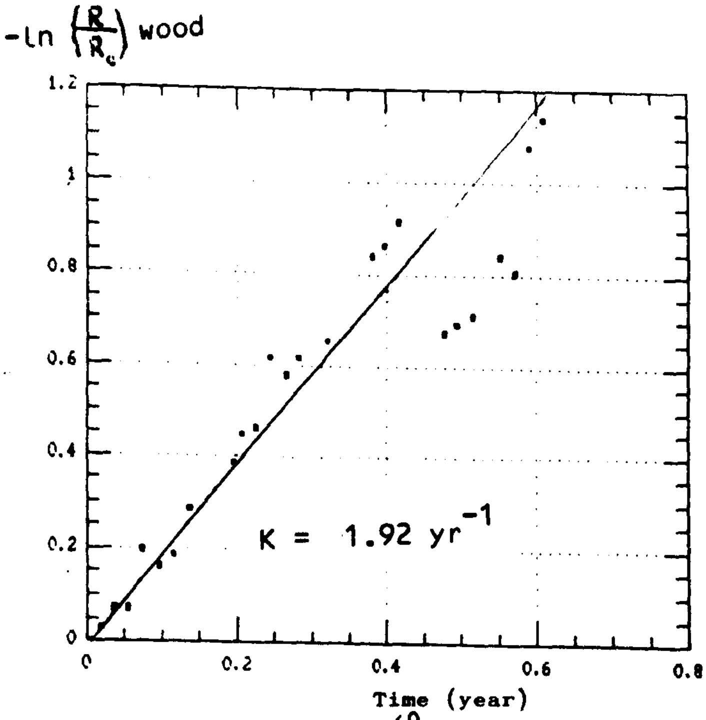


Figure 5.6 A plot of -ln of $\left(\frac{R}{R_a}\right)$ with time

Using Haynie's model as described in Section 4.2.2 and an inserting value of TSP for the tunnel of 200 µg m^{-3} a value for K of 1.73 $year^{-1}$ is derived. Similarly for Lanting's model and using an elemental carbon value of 36 µg m^{-3}, a value of K equal to 3.7 $year^{-1}$ is obtained. Figure 5.7 shows the Haynie, Lanting and the experimentally derived soiling curves fitted with the data points for wood. Likewise, Figure 5.8 shows the various models fitted for the tile results. From these figures it is seen that the soiling rate is overestimated by Lanting for both tile and wood and the model predicted by Haynie slightly underestimates the soiling rate. This is assuming that the ambient pollutant values inserted into the various models are correct and representative of the usual conditions existing in the tunnel and the models themselves are theoretically correct. Also, the experimentally derived constant indicates that wood soils at a slightly faster rate than tile, as was indicated by the initial results presented in Figure 5.2.

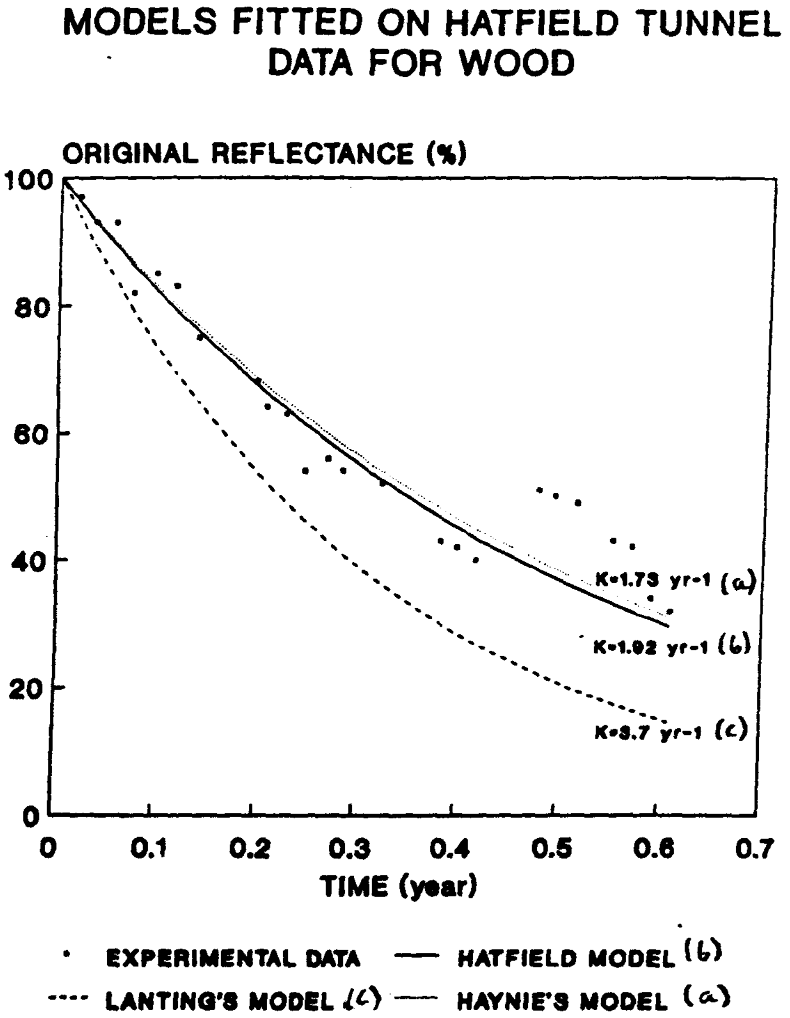


Figure 5.7 Models fitted on Hatfield tunnel data for wood

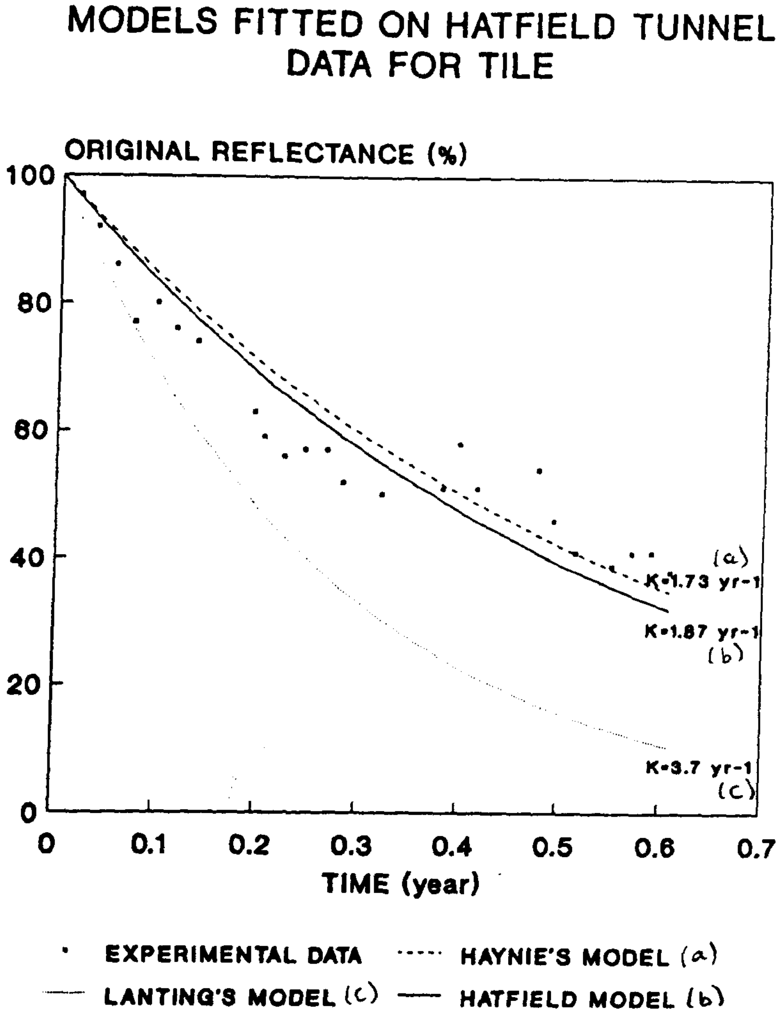


Figure 5.8 Models fitted on Hatfield tunnel data for tile

5.2.2 Empirical models

The former models were based on experimentally derived results and the theory of Haynie and Lanting. That theory involved an exponential model with only one fitting parameter, the slope, which is equal to K. The physical basis for the exponential model was described in Chapter 4. However, it was stressed in Section 4.2.3 that the processes responsible for smoke deposition and accumulation, as well as dry and wet removal processes, are more complex than was considered in that model. However, an attempt was made at fitting the data to other empirical models using STATGRAPHICS computer package. An earlier example of an empirical model was that used by Beloin and Haynie (1975)$^{(111)}$ as described in Section 4.1.2, where:

$$100 - R = B\sqrt{(TSP) \times t} + A$$

$$\text{Therefore } R = 100 - A - B\sqrt{(TSP) \times t}$$

The models used in this analysis included a second type of exponential model where

$$Y = \exp(a + b\,x)$$

$$b = -K, \quad x = \text{time}$$

$$Y = \text{reflectance} \qquad \text{intercept} = e^{a}$$

This model has two variables so that $R_0 = 100$ is treated as one of the data points rather than a fixed point through which the curve must pass.

The correlation coefficient for this model on the wood data was -0.94.

Table 5.6 gives the results of the analysis and the results are shown in Figures 5.9 and 5.10. The plot of residuals against time yields information on how well the model fits the data. Ideally, all the

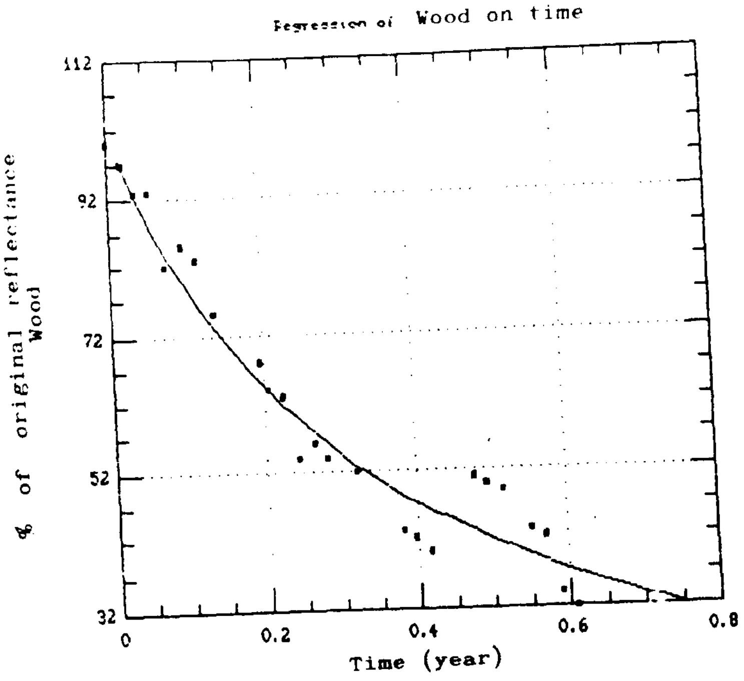


Figure 5.9 Exponential model for wood with time

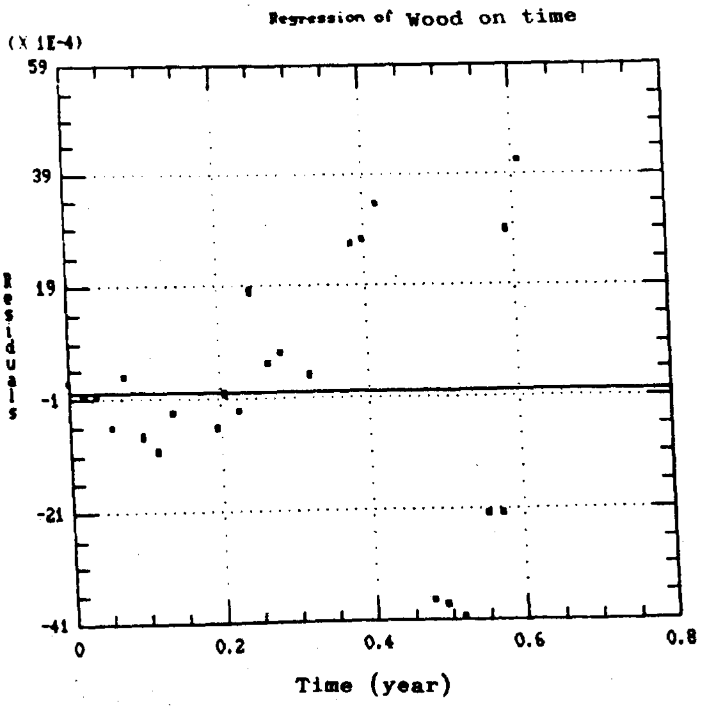


Figure 5.10 The residuals of the exponential model for wood with time

points would fit on to the line x = o, however, if the points are spread evenly above and below this line it is an indication that the model fits the data points fairly well. The results for tile for this model gave a correlation coefficient of - 0.95 as shown in Table 5.6 and the results are shown in Figures 5.11 and 5.12.

Next a reciprocal model was fitted to the data points where

$$\frac{1}{Y} = a' + b' x$$

$b' = -K$, x = time

Y = reflectance   intercept = a'

The correlation coefficient for this model with wood was 0.93 and is shown in Table 5.6 as well as in Figures 5.13 and 5.14. Likewise Table 5.6 gives a correlation coefficient of 0.96 for this model with tile and other results illustrated in Figures 5.15 and 5.16. These results for both the exponential and reciprocal models are examples of empirical models for despite the models fitting the data points well, the reasons why they do cannot be easily explained by theory. A summary of all the models' results is given in Table 5.6.

Table 5.6 A comparison of the correlation coefficients for wood and tile exposed in the Hatfield tunnel with different fitting models

Model	Figure		Correlation coefficient	
Exponential	WOOD	TILE	WOOD	TILE
$R = 100e^{-Kt}$	5.6	5.5	0.96	0.96
Reciprocal $\frac{1}{R} = a' + b' t$	5.13	5.15	0.93	0.96
Exponential $R = \exp(a + b\,t)$	5.9	5.11	-0.94	-0.95

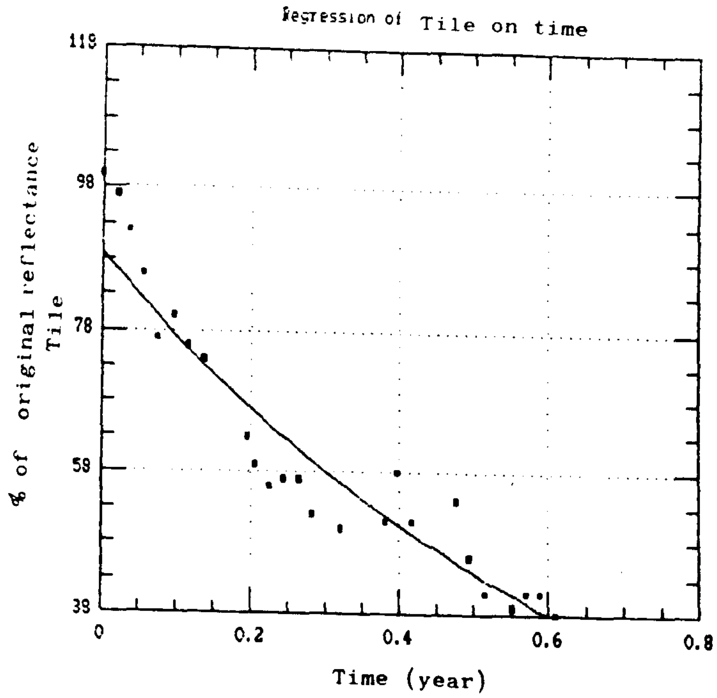


Figure 5.11 The exponential model for tile with time

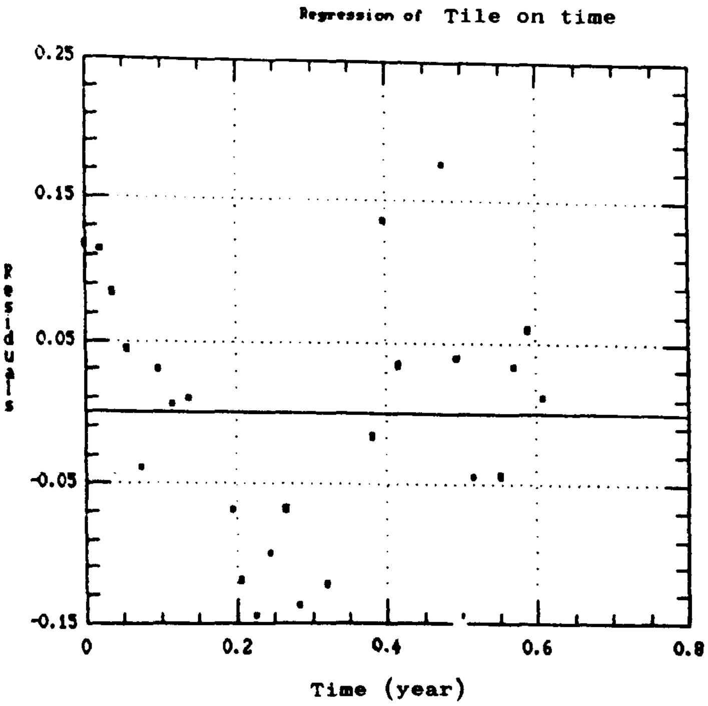


Figure 5.12 The residuals of the exponential model for tile with time

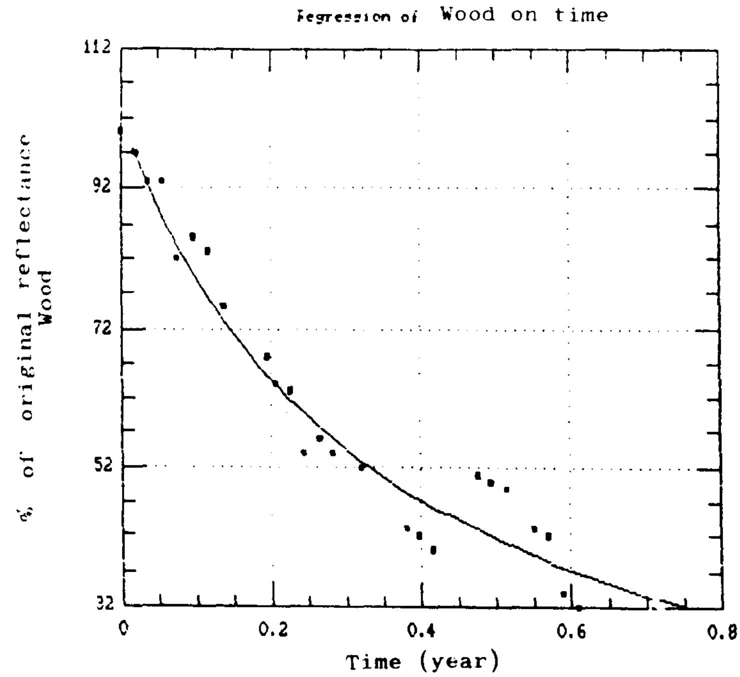


Figure 5.13 The reciprocal model for wood with time

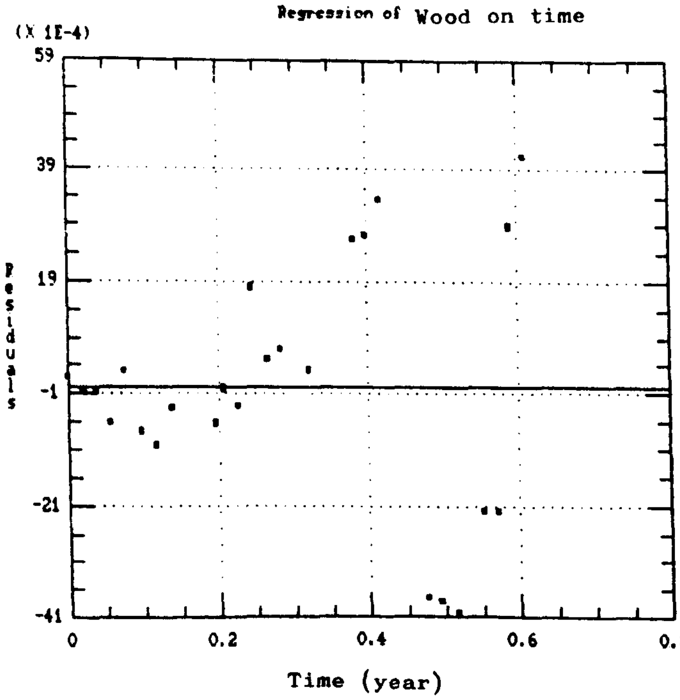


Figure 5.14 The residuals of the reciprocal model for wood with time

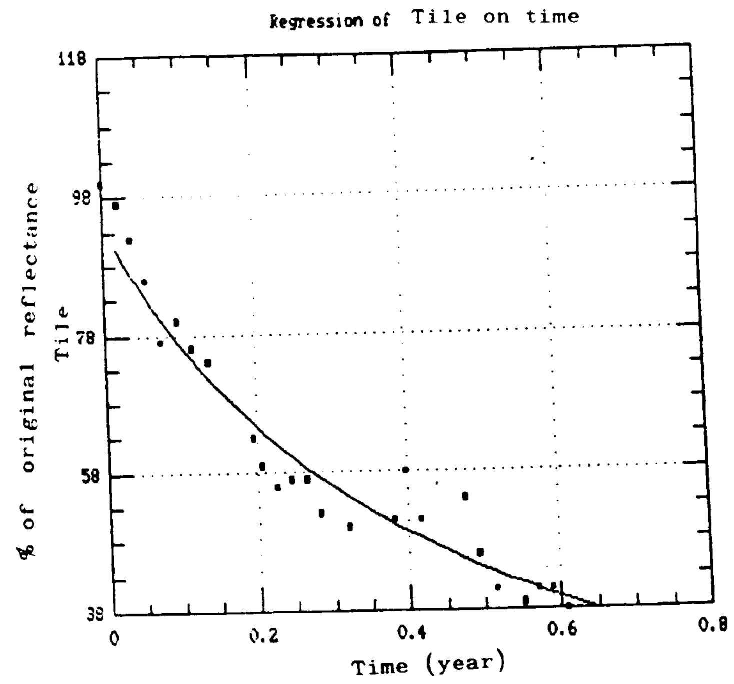


Figure 5.15 The reciprocal model for tile with time

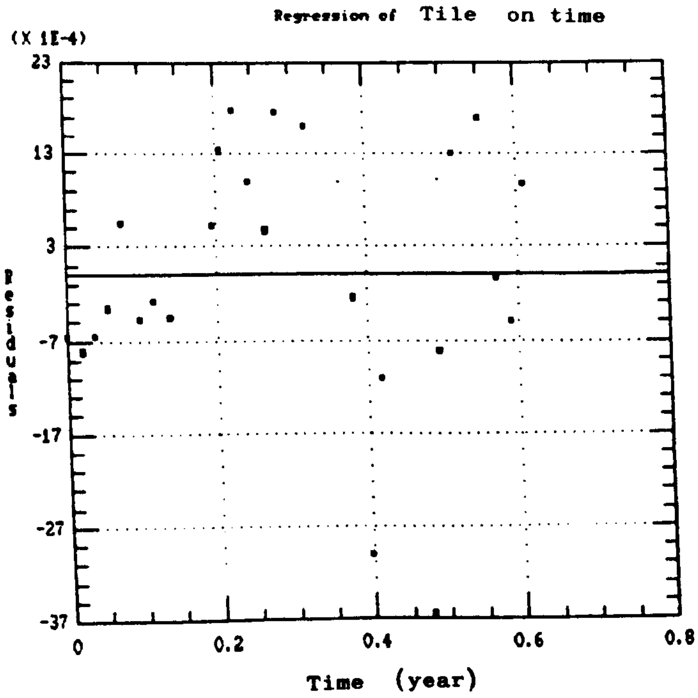


Figure 5.16 The residuals of the reciprocal model for tile with time

5.3 Summary and Conclusion

Soiling in the Hatfield Tunnel can be modelled by the equation :

$R = 100\ e^{-Kt}$ (as shown in Figures 5.7 and 5.8)

where $K = 1.92\ yr^{-1}$ for wood, $K = 1.87\ yr^{-1}$ for tile; correlation coeff = 0.96 for wood and 0.96 for tile.

Lanting's theory predicted $K = 3.7\ year^{-1}$ for the site, while Haynie's theory predicted $K = 1.73\ year^{-1}$ for the site.

Two empirical fits to the experimental data were tested. They gave acceptable correlation coefficients (in the range 0.93 - 0.96), but a survey of the trends exhibited by the residuals revealed that the fits were less acceptable than those provided by the exponential model.

5.4 Some economic considerations with respect to soiling in tunnels

The walls of tunnels are used to reflect light thus aiding visibility within the tunnel. The reflectance of the walls and carriageways can greatly influence the capital cost of lighting and the energy it consumes. So if the walls are soiled this reflectance will be diminished and thus extra electricity will have to be used to compensate for the decrease in reflectance from the walls. Cleaning in tunnels varies with individual managers. For example, the Dartford tunnel is cleaned once a week, each bore of the tunnel is shut in turn during cleaning for a few hours. The ceramic tile walls are high-pressure sprayed with a solution of water and detergent. The cleaning cost for the tunnel walls is £75,000 p.a. (this figure does not include policing costs). However, the newly designed Hatfield tunnel walls have been painted with 'Ceramicoat' which is a solvent based two pack reinforced polymer coating system containing a Teflon-like substance. Cleaning is carried out every three months and the total cleaning cost for wall cleaning is in the region of £5000 per year.

The 'Ceramicoat' surface does stay cleaner for a lot longer than that witnessed in the Dartford Tunnel. One measurement of soiling was carried out in the Dartford tunnel in this study and showed an 18% decrease in original reflectance over a 48 hour working day period with an average traffic flow of over 40,000 vehicles per day per bore.

In the light of experimental soiling data gained from measurements from the Dartford and Hatfield tunnels, it may be that soiling is apparently very rapid in the Dartford tunnel because soiling rates are only observed for the start of the exponential curve, and thus if the walls were cleaned less regularly slower soiling rates would be observed. Given that extra electricity can be supplied to compensate for the decrease in wall reflectances, money may be saved as well as avoiding traffic flow problems and delays whilst only one bore is used for both north and south-bound traffic. Alternatively, use of a different wall surface may aid in decreasing soiling rates, this field has been the subject of recent attention by a number of civil engineering companies and the Department of Transport.(132)

It should be remembered that in order to sustain the reflectance within acceptable limits the tunnel walls must obviously be cleaned. However, the cleaning frequency may not be the optimum required, based on a simple cost-benefit comparison. Traffic demand, for one, may dictate the available opportunities.(132) Likewise, the cleaning and painting of exterior building surfaces does not often follow the optimum frequency required for reasons further explained in Chapter Eight.

CHAPTER SIX

6. Measurement of soiling rates in the ambient environment

6.1 Introduction and objectives of experimental programmes

As illustrated in Chapter Five, soiling rates within a road traffic tunnel are in the order of 1.7 to 1.9 year^{-1} and these experimentally derived rates lay within the bounds of predicted rates of Haynie and Lanting of 1.8 and 3.7 year^{-1} respectively. Experimental programmes were devised in order to see if observed soiling rates within the ambient environment also lay within the predicted theoretical rates and to what extent meteorological effects such as rainfall influence the reflectance of exposed materials. The first experimental programme described in this section gives the soiling rates calculated from daily measurements carried out for a period of 111 days at the Enfield site, which is a London suburban location. Further details about this site are given in Section 6.2. Samples of wood and tile were exposed on a rooftop 20 m above ground level, one set of wood and tile were exposed to the open environment, another set were exposed beneath a table on the roof representing a sheltered environment. The second experimental programme described in Section 6.2 describes soiling rates measured in a nine-site exposure programme throughout central and metropolitan London and carried out for an eighteen-month period. The conclusions from these programmes are given in Section 6.3.

6.1.1 Measurement of soiling rates for exposed and sheltered materials derived from a daily measurement programme at a suburban location

A piece of wood painted with white gloss (40 cm x 30 cm) with a white ceramic tile (15 cm x 15 cm) mounted in the middle of the wood was exposed horizontally on a roof 20 m above ground level. A replica was also exposed on the roof 2 m away from the former but beneath a table (165 cm x 135 cm). Reflectance measurements of the exposed and sheltered tile and wood were taken on daily working days for a total of 111 days. Rainfall and smoke shade measurements were also recorded daily. The results are presented in Table 6.1. The change in reflectance is recorded as :

(% of original reflectance reading)-(previous % of original reflectance reading)

Thus, a value of -3 indicates that the material has soiled and its reflectance has decreased by a value of 3 from the previous reflectance measurement. Because of the absence of data during the weekends, the value recorded from a Friday to a Monday was divided by the relevant number of days and added to the data set the relevant number of times. Rainfall data was available on a daily basis as was smoke shade measurements provided by the use of an eight-port sampler, (as described in 5.1.2). The average smoke shade level during this time was 18 $\mu g\ m^{-3}$ and the average daily rainfall was 1.9 mm. Some initial observations are given in Figure 6.1 - 6.4. Figure 6.1 gives the temporal variation in percentage of original reflectance for the sheltered and exposed tile and wood with rainfall. Examination of these results shows that there is much oscillation in reflectance levels on a daily basis for all the materials be they exposed or sheltered. Thus, unlike the results given in Figure 5.2 for the Hatfield tunnel, the daily Enfield results do not follow a steady decrease in reflectance.

The daily results between the exposed and sheltered wood and tile were compared, in order to see whether the type of exposure affected the

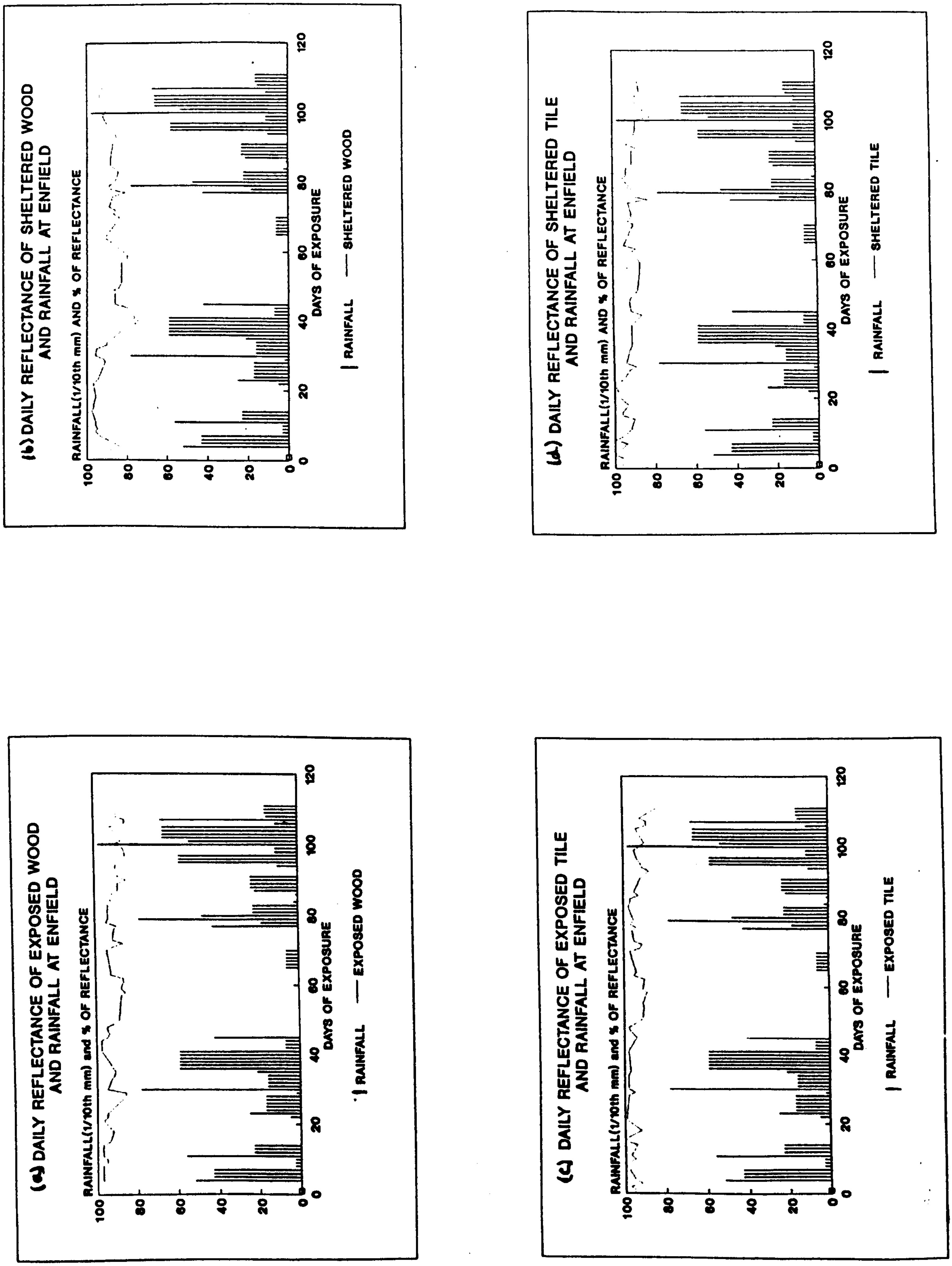
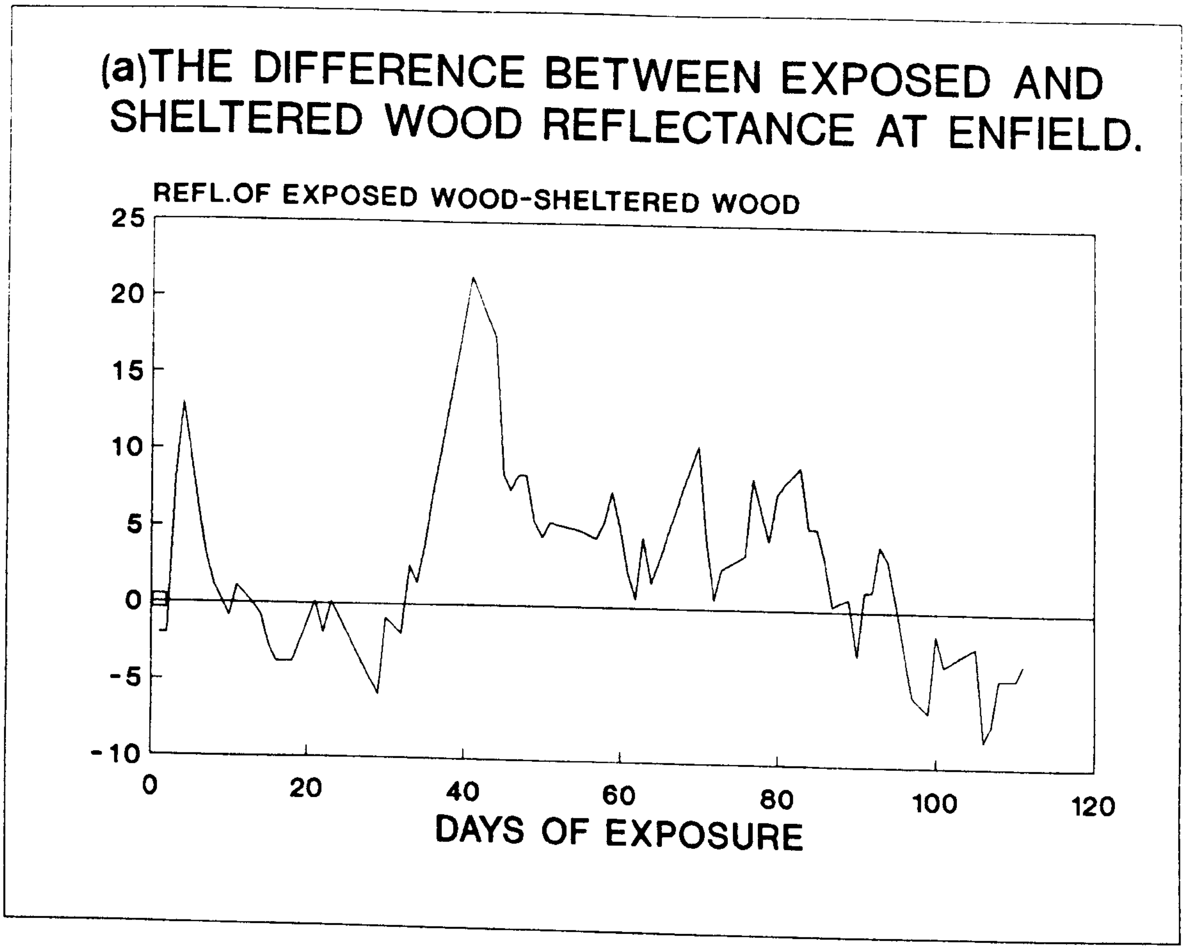


Figure 6.1 (a) – (d) The daily reflectance of exposed and sheltered samples of wood and tile with rainfall at the Enfield site

key | = rainfall ⁄\⁄ = % of original reflectance for the given material reflectance level recorded. These results are given in Figure 6.2, here the percentage of original reflectance for the sheltered tile/wood are subtracted from the percentage of original reflectance recorded for the same day of the exposed tile/wood. Thus, a value of 95% for the exposed wood compared with a value of 90% for sheltered wood would give a value of +5; indicating that the exposed wood is less soiled than the sheltered wood. Figure 6.2 does show that for the majority of the exposure period, the exposed materials of tile and wood are cleaner than those of the sheltered materials. The difference between the exposed and sheltered tile suggest that, tile is cleaner for more of the exposure time than is the case for wood.



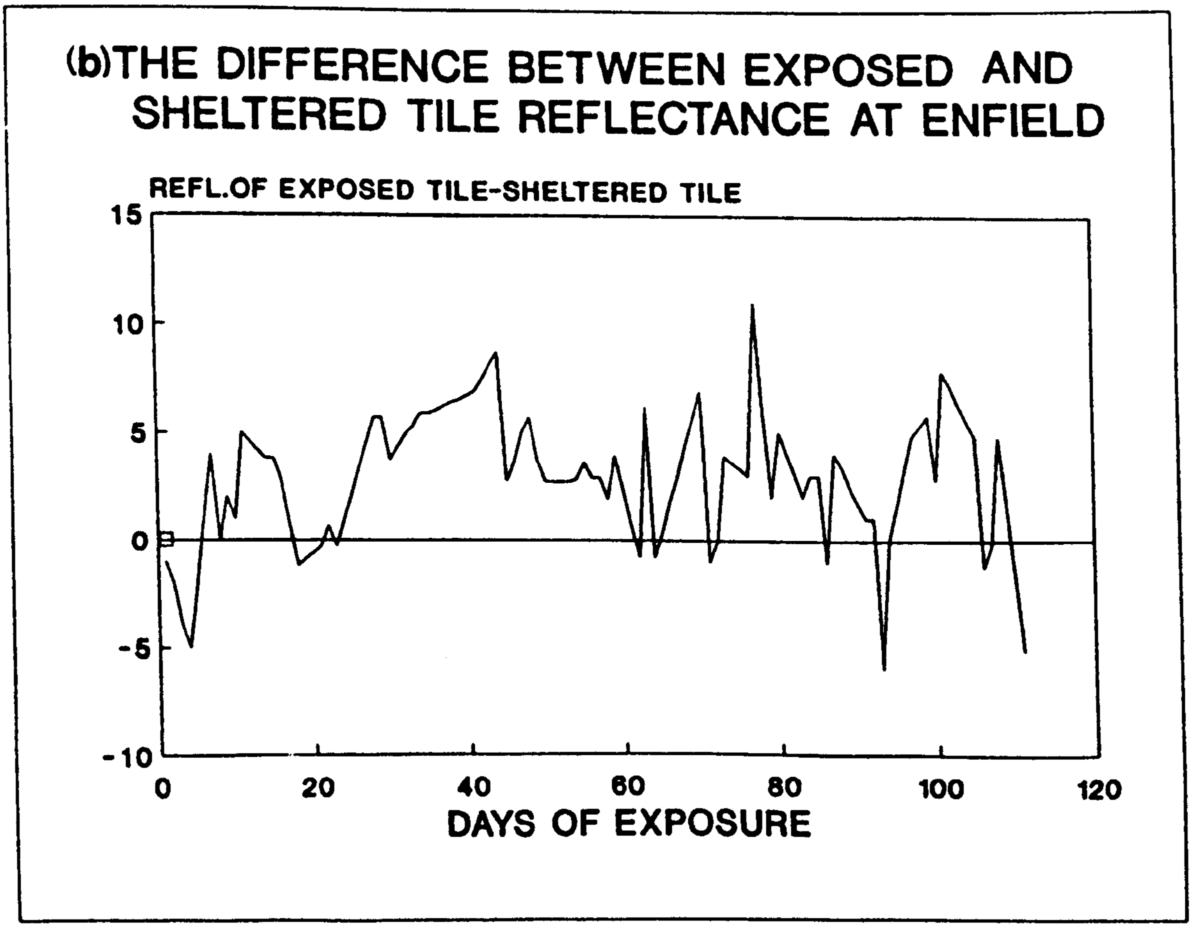


Figure 6.2 (a)-(b) The difference between exposed wood - sheltered wood and exposed tile - sheltered tile reflectance values

Table 6.1 Change in reflectance for materials exposed and sheltered with rain and smoke shade daily data at the Enfield site

Days of exposure	Exposed Tile	Exposed Wood	Rainfall (mm)	Smoke ($\mu g\ m^{-3}$)	Sheltered Tile	Sheltered Wood
1	-5.00	-5.00	0.0	36	-4.00	-3.00
2	2.00	2.00	0.0	36	3.00	2.00
3	-5.00	-3.00	0.0	37	-3.00	-13.00
4	-3.00	3.00	5.2	22	4.00	-2.00
5	1.00	0.00	4.3	33	-2.00	3.30
6	1.00	0.00	4.3	33	-2.00	3.30
7	1.00	0.00	4.3	33	-2.00	3.30
8	2.00	0.00	0.3	5	6.00	2.00
9	-2.00	-2.00	0.3	16	-4.00	-1.00
10	-3.00	0.00	0.3	23	-2.00	1.00
11	2.00	2.00	5.6	36	-2.00	0.00
12	-1.00	0.00	2.3	32	-0.60	0.60
13	-1.00	0.00	2.3	32	-0.60	0.60
14	-1.00	0.00	2.3	32	-0.60	0.60
15	6.00	-3.00	0.0	44	6.00	-1.00
16	-1.00	-1.00	0.0	32	0.00	0.00
17	-3.50	-0.50	0.0	23	-1.50	-0.50
18	-3.50	-0.50	0.0	23	-1.50	-0.50
19	2.30	1.60	0.0	20	2.00	0.30
20	2.30	1.60	0.0	20	2.00	0.30
21	2.30	1.60	0.0	20	2.00	0.30
22	0.00	-2.00	0.5	28	-1.00	0.00
23	0.00	0.00	2.5	17	1.00	-2.00
24	-0.20	-1.80	1.7	22	-1.40	-0.80
25	-0.20	-1.80	1.7	22	-1.40	-0.80
26	-0.20	-1.80	1.7	22	-1.40	-0.80
27	-0.20	-1.80	1.7	22	-1.40	-0.80
28	-0.20	-1.80	1.7	22	-1.40	-0.80
29	-3.00	0.00	0.2	22	-3.00	1.00
30	3.00	9.00	7.8	16	5.00	4.00
31	0.00	-0.75	1.6	11	-0.60	-0.25
32	0.00	-0.75	1.6	11	-0.60	-0.25
33	0.00	-0.75	1.6	11	-0.60	-0.25
34	0.00	-0.75	1.6	11	-0.60	-0.25
35	-1.00	-1.00	2.1	20	-1.00	-3.00
36	0.16	1.10	5.9	20	0.00	-1.80
37	0.16	1.10	5.9	20	0.00	-1.80
38	0.16	1.10	5.9	20	0.00	-1.80
39	0.16	1.10	5.9	20	0.00	-1.80
40	0.16	1.10	5.9	20	0.00	-1.80
41	0.16	1.10	5.9	20	0.00	-1.80
42	-1.00	0.00	0.7	10	-1.60	1.30
43	-1.00	0.00	0.7	10	-1.60	1.30

Table 6.1 Change in reflectance for materials exposed and sheltered with rain and smoke shade daily data at the Enfield site (continued)

Days of Exposure	Exposed Tile	Exposed Wood	Rainfall (mm)	Smoke ($\mu g\ m^{-3}$)	Sheltered Tile	Sheltered Wood
44	-1.00	0.00	0.7	10	-1.60	1.30
45	-1.00	-4.00	4.2	27	5.00	6.00
46	1.30	0.00	0.0	6	0.30	0.00
47	1.30	0.00	0.0	6	0.30	0.00
48	1.30	0.00	0.0	6	0.30	0.00
49	-3.00	-4.00	0.0	35	-1.00	-1.00
50	-3.00	-2.00	0.0	15	-2.00	-1.00
51	-1.00	0.00	0.0	7	-1.00	-1.00
52	-0.16	-0.16	0.0	14	-0.20	0.00
53	-0.16	-0.16	0.0	14	-0.20	0.00
54	-0.16	-0.16	0.0	14	-0.20	0.00
55	-0.16	-0.16	0.0	14	-0.20	0.00
56	-0.16	-0.16	0.0	14	-0.20	0.00
57	-0.16	-0.16	0.0	14	-0.20	0.00
58	-1.00	-2.00	0.0	17	0.00	-3.00
59	2.00	2.00	0.0	20	0.00	0.00
60	-0.30	-0.30	0.0	17	1.30	2.00
61	-0.30	-0.30	0.0	17	1.30	2.00
62	-0.30	-0.30	0.0	17	1.30	2.00
63	5.00	6.00	0.0	47	-2.00	2.00
64	-1.00	0.00	0.0	25	6.00	3.00
65	0.50	0.30	0.6	21	-0.80	-1.20
66	0.50	0.30	0.6	21	-0.80	-1.20
67	0.50	0.30	0.6	21	-0.80	-1.20
68	0.50	0.30	0.6	21	-0.80	-1.20
69	0.50	0.30	0.6	21	-0.80	-1.20
70	0.50	0.30	0.6	21	-0.80	-1.20
71	-5.00	-3.00	0.0	19	3.00	3.00
72	-1.00	-5.00	0.0	16	-2.00	-1.00
73	4.00	5.00	0.0	13	0.00	3.00
74	0.30	-0.30	0.0	10	0.60	-0.60
75	0.30	-0.30	0.0	10	0.60	-0.60
76	0.30	-0.30	0.0	10	0.60	-0.60
77	-2.00	-1.00	4.2	5	-10.00	-6.00
78	3.00	5.00	1.8	3	8.00	7.00
79	-2.00	-1.00	7.8	13	2.00	1.00
80	1.00	0.00	4.7	13	-2.00	-3.00
81	0.60	0.00	2.2	16	1.60	-0.60
82	0.60	0.00	2.2	16	1.60	-0.60
83	0.60	0.00	2.2	16	1.60	-0.60
84	-1.00	-2.00	0.2	13	-2.00	2.00
85	0.00	2.00	0.0	13	0.00	2.00

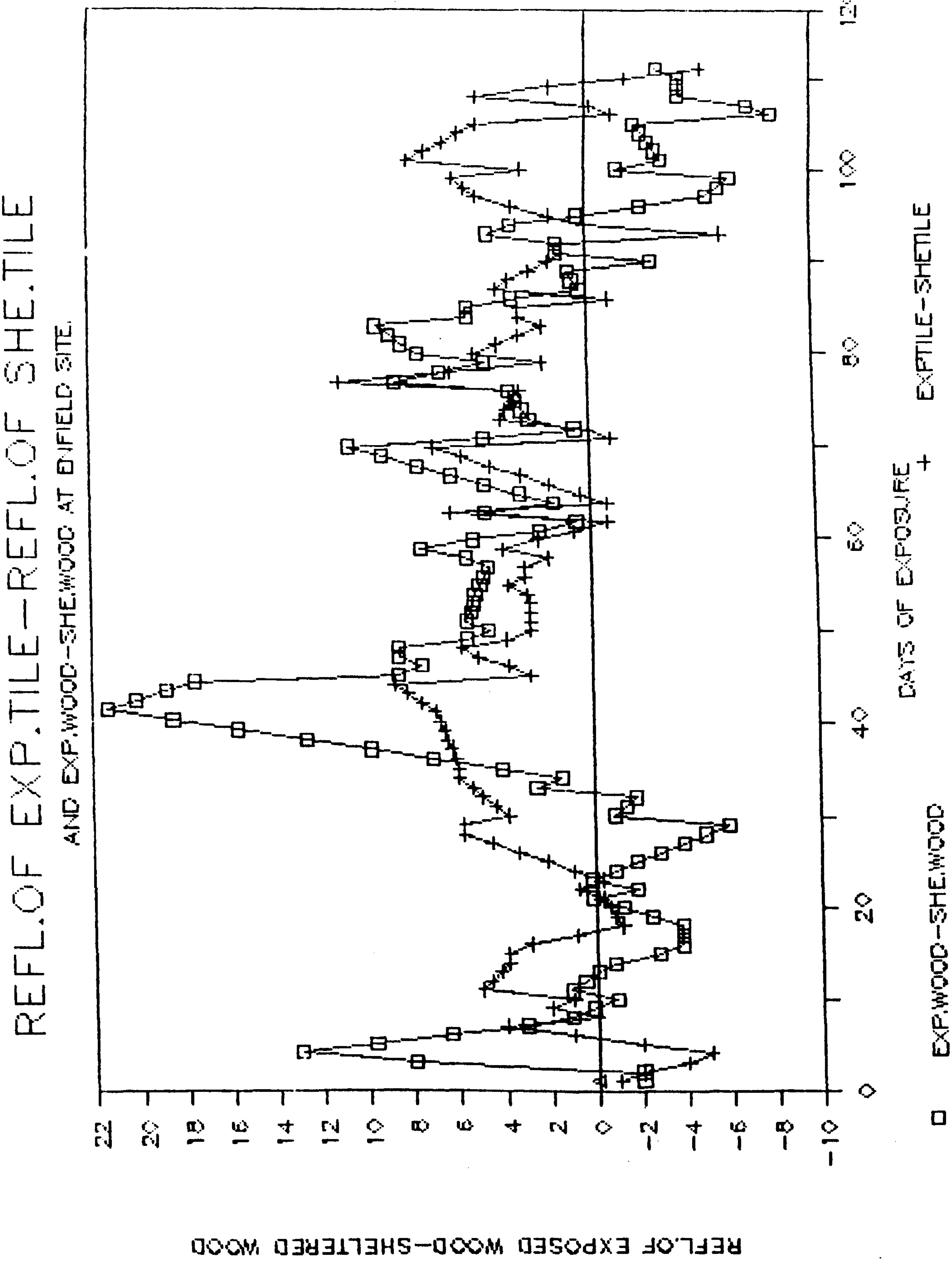
Table 6.1 Change in reflectance for materials exposed and sheltered with rain and smoke shade daily data at the Enfield site (continued)

Days of Exposure	Exposed Tile	Exposed Wood	Rainfall (mm)	Smoke ($\mu g\ m^{-3}$)	Sheltered Tile	Sheltered Wood
86	-4.00	-2.00	0.1	10	0.00	0.00
87	2.00	-3.00	2.1	8	-3.00	0.00
88	-0.75	0.00	2.3	13	0.00	-0.25
89	-0.75	0.00	2.3	13	0.00	-0.25
90	-0.75	0.00	2.3	13	0.00	-0.25
91	-0.75	0.00	2.3	13	0.00	-0.25
92	-2.00	-1.00	0.0	10	-2.00	-1.00
93	-2.00	2.00	0.0	5	5.00	-1.00
94	3.00	0.00	1.0	11	3.00	1.00
95	1.00	-1.60	5.8	14	-0.60	-1.30
96	1.00	-1.60	5.8	14	-0.60	-1.30
97	1.00	-1.60	5.8	14	-0.60	-1.30
98	0.50	0.50	1.1	10	0.00	1.00
99	0.50	0.50	1.1	10	0.00	1.00
100	-3.00	4.00	9.8	14	0.00	-1.00
101	-2.00	-3.00	5.3	19	-0.70	-1.00
102	1.00	1.30	6.6	26	1.75	0.75
103	1.00	1.30	6.6	26	1.75	0.75
104	1.00	1.30	6.6	26	1.75	0.75
105	1.00	1.30	6.6	26	1.75	0.75
106	-5.00	-7.00	1.1	8	1.00	-1.00
107	0.00	0.00	6.7	14	-1.00	-1.00
108	3.00	5.00	1.5	7	-2.00	2.00
109	-3.00	-2.00	1.6	12	0.30	-2.30
110	-3.00	-2.00	1.6	12	0.30	-2.30
111	-3.00	-2.00	1.6	12	0.30	-2.30

However, the negative results obtained from (exposed minus sheltered) tile values exhibit a more dramatic sharp decrease than is the case for the wood results. A comparison of the behaviour of exposed materials minus sheltered materials results is further illustrated in Figure 6.3, during approximately days 30 to 90 the pattern of either soiling or cleaning is similar for the wood and tile. However, at other times this trend is not apparent. The reason for this is not certain though the fact that the tile is mounted in the middle of the wood and the materials are displayed horizontally may be a factor in explaining this fact. For rainfall falling on to the tile may wash off deposited matter from the tile on to the wood's surface. Thus the tile's reflectance may increase as a result of some particles being removed by rain but the wood's decreases as a result of accumulating these particles. The rates of soiling for these materials are given and more fully discussed in Section 6.1.2.

Thus, having seen that exposed materials were generally cleaner than those of the sheltered ones, further work was carried out in order to see if rainfall was responsible for this trend. Figure 6.4 (a) & (b) gives the difference between exposed minus sheltered tile/wood plotted with the daily rainfall observed. A (↑) indicates that rainfall has occurred and a positive increase has been noted in the exposed minus sheltered value, likewise (↓) indicates that no rainfall occurred and a decrease was noted in the difference between the two latter values. These signs appear at some of the same points for both tile and wood on Figures 6.4(a) and (b) indicating that soiling or cleaning is occurring on both surfaces. However, the trends are not identical for both materials, the results for wood show larger differences than those for tile and this is further discussed in Section 6.1.2.

Figure 6.3 The difference between the soiling/cleaning patterns observed for the values of the exposed materials reflectance value



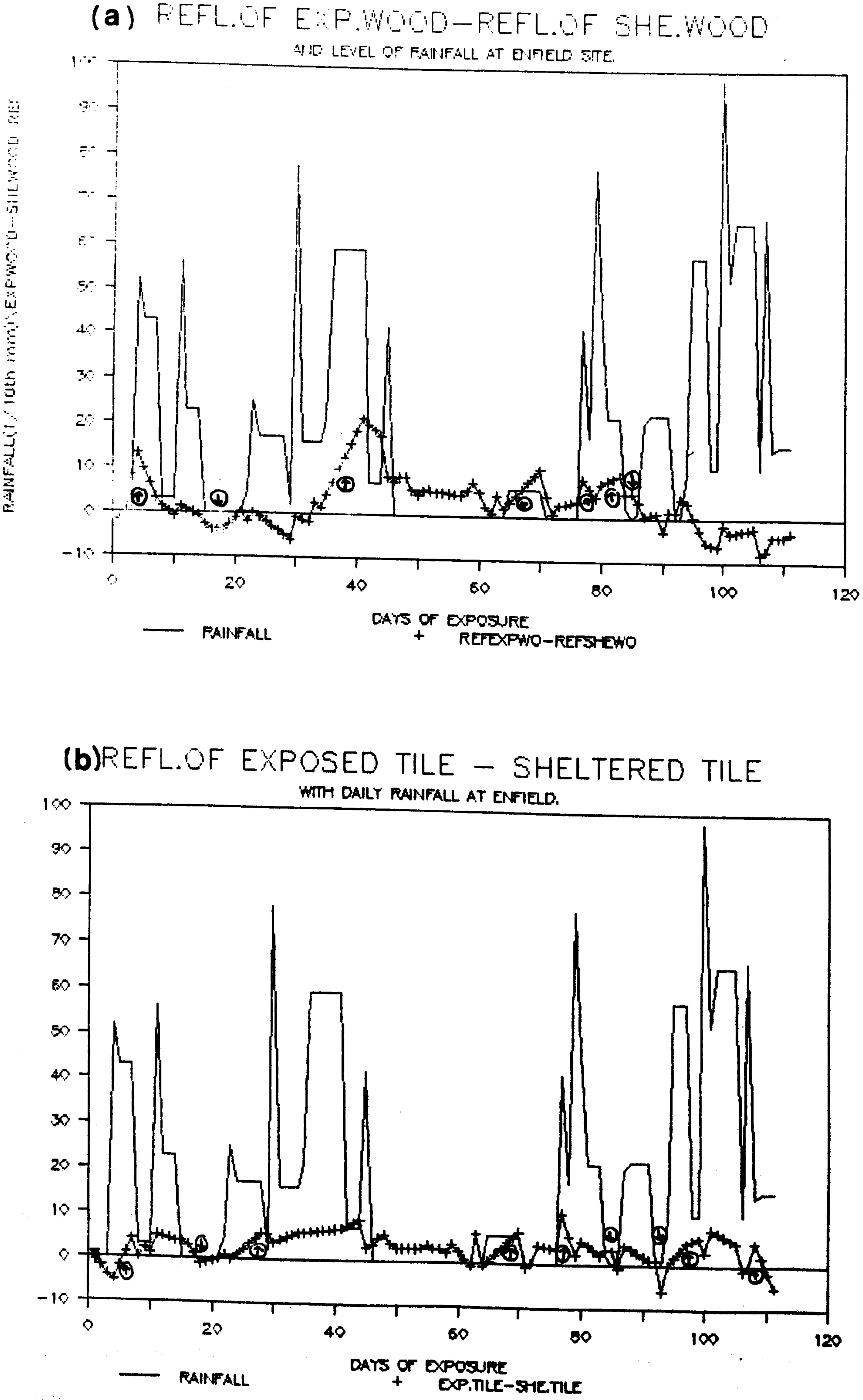


Figure 6.4 (a)&(b) The difference in reflectance of the exposed and sheltered materials plotted with rainfall

Correlation coefficients were calculated for the sheltered/exposed materials with rain and are presented in Table 6.2. As a consequence of these results, further statistical analysis was carried out to see if the level of rainfall affected the correlation coefficients previously obtained. So, all data with rainfall between 0 to 1 mm was discarded together with the reflectance values recorded for that day. These results are also given in Table 6.2, the total number of data points used in this analysis was 57 and not 111 as used in the former analysis.

Table 6.2 <u>The correlation coefficients between exposed/sheltered materials with rain using all data points and points only where rainfall is greater than 1 mm</u>

Material	Correlation Coefficient(r) with rain		Value of r at 5% level of confidence	
	using all data points (111)	rainfall >1 mm only (57)	all data points (111)	rainfall >1 mm (57)
EXPOSED wood	0.25	0.40	0.18	0.25
EXPOSED tile	0.13	0.13	0.18	0.25
SHELTERED wood	-0.02	-0.01	0.18	0.25
SHELTERED tile	0.05	0.11	0.18	0.25

As can be seen in Table 6.2, the correlation coefficient was increased for both exposed/sheltered materials when only rainfall greater than 1mm was used instead of all the data points. However, it is only the correlation coefficients for exposed wood that are significant at the 5% level of confidence. The value of the exposed tile is not significant even at the 10% level, where a value of r = 0.157 is needed. As may be expected, the correlation coefficients of the materials with rain are greater for the exposed than sheltered materials, where the action of rain on the latter is assumed to be more restricted. It is interesting to note that the exposed wood correlation coefficient is higher than that of exposed tile, which may be due to the fact, as previously mentioned, that particles may be removed from the tile's surface and washed on to the wood's surface by the action of rainfall. However, the particles from this source and those deposited on the wood's surface initially, may ultimately be removed with the action of rainfall (if perhaps rain is of a sufficient amount/duration and the nature/size of the particles is suitable for removal). Thus, ultimately some of the deposited particulate matter is removed entirely from the exposed materials surfaces. The correlation coefficient for wood, therefore, may be greater than tile with rain, if indeed this redeposition of particles from the tile's surface on to the wood surface occurs.

6.1.2 Calculation of soiling rates for the exposed and sheltered materials and a comparison with predicted theoretical rates

In order to calculate the experimentally derived soiling rates for the materials, the same procedure as described in Chapter Five was applied. The percentage of the original reflectance value was taken for each of the materials and converted into the negative natural logarithm and plotted against time (in years). Ideally, if soiling fitted an exponential decay pattern, the points would form a straight line. However, as is shown in Figure 6.5 (a) to (d), the points are widely scattered. Despite this fact, a straight line of best fit emanating from the origin was drawn (by eye) for these plots, so that a soiling rate could be calculated and this is given in Table 6.3. Also given are the predicted soiling rates of Haynie and Lanting using a TSP value of 30 $\mu g\ m^{-3}$ and an EC level of 3 $\mu g\ m^{-3}$ respectively. These values

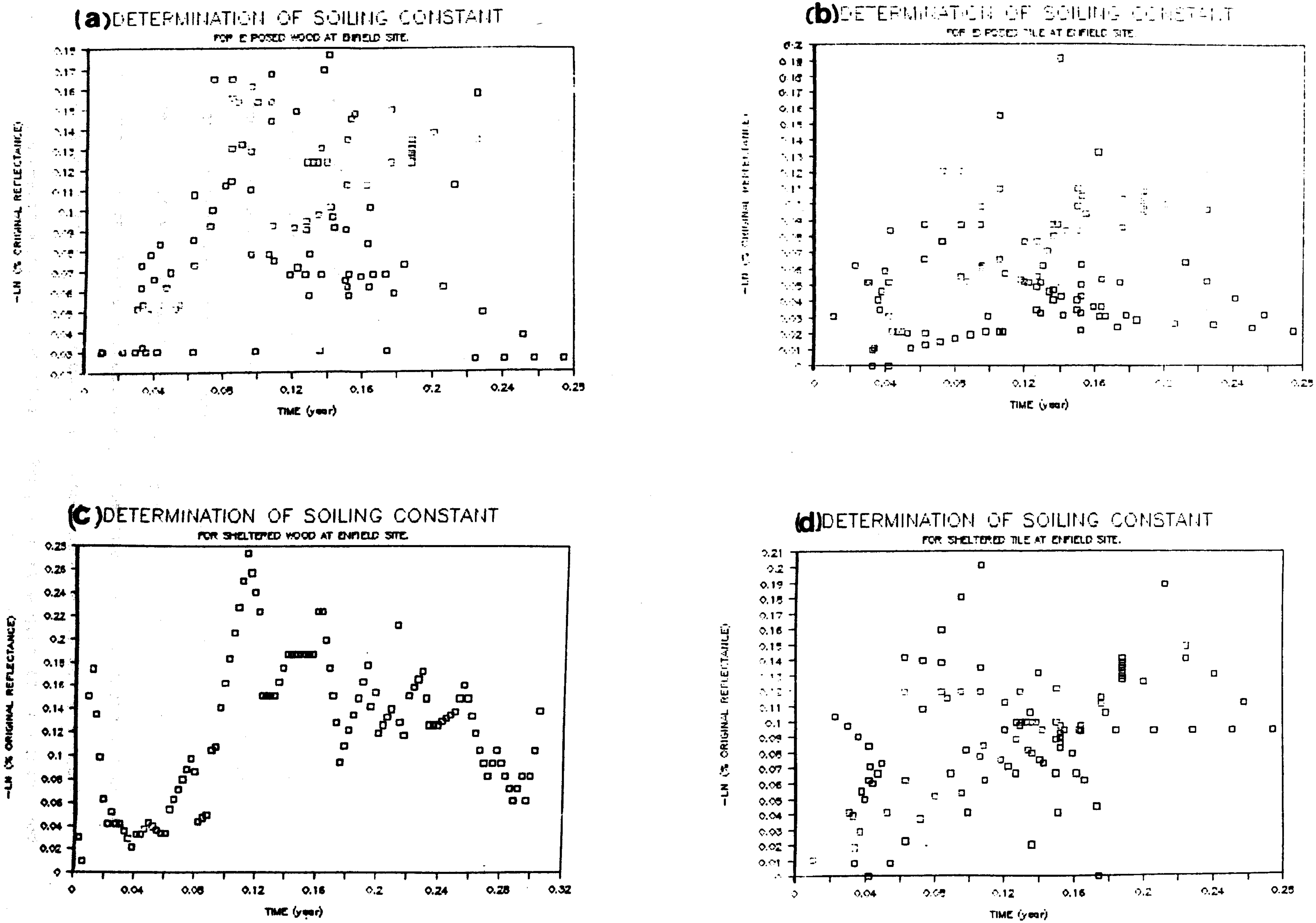


Figure 6.5(a)-(d) Determination of the soiling constant for the exposed and sheltered samples of wood and tile

were derived using the average smoke shade value for the site and the relationship reported in Sections 2.4.4 and 3.5.2.

Table 6.3 The experimentally derived soiling constants for exposed and sheltered materials together with those predicted by theoretical models

EXPERIMENTALLY DERIVED VALUE	SOILING CONSTANT (yr^{-1})
EXPOSED WOOD	0.7
EXPOSED TILE	0.5
SHELTERED WOOD	0.8
SHELTERED TILE	0.6
PREDICTED THEORETICAL VALUE	
LANTING	0.37
HAYNIE	0.25

The data in Table 6.3, shows that the values derived for the daily exposure programme are greater than those predicted by Haynie and Lanting. Unlike the case for the Hatfield tunnel where the values predicted by Haynie and Lanting laid within the experimentally derived results. Likewise, wood appears to soil more rapidly than tile in the Enfield programme where the opposite applied in the Hatfield tunnel study. However, as was shown earlier in this section, sheltered wood and tile have a higher rate of soiling, 0.8 and 0.6 yr^{-1} respectively, than exposed wood and tile whose rates were 0.7 and 0.5 yr^{-1} respectively. It may be that wood would be expected to soil more rapidly than tile surfaces, apart from the possible redeposition of particles from the tile on to the wood surface; wood is a rougher aerodynamic surface than tile. Thus, air flow over the rougher wood surface is likely to be more interrupted than over the tile, thus increasing the chance of particles contained within that airstream being deposited on to the wooden surface and also reducing the possibility of removal by wind. The fact that tile soiled more rapidly than wood in the Hatfield tunnel may be because there was no rain to transfer the deposited particles from the tile on to the wood. However, this effect may be smaller in the case of the Hatfield tunnel where the materials were displayed vertically and not horizontally as were the daily exposure materials. Another factor which might aid in the explanation is that the vertically displayed tile protruded by 0.5 cm from the wood's surface and this may have altered the air flow around the materials and elevated the deposition rate on to the tile rather than the less protruding wooden surface.

The results from this exposure programme agree with the findings of the following section, where short and longer-term soiling rates have been calculated for a variety of sites. Indeed, as will be shown in Section 6.2, soiling rates calculated over longer term exposure periods produce a lower soiling constant than those derived over short term exposure periods and these former constant are usually closer to the values predicted by the theoretical models of Haynie and Lanting. Thus, as presented in Table 6.3 and shown in Figure 6.6(a)-(d) the experimentally derived rates are greater than those predicted by Haynie and Lanting. Yet, as is shown in Figure 6.18 and Table 6.5 the soiling constant and curve fitted for the longer term exposure programme for the exposed materials at Enfield are closer to the predicted values of Haynie and Lanting and half the value of the constant derived for the daily exposed materials. These results are further discussed in Section 6.3. The results obtained from a daily exposure programme carried out over a

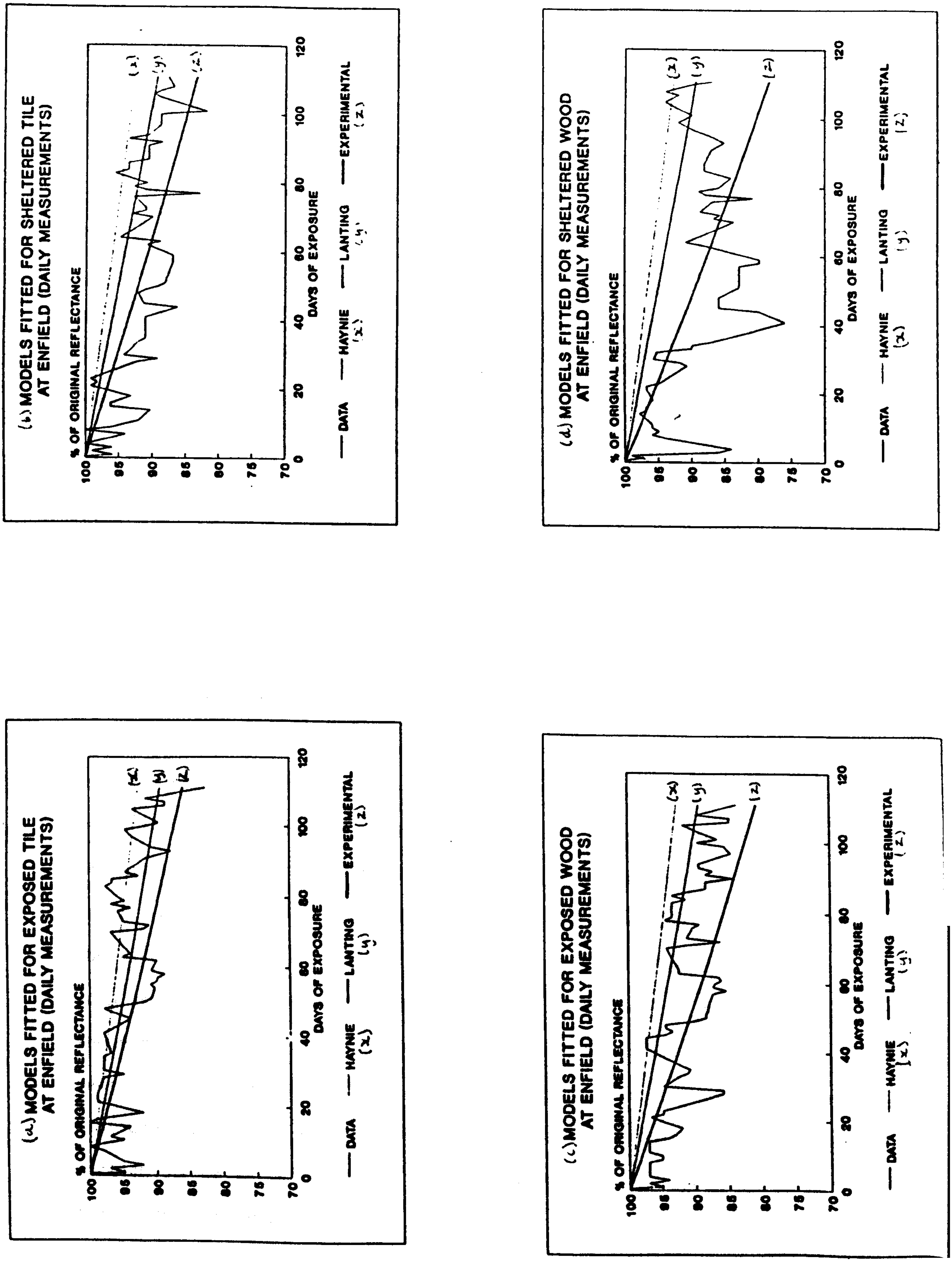


Figure 6.6 (a) – (d) The soiling constants derived experimentally and horizontally fitted with the data points of the exposed and sheltered samples of wood and tile

short exposure programme (less than 200 days) may produce a soiling constant which over-estimates the true soiling constant for a particular location. The raw data may produce a lot of 'noise', from which it may be difficult to calculate the true soiling constant for that site. Daily results carried out over a longer exposure programme may produce results by which the true soiling pattern and its extent of fluctuation becomes apparent. This is because soiling is a long-term process and needs data accumulated over such a time scale. From such results, one would be able to obtain prediction limits of how much fluctuation one may naturally anticipate for a site, if it was correlated with rainfall, high or low smoke levels, etc. However, unfortunately, time and financial resources do not usually permit daily measurements of results to be taken for a large number of exposure sites over a long period of time. Thus, the reflectance values collected at weekly/monthly intervals may be dependent on the extent of rainfall immediately prior to the measurement being taken. As was illustrated in Section 4.2, Haynie's conclusion that it was larger sized particles that are chiefly responsible for soiling may have been different if it had rained previously on to the exposed surface (and perhaps removed the larger, usually more water-soluble components of the deposited matter) before the slide was analysed. Ideally, then measurements should be taken as soon after a rainfall event and the surface to be measured has dried. These results are likely to produce more valid values of percentage decrease in reflectance due to soiling rather than due to dustiness. As mentioned in Section 2.1, soiling is the permanent deposition of particulate matter on to a surface, whereas dustiness may be only temporary in nature.

6.2 Measurement of soiling rates for exposed materials derived from an eighteen month experimental programme at nine sites in and around central and metropolitan London

6.2.1 Experimental details

Breeze blocks measuring 0.44 m x 0.11 m x 0.20 m were mounted on each corner of a 1.2 m x 0.6 m wooden base. The vertical and top horizontal surfaces of each block were covered to give exposed surfaces of glass, white ceramic tiles, white cotton and white painted wood. A wire mesh frame was placed over the block where the cotton was exposed, to ensure that moisture within the block did not reach the cotton surface and increase the amount of time the cotton was usually wet as after a period of rainfall. A set of samples was mounted at each of nine sites on a transect from central to north London. Figure 6.7 shows the geographical location of the sites within London and photographs of the sites are given in Appendix C. Details of the sampling sites are given in Table 6.4. The horizontal and vertical reflectance of the different materials was measured initially at 2-week intervals and later on in the survey at approximately monthly intervals. Measurements were taken as previously described in Section 5.12 using an Eel Reflectometer. Three measurements were taken when measuring the horizontal surfaces and three for each of the four vertical surfaces. The average value for the horizontal and vertical surfaces was used and converted into the percentage of the original reflectance for each of the materials. Calibration of the reflectometer was undertaken after every three measurements.

A dark cover was placed over the top of the reflectometer, as without this, extraneous light can enter it and cause a fluctuation in the

Site		Height above ground level (m)
1	High Holborn	22
2	Euston fire station	1
3	Bidborough Street	18
4	Islington	10
5	Haringey	6
6	Bounds Green	20
7	Enfield	12
8	Brimsdown	3
9	Trent Park	8

Table 6.4 *Details of Sampling sites*

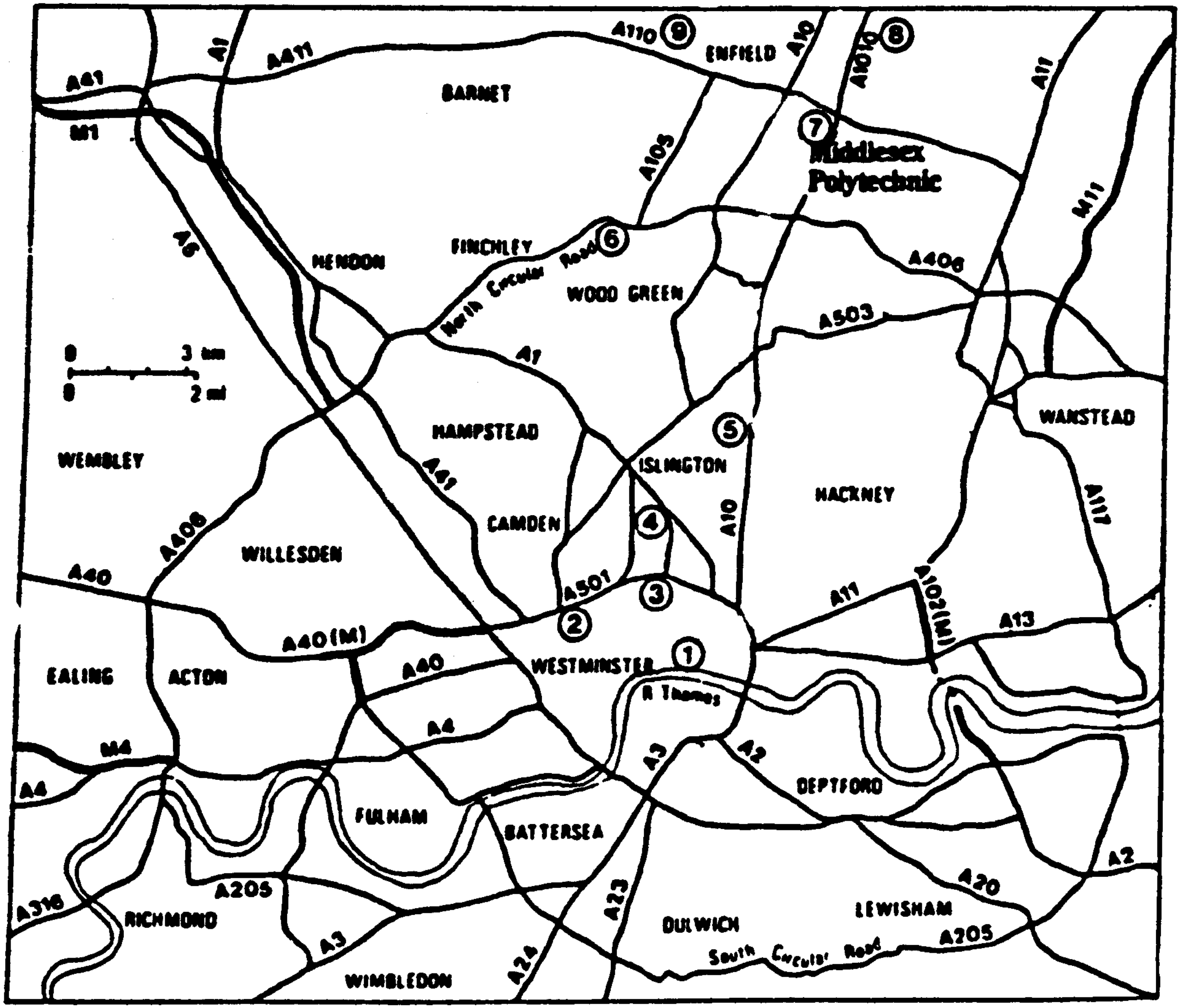


Figure 6.7 The geographical location of the nine sites

results recorded. Measurements for glass were taken by inserting a piece of thin white plastic material behind the glass. This plastic was vigorously wiped between each measurement. Figure 6.8 shows the materials mounted on the board at the Enfield site (number 7 on Figure 6.7).

Figure 6.8 A set of the exposed materials displayed on the Enfield site roof (20 m above ground level)

Smoke shade levels were monitored continuously by the UK National Survey smoke stain method. Indeed sites 1 to 5 are part of the national smoke survey and run by the local authorities within that area. Sites 6-9 were set up and run only during the experimental programme.

As mentioned in Section 2.4.1, the siting of the Warren Spring survey sites are often located over 10 m above ground level and at the rear of the buildings. The materials were also displayed adjacent to the smoke shade apparatus, so the reflectance levels recorded for each site were representative of the smoke shade level measured there. Thus, it may be that the rates of soiling derived from some of the higher located and rear situated sites in this research may be underestimating the rate of soiling that is actually occurring lower down the front of the building facade.

6.2.2 Reflectance values recorded during the exposure programme for the nine sites

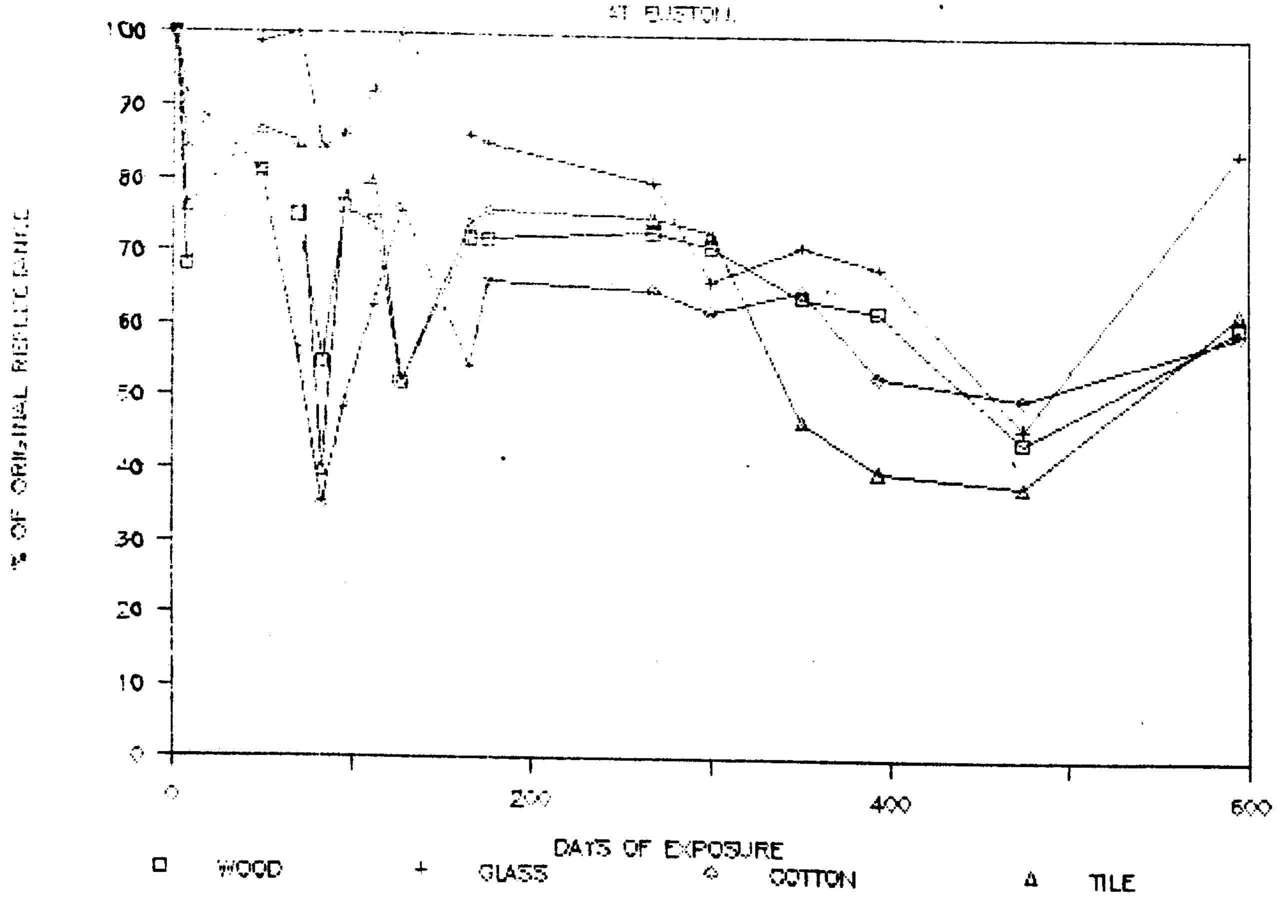
Appendix C gives the percentage of original reflectance for each of the horizontal and vertical surfaces of the materials recorded at various times throughout the exposure programme. The results given in the tables have been plotted in terms of:

(a) the horizontal and vertical soiling results for each material, so a comparison can be made between the level of soiling and the orientation of the material;

(b) the soiling levels of all the materials either displayed horizontally or vertically.

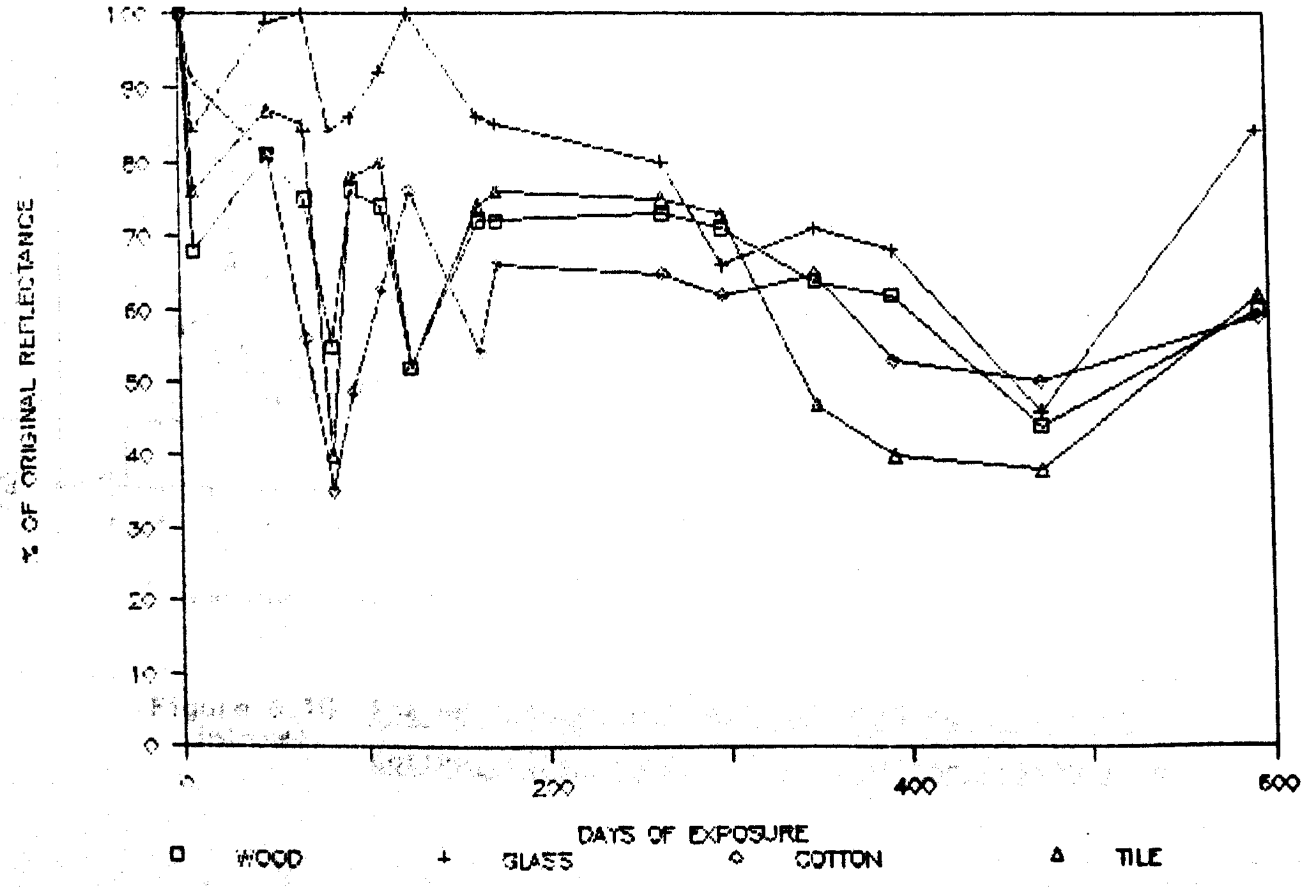
A selection of such graphs taken from Euston, Enfield and Trent Park sites are displayed and discussed in this section. Graphs derived for the other sites are given in Appendix C. The site at Euston was chosen to be illustrated as it had the highest smoke value, Enfield was taken as a representative sample of all the other remaining sites (except that of Trent Park) as their smoke shade levels were very similar. Trent Park is illustrated here because it has the lowest smoke value and represents a control site in that by virtue of its location in a country park, where sources of ambient smoke/soiling particulate are deemed to be small. Examination of Figures 6.10, 6.12 and 6.14 for both horizontal and vertical surfaces of most materials (except glass) follow a similar initial soiling pattern. All sites show a dramatic decrease in the reflectance of wood in the range of 20-30% of the original reflectance within 20 days of exposure. Cotton and tile also decrease by a value of approximately 10-20% original reflectance. However, levels of reflectance recorded after this initial exposure do increase though (with the exception of glass) never enough to restore the value of 100% original reflectance. The results oscillated throughout the exposure programme; wood, tile and cotton usually followed a similar soiling or cleaning pattern. Wood generally soiled the most, then followed by tile and cotton, the samples of glass soiled the least of the materials. This agrees with the results of the daily programme at Enfield, where wood soiled more rapidly than tile. The results for cotton may be subject to a greater error in measurement than the other materials. This is because if the cotton is damp due to rainfall, the colour of the partially-soiled material appears slightly darker than when dry. Facilities were not available to dry the cotton before the measurement was taken, thus the levels recorded may be slightly elevated.

A comparison of Figures 6.9, 6.11, and 6.13 show that the horizontal surfaces of wood and tile generally soil more rapidly than the vertical surfaces. The soiling between the horizontal and vertical levels noted for cotton are less apparent, probably because the cotton



(a)SOILING CURVES OF VERTICAL MATERIALS

AT EUSTON



(b)SOILING CURVES OF HORIZONTAL MATERIALS

AT EUSTON SITE.

Figure 6.9 (a) & (b) The soiling curves of vertical and horizontal materials at the Euston site

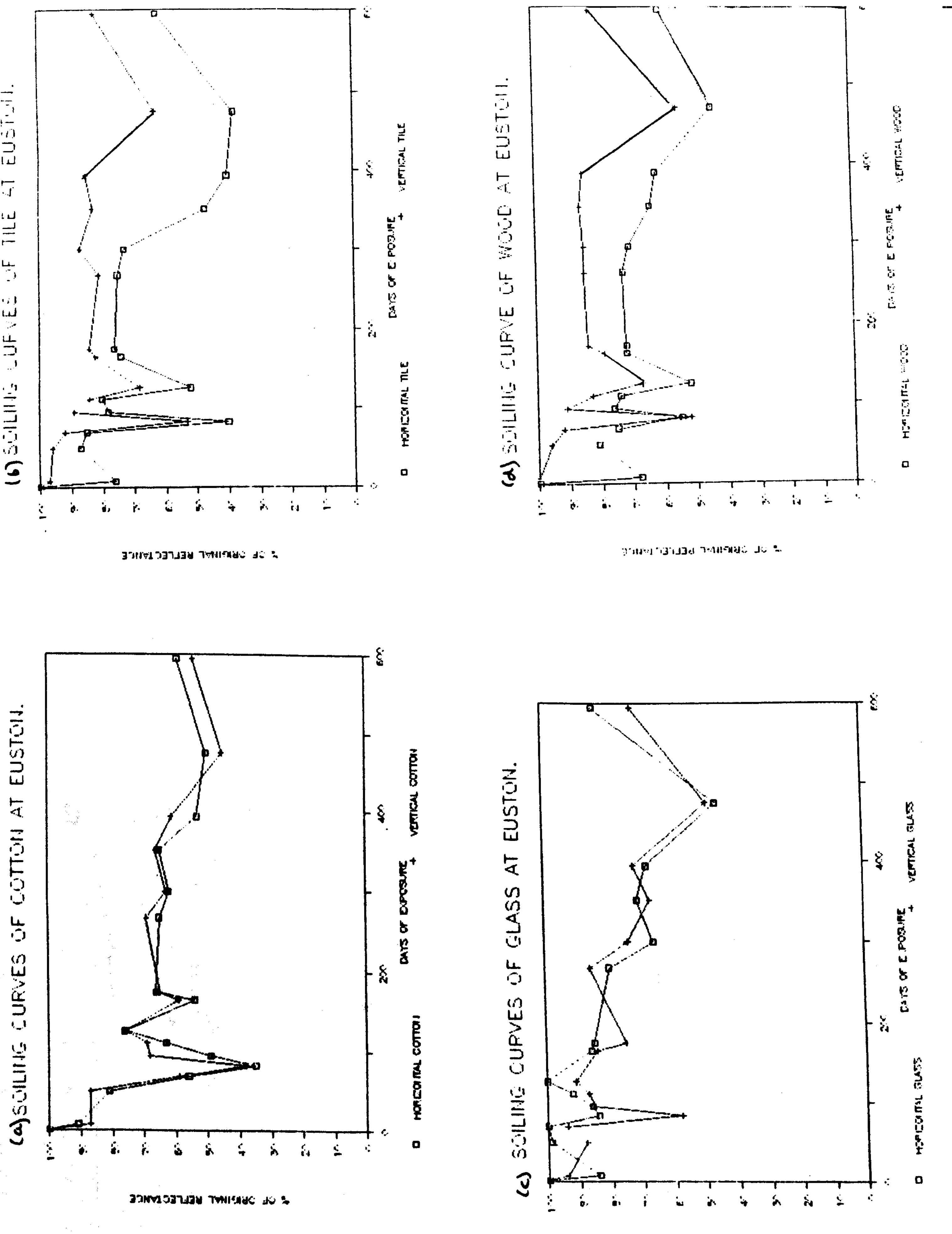
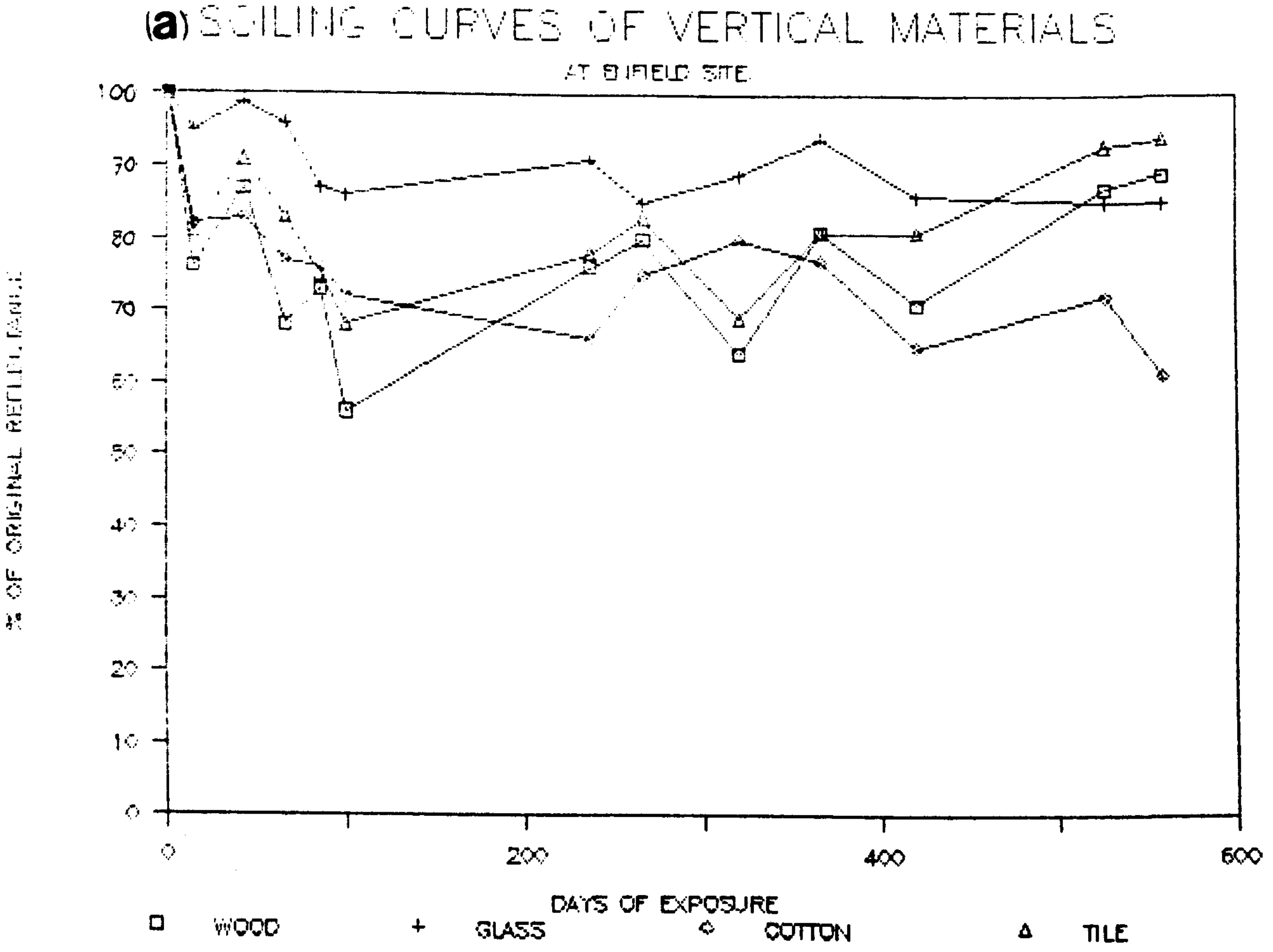


Figure 6.10 (a) – (d) The horizontal and vertical soiling curves of cotton, tile, glass and wood at the Euston site



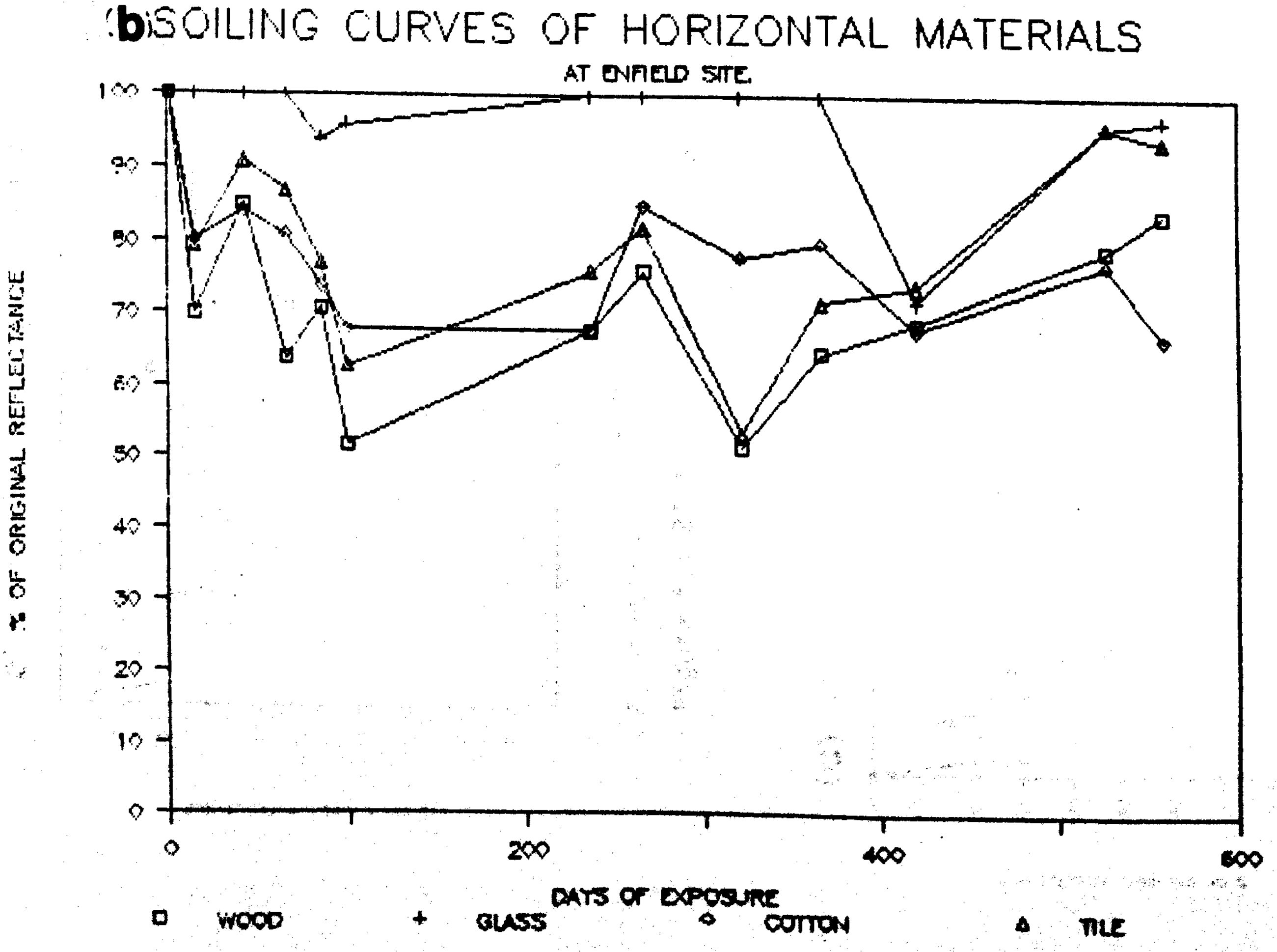


Figure 6.11 (a) & (b) The soiling curves of vertical and horizontal materials at the Enfield site

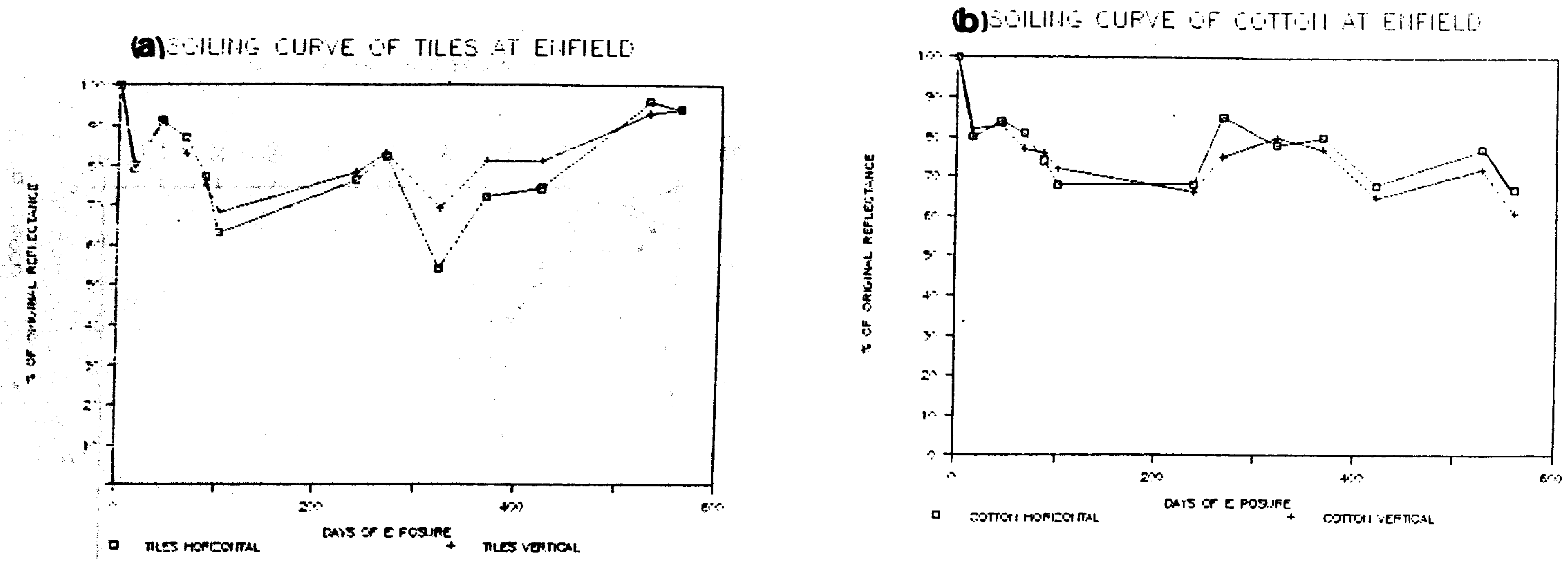
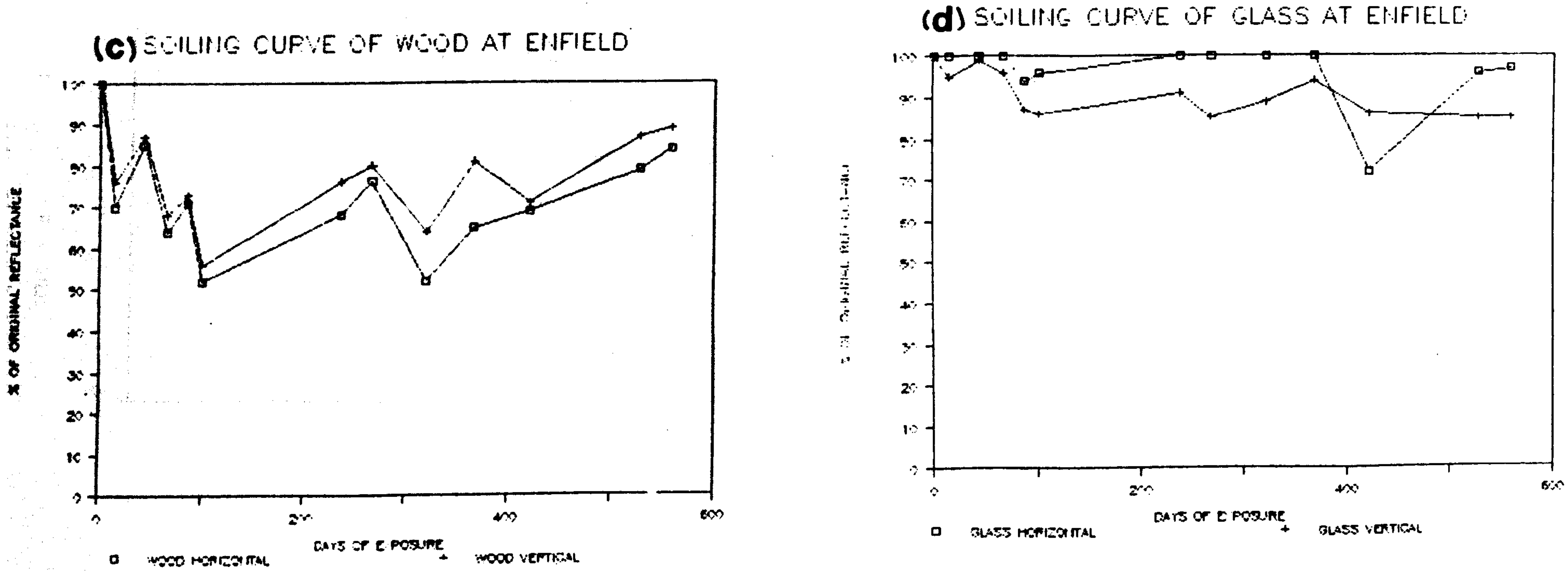
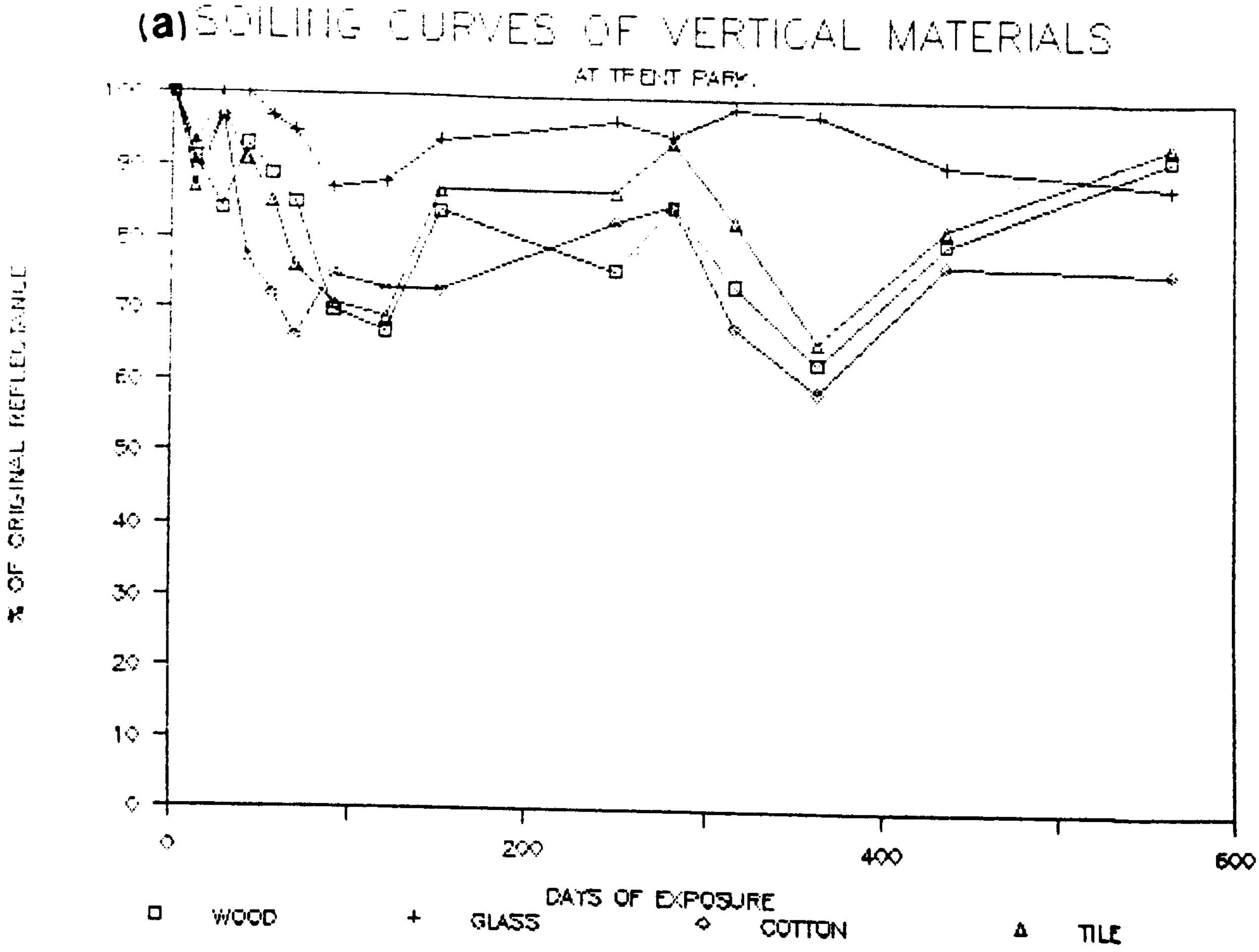


Figure 6.1.2(a)-(d) The horizontal and vertical soiling curves of tile, cotton, wood and glass at the Enfield site





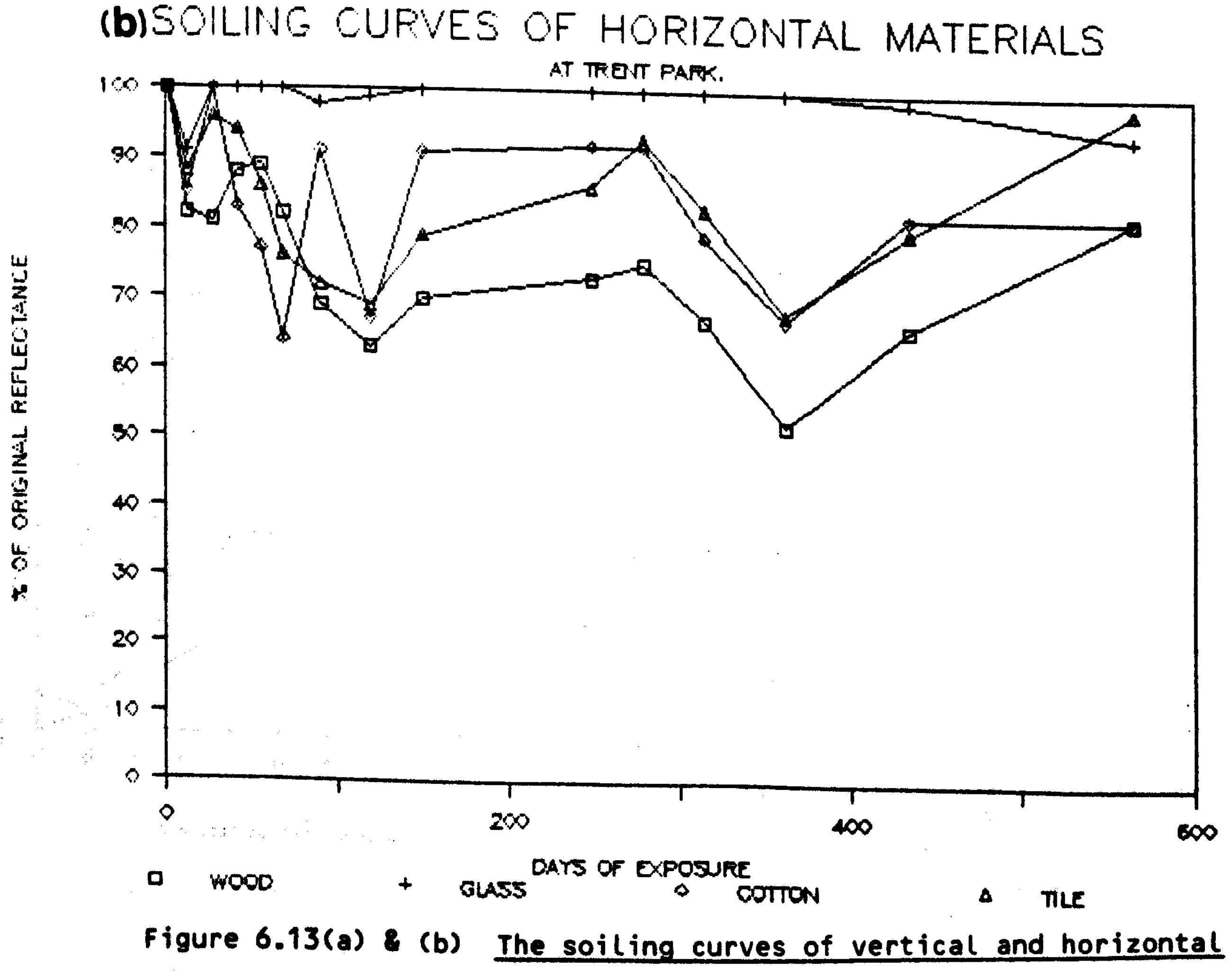


Figure 6.13(a) & (b) The soiling curves of vertical and horizontal materials at the Trent Park site

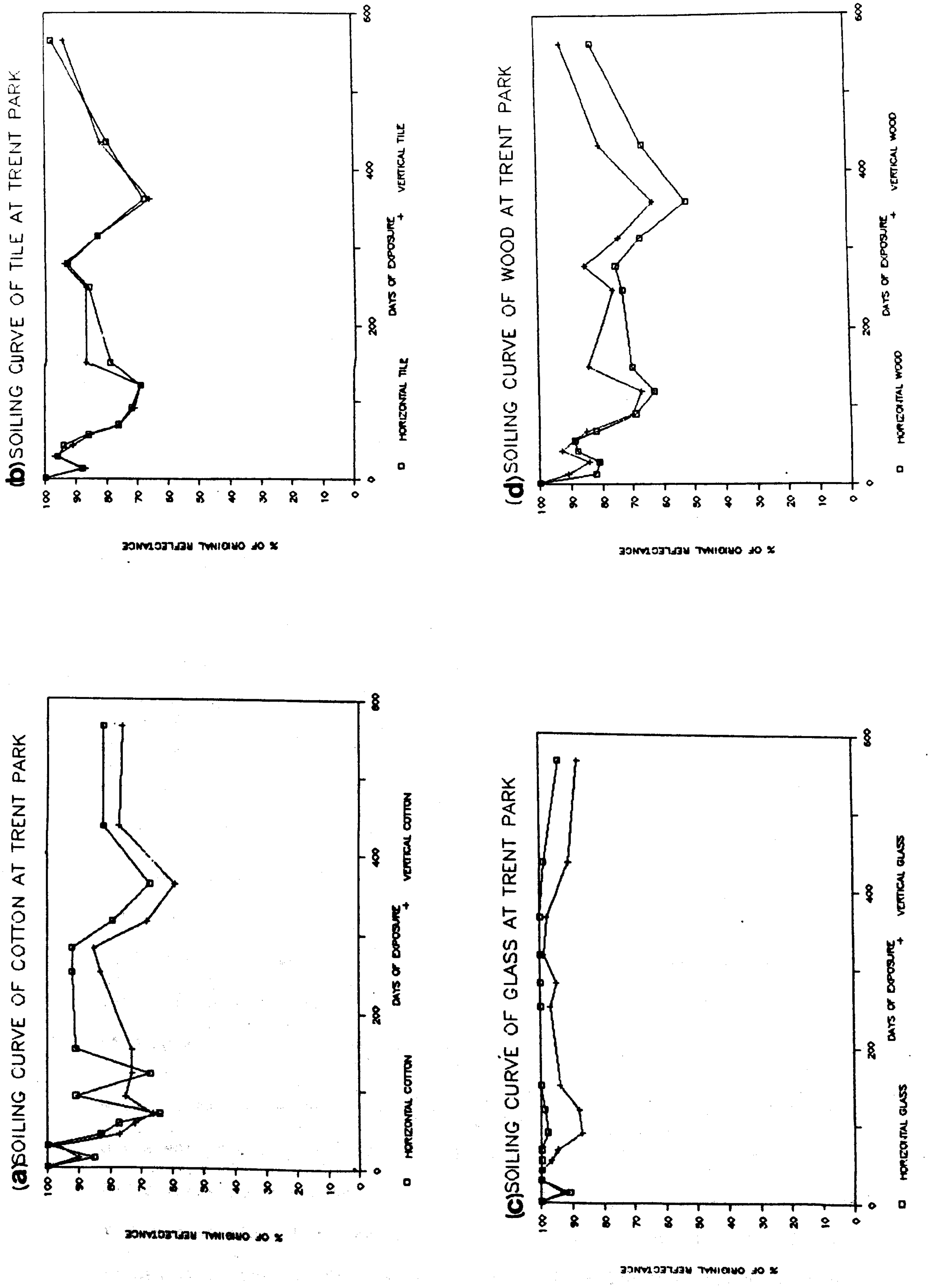


Figure 6.14 (a)-(d) The horizontal and vertical soiling curves of cotton, tile, glass and wood at the Trent Park site

(a pillow-case), the horizontal surface is less well defined than the other materials. The reverse soiling pattern, as noted for tile and wood, appears to be true for glass.

6.2.3 Calculation of soiling rates for the materials and comparison with predicted theoretical rates

The same procedure as described in Section 6.1.2 was carried out to deduce soiling rates within this experimental programme. The negative natural logarithm of the reflectance was plotted with time (in years). This was done for each material's orientation at the nine sites and a selection of the graphs is given in Figure 6.15.

Initially, the experimentally derived soiling rate was calculated with all the data points for each site and these results were used to derive a soiling curve as illustrated in Figure 6.16. As can be seen from this figure, the curves derived from the experimental results and the results of Haynie and Lanting underestimate the soiling rates over the first two hundred days of exposure, after this time there appears to be a closer agreement between the soiling curves and the data points - with the experimentally derived soiling curve for horizontal wood at Enfield lying between the curves predicted by Haynie and Lanting. The value of TSP of 30 $\mu g\ m^{-3}$ was used in the Haynie models, and a value of 3 $\mu g\ m^{-3}$ of EC was used for the Lanting model.

However, as can be seen from Figures 6.15(a)-(d) there appears to be two different groups of points over the exposure period. One is between 0-0.2 years and the other is from 0.2 to the end of the exposure period. Thus two straight lines can be fitted for each of these groups of data points (the first is for the period 0-0.2 years and the second for the

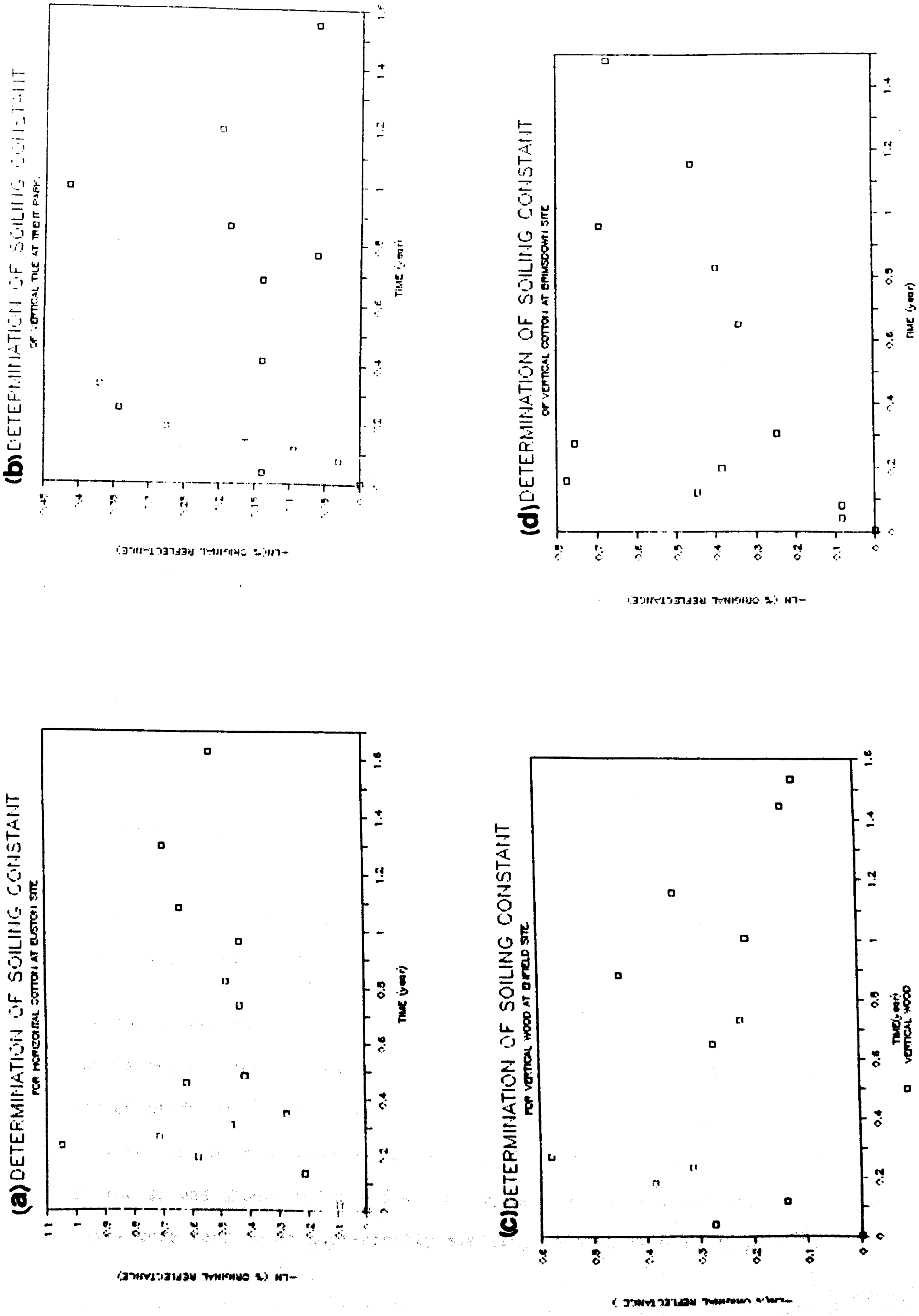


Figure 6.15 (a)-(d) Plots of -ln (% of original reflectance) against time for a selection of sites and materials

period 0.2 years to the end of the period) and from these lines two different soiling constants can be calculated. For horizontal wood at Enfield the soiling constant between 0 to 0.2 years was 2.0 yr^{-1} and the soiling constant after 0.2 years was 0.4 yr^{-1}. These two experimentally derived soiling constants were then plotted as exponential soiling curves together with the values of Haynie and Lanting for the data points and as can be seen from Figure 6.17. The first experimentally derived soiling constant of 2.0 yr^{-1} appears to fit the data better than the previously presented curves in Figure 6.16. However, after approximately 100 days of exposure the data points do not follow this soiling curve and appear closer to the values predicted by the second experimentally derived curve and Haynie and Lanting. This same procedure was applied for all the materials and their orientation at the Enfield site and is given in Figure 6.18. The same fitting trend as seen in Figure 6.17 applies to Figure 6.18. The first experimentally derived soiling curves (using data points from 0-0.2 years exposure period only) fits the data points better than the second derived curve or those of Haynie and Lanting. Lanting's curve appears to overestimate the rate of soiling observed here. The value of the second derived experimental curve (using points only from 0.2 years to the end of the exposure period) are closer to the values predicted by Haynie and Lanting.

The two experimentally derived soiling constants and those predicted by Haynie and Lanting are presented in Table 6.5. The same value of TSP and EC of 30 $\mu g\ m^{-3}$ and 3 $\mu g\ m^{-3}$ have been used to derive the soiling constants of Haynie and Lanting for sites 1, 3, 4, 5, 6, 7 and 8, for as was shown in Table 6.4, the smoke shade values for all these sites were felt to be sufficiently similar, ranging from 13-23 $\mu g\ m^{-3}$.

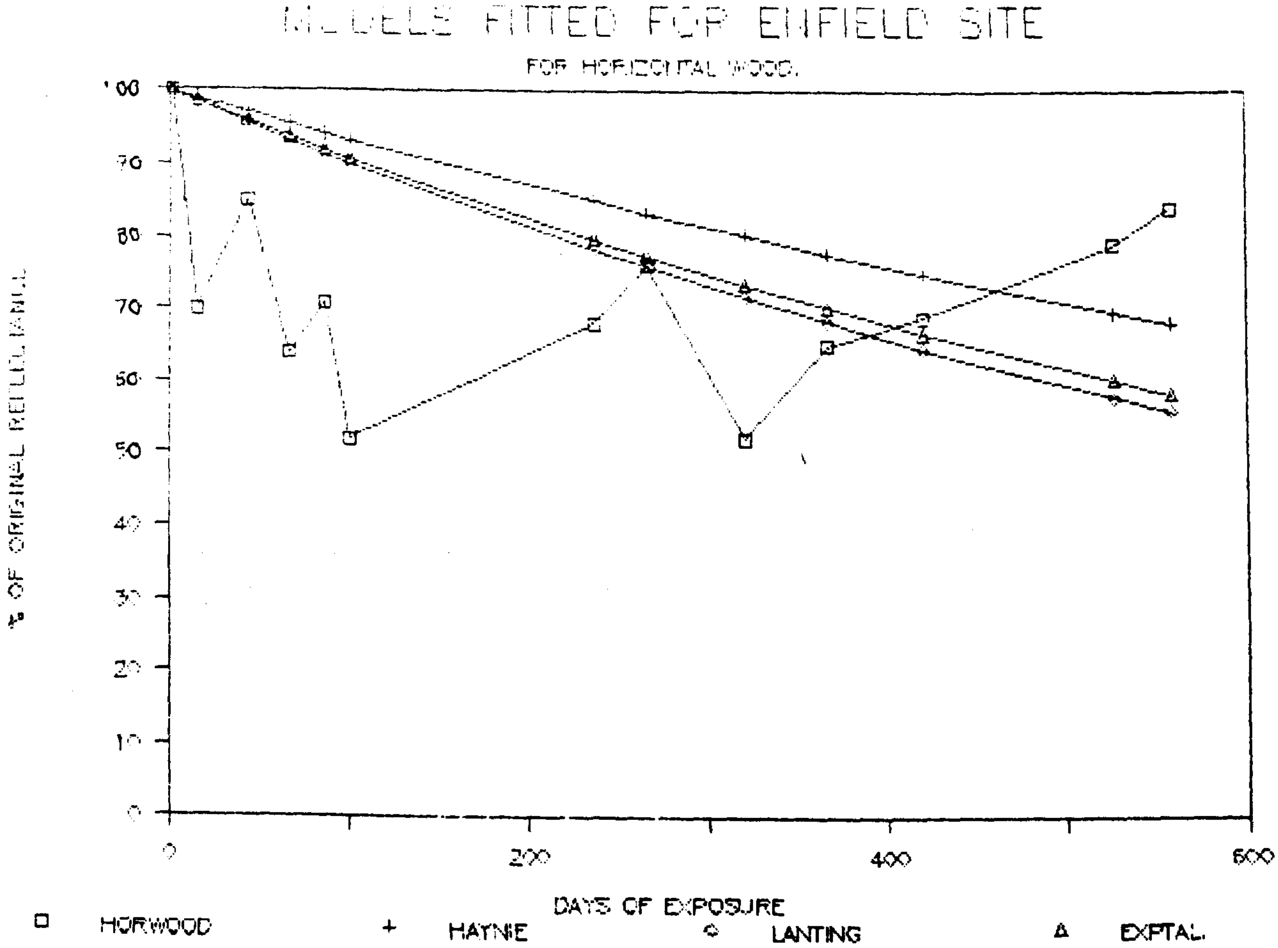


Figure 6.16 The soiling curve derived experimentally and from the theoretical curves of Haynie and Lanting plotted with the data points of horizontal wood exposed at the Enfield site

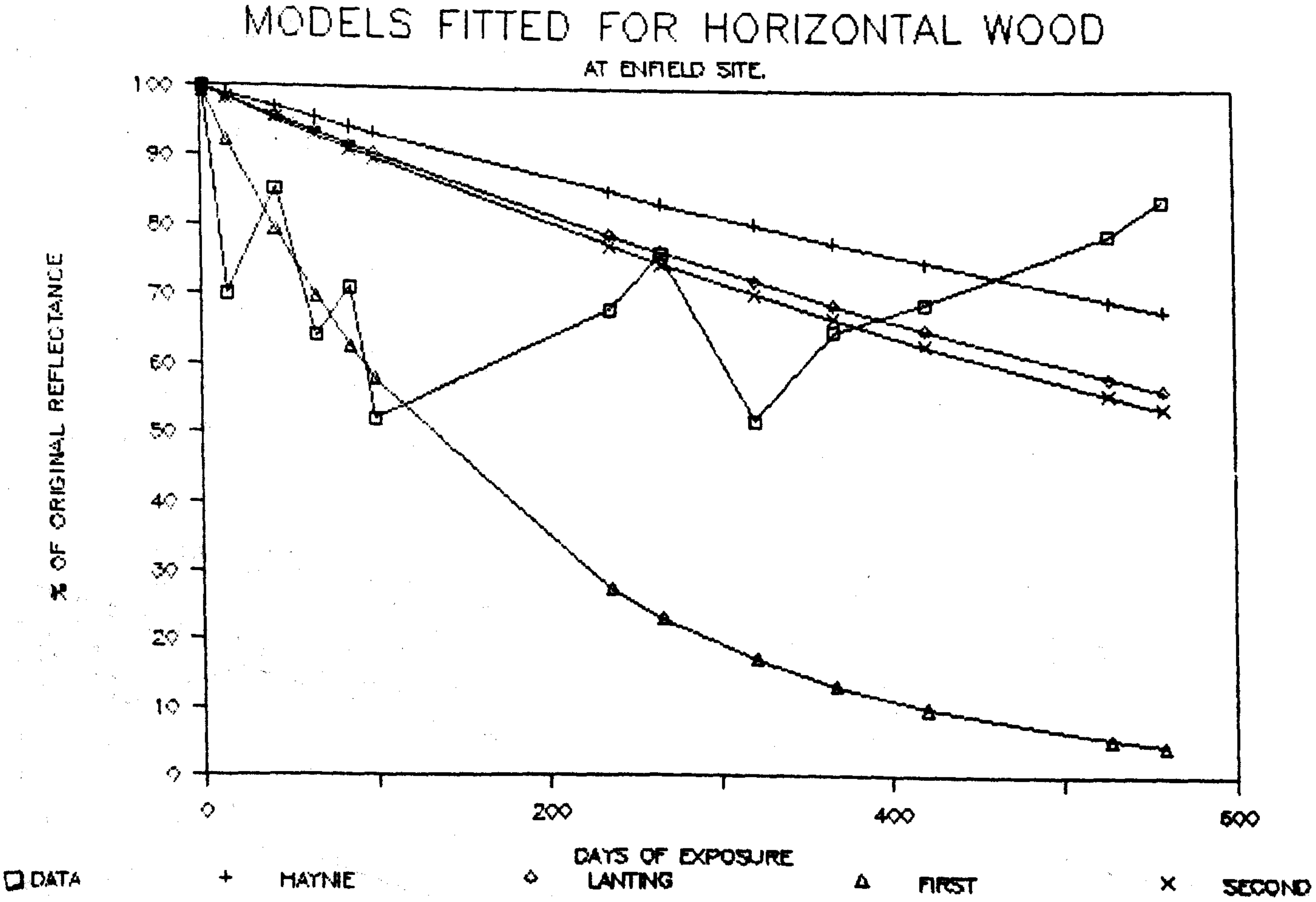


Figure 6.17 The soiling curves derived experimentally and from the theoretical curves of Haynie and Lanting plotted with the data points of horizontal wood exposed at the Enfield site

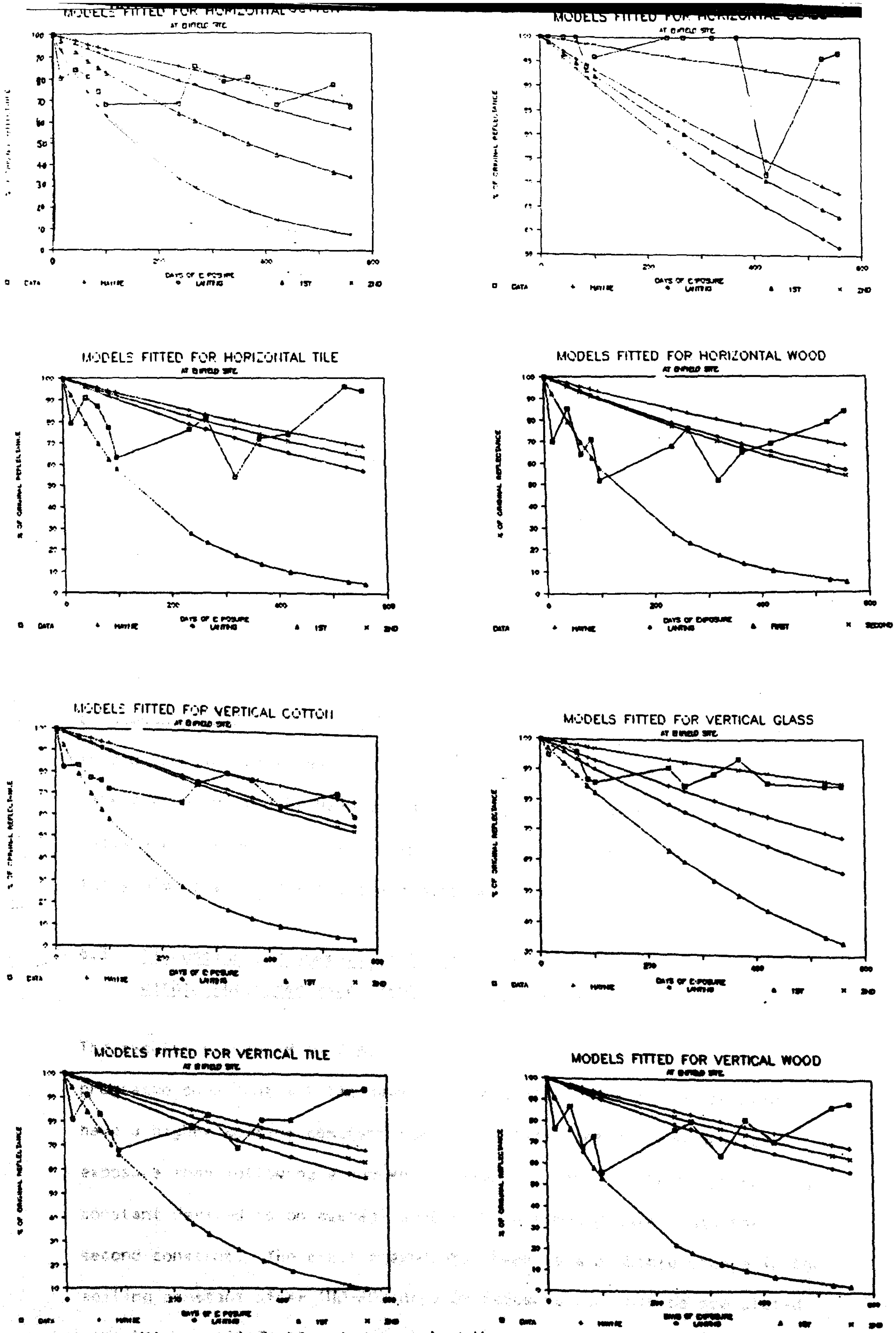


Figure 6.18 The soiling curves obtained from the two experimentally derived soiling constants and those from the theoretical curves of Haynie and Lanting plotted with the data points for all horizontal and vertically displayed at the Enfield site

Values for TSP of 50 and EC of 7 μg m^{-3} were used to calculate the soiling constants of Haynie and Lanting for the Euston site where the average smoke level was 48 μg m^{-3}, similarly for the Trent Park site a TSP value of 10 μg m^{-3} and EC level of 1 μg m^{-3} was used, the average smoke shade level for this site was 7 μg m^{-3}. Only one soiling constant is obtained for all of the material from each of Haynie's and Lanting's models as they did not differentiate between the soiling propensity of the various materials.

The two experimentally soiling constants were plotted with the curves of Haynie and Lanting for all the nine sites data for horizontal and vertical wood. These results are presented in Figure 6.19(a)-(p). Here again as in Figures 6.17 and 6.18, the first experimentally derived soiling curve fits the data points better for the first two hundred days of exposure than the other curves presented in Figure 6.19. Also, the second experimentally derived curve generally predicts a slower soiling rate than predicted by Haynie and Lanting. The reasons why the soiling rates vary during the initial exposure and long-term exposure are more fully discussed in the following section.

6.3 Discussion and summary of the soiling rates obtained within the three experimental exposure programmes

The results presented in Table 6.5 for the nine site long-term exposure programme show that all the materials regardless of their orientation have a higher soiling constant during the first one hundred days of exposure than following a subsequent exposure time. The first soiling constant derived is on average usually five times greater than the second constant. The exact reason why there is a probable change in the soiling constant after 100-200 days of exposure can only be speculated upon here, until further research investigates this apparent phenomenon.

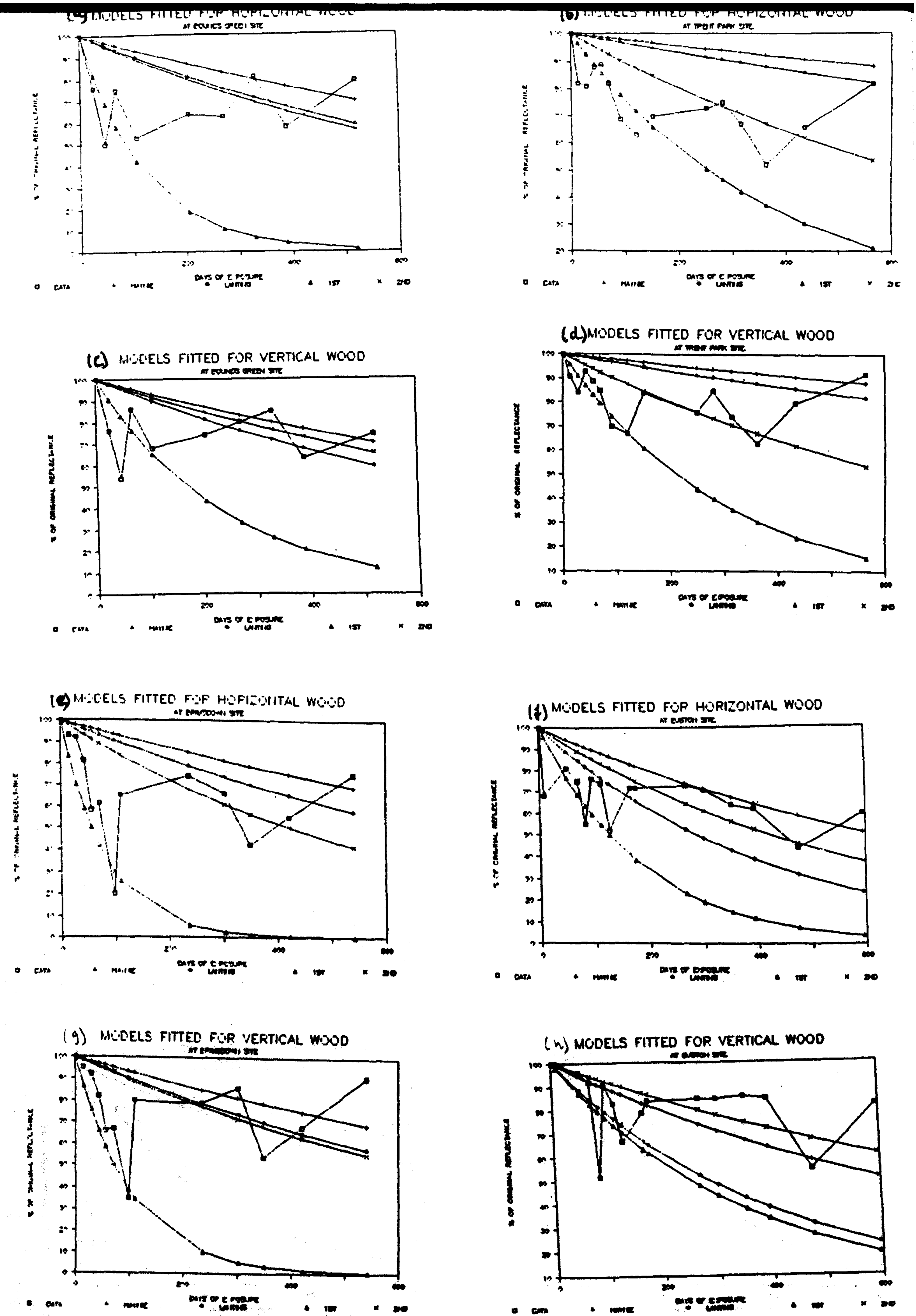
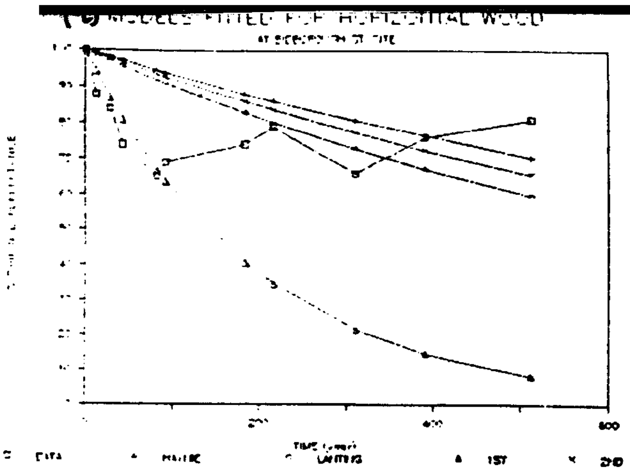
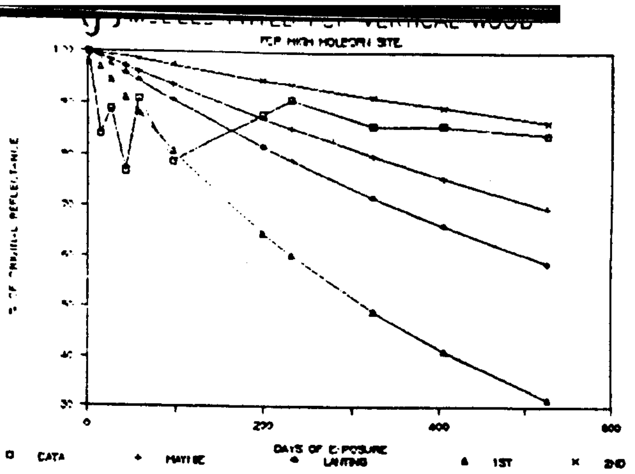


Figure 6.19 (a) - (h) The soiling curves obtained from the two experimentally derived soiling constants and those from the theoretical curves of Haynie and Lanting plotted with the data points for all horizontal and vertically displayed wood for the remaining eight sites

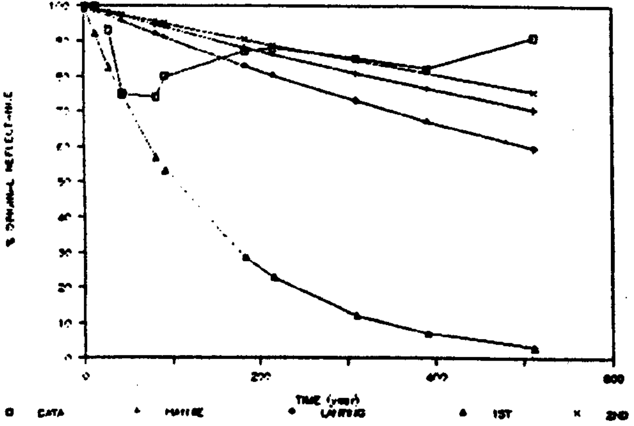
(i) MODELS FITTED FOR HORIZONTAL WOOD



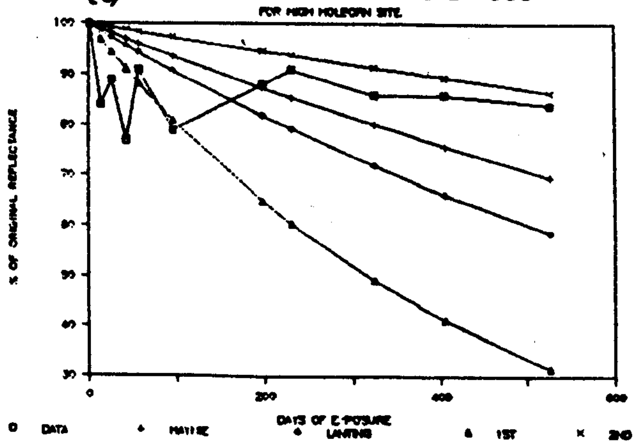
(j) MODELS FITTED FOR VERTICAL WOOD



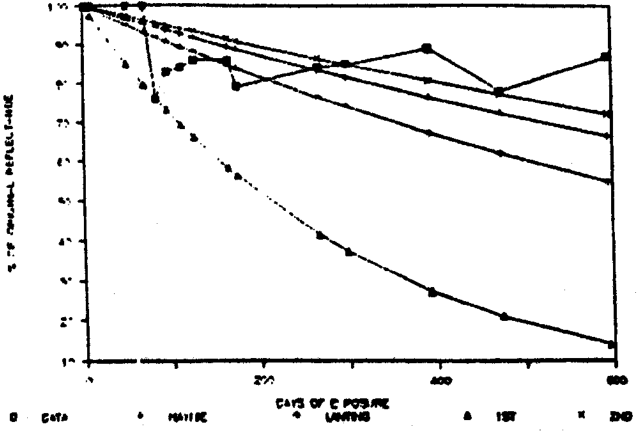
(k) MODELS FITTED FOR VERTICAL WOOD



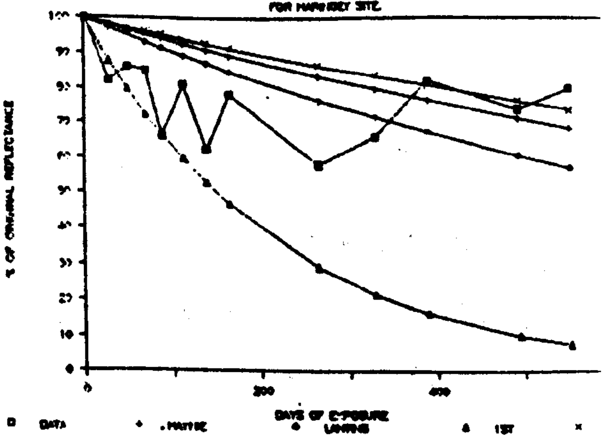
(l) MODELS FITTED FOR VERTICAL WOOD



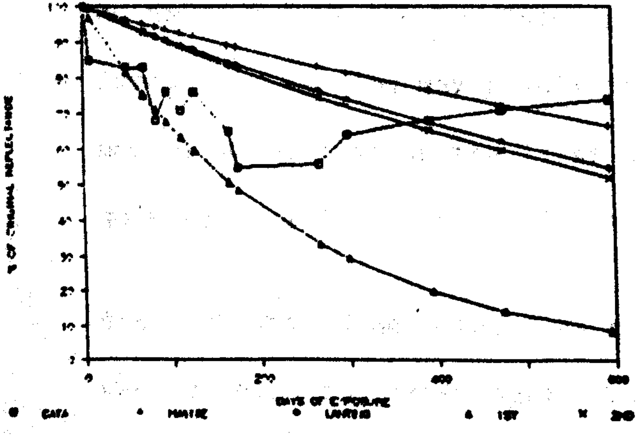
(m) MODELS FITTED FOR VERTICAL WOOD



(n) MODELS FITTED FOR HORIZONTAL WOOD



(o) MODELS FITTED FOR HORIZONTAL WOOD



(p) MODELS FITTED FOR VERTICAL WOOD

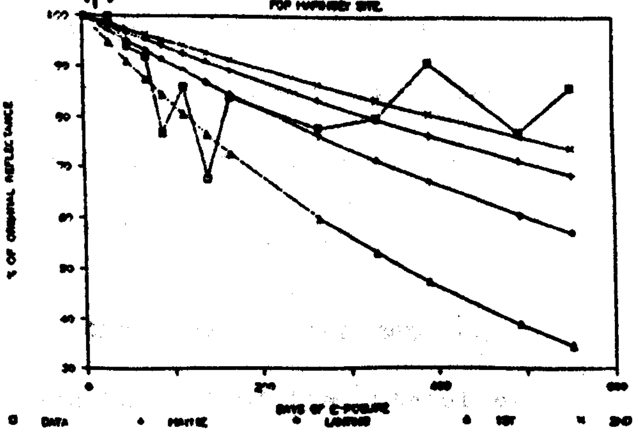


Figure 6.19 (continued)

If there has been no rainfall for some days, the reflectance value recorded for an exposed material will be lower than had it been taken after a rainfall event. Thus, results obtained may be dependent on this fact. Unfortunately, measurements taken in the nine site exposure programme could not always be standardised i.e. always taken a fixed time before/after a rainfall event. Thus, reflectance levels recorded where a long period had elapsed between rainfall, may overestimate the time soiling rate for that material at that time; for it is likely that one will be measuring here a reflectance value that is combined from a soiling and dustiness contribution. However, fortunately, a sufficient number of sites was used in this experimental programme and all show two clear soiling rates for the exposed materials. Thus, the likelihood that these results were obtained by chance is diminished.

Other reasons mooted to explain the difference in soiling rates between early and later exposure times may include the fact that previously unexposed clean surfaces have a greater electrostatic attraction for particulate matter that is deposited on to it. With increased exposure time, the surface's attraction for such matter may be diminished as its surface becomes covered with deposited matter. This deposited matter's attraction for other matter may be lower than that of the clean surface and thus deposition rates on to the soiled surface are slower than on to a clean surface. Another possible reason for two soiling constants can be deduced from the two theories for soiling presented in Chapter Four. Short-term soiling may result from the difference between covered and uncovered surface as the first monolayer is deposited, while long-term soiling is a function of the thickness of the deposited layer.

Also, it should be noted that soiling is a long-term process and that values taken too often during early exposure may not be that useful at providing relevant data on soiling rates for a prescribed material and site. As was shown in Section 6.1.2, the results from the daily exposure programme produce a lot of 'noise' which makes the true trend in soiling rates difficult to recognise. It is interesting to compare the results obtained for the exposed wood displayed at Enfield - the soiling constant derived from a daily measurement programme of 111 days gave a value of 0.7 yr^{-1}, the value obtained from the 0.2 years of the long exposure programme gave 2.0 yr^{-1} and the 1 year value from the long exposure programme gave 0.4 yr^{-1}. Thus three different soiling rates have been obtained for the same material at the same site and during some of the same exposure period. Here, as previously stated soiling is a long-term process, so perhaps the value of 0.4 yr^{-1} derived for horizontal wood at Enfield best describes the soiling propensity and rate for that site.

Indeed in comparison with the one year soiling constant derived for all sites and their materials, the value obtained here is generally more correlated with the smoke value recorded for that site. For example, the soiling rate of horizontal and vertical tiles is greatest where the smoke level is highest; in that Euston has a soiling rate of 0.6 yr^{-1} for horizontal tile, whereas all the other sites have a lower soiling rate than this. The fact that Trent Park site has some soiling rates higher than other sites which have higher smoke levels, may in part be attributable to local meteorological and dispersion differences between the various sites. Also, the difference between the average smoke level between the highest Euston and the lowest Trent Park is 41 $\mu g\ m^{-3}$. This may not be such a large difference in real terms and thus one may not actually expect the soiling rates to be so very different. It is interesting to see that the predicted values of Haynie and Lanting for the Trent Park site for all of the materials (with the exception of vertical glass) are below those actually recorded. This may be because the site at Trent Park is in the middle of a country park and that the models of Haynie and Lanting are only applicable for urban situations where smoke and EC levels are greater than those at Trent Park. Also, it should be noted here that the values predicted by Haynie and Lanting for the nine site and daily exposure programme have been calculated from the relationship between those parameters and smoke levels described in Sections 2.1.4 and 3.5.2. Thus, because the TSP and EC values used to predict the theoretical soiling rates were not actually experimentally recorded, they should only be treated as an approximate value. It may be that the actual TSP or EC levels are significantly different to those derived from using the smoke shade relationship and thus the rates given in Table 6.5 may over or underestimate the true theoretical rate. However, the sites were examined for other sources of particulate matter that may contribute to the concentration of particulate matter within the atmosphere but are not recorded by the smoke shade apparatus. Such sources were not obviously apparent and the materials were placed as close as possible to the apparatus so that the level recorded for smoke reflected the approximate level the materials were subjected to.

The soiling rate results obtained for the exposed vertical wood and tile in the Hatfield tunnel of 1.92 and 1.87 yr^{-1} are interesting to compare with the results from the nine site programme. Smoke shade values recorded in the Hatfield tunnel were approximately 200 $\mu g\ m^{-3}$. The nine-site programme sites, with the exception of Euston and Trent Park, had an average smoke shade value of 20 $\mu g\ m^{-3}$. Thus, there is a factor of 10 difference between the smoke shade values between the Hatfield enclosed exposure programme and seven of the nine-site ambient exposure programme. The average soiling rate for exposed vertical wood for a site where the smoke shade value is around 20 $\mu g\ m^{-3}$ is in the order of 0.3 yr^{-1}. Likewise for exposed vertical tile the value is

Table 6.5 The two soiling constants derived experimentally during the nine-site programme for all materials, as well as those predicted by Haynie and Lanting for such sites. The soiling constants derived from the daily programme of exposed and sheltered samples of wood and tile are also given as are the results obtained for the Hatfield tunnel

SITE	WOOD HORIZONTAL		WOOD VERTICAL		GLASS HORIZONTAL		GLASS VERTICAL	
	0.2	1.0yr	0.2	1.0yr	0.2	1.0yr	0.2	1.0yr
1. High Holborn	2.5	0.3	0.8	0.1	1.7	0.2	1.3	0.2
2. Euston	2.0	0.6	1.0	0.3	1.0	0.4	1.3	0.4
3. Bidborough Street	1.8	0.3	2.5	0.2	NR	0.05	0.6	0.08
4. Islington	1.5	0.4	1.2	0.2	0.5	0.2	0.7	0.2
5. Haringey	1.7	0.2	0.7	0.2	1.1	0.15	0.8	0.1
6. Bounds Green	3.0	0.4	1.5	0.3	0.2	0.08	0.5	0.2
7. Enfield	2.0	0.4	2.3	0.3	0.3	0.06	0.7	0.1
7a Enfield daily	exposed 0.7	sheltered 0.8	-	-	-	-	-	-
8. Brimsdown	4.5	0.6	3.5	0.4	1.5	0.3	1.0	0.2
9. Trent Park	1.0	0.4	1.2	0.4	0.1	0.02	0.35	0.08
10. Hatfield tunnel	1.93		-	-	-	-	-	-

SITE	COTTON HORIZONTAL		COTTON VERTICAL		TILE HORIZONTAL		TILE VERTICAL		HAYNIE	LANTING
	0.2	1.0yr	0.2	1.0yr	0.2	1.0yr	0.2	1.0yr		
High Holborn	2.0	0.3	2.0	0.3	1.7	0.2	1.2	0.2	0.25	0.37
Euston	3.5	0.6	2.0	0.7	2.5	0.6	1.0	0.4	0.41	0.88
Bidborough Street	1.0	0.3	1.5	0.4	2.0	0.3	1.5	0.1	0.25	0.37
Islington	3.5	0.6	2.0	0.5	1.2	0.3	1.2	0.3	0.25	0.37
Haringey	2.4	0.4	2.0	0.4	1.3	0.2	0.8	0.1	0.25	0.37
Bounds Green	2.5	0.5	2.5	0.7	2.5	0.3	2.0	0.2	0.25	0.37
Enfield	1.7	0.3	1.2	0.4	2.0	0.5	1.5	0.3	0.25	0.37
Enfield daily	-	-	-	-	exposed 0.5	sheltered 0.6	-	-	0.25	0.37
Brimsdown	4.0	0.5	2.5	0.5	3.5	0.6	2.2	0.3	0.25	0.37
Trent Park	1.5	0.3	2.0	0.4	1.3	0.3	1.2	0.2	0.08	0.12
Hatfield tunnel	-	-	-	-	1.7		-	-	1.73	3.7

approximately 0.2 yr^{-1}. The difference in soiling constant between the exposed wood in the Hatfield tunnel and the ambient environment is of a factor of 6.5 and a factor of 8.5 for the exposed tile.

The fact that the difference in soiling rates between the Hatfield and ambient exposed materials is not as great as the factor of 10 difference in smoke, may be attributable to the fact that deposition velocities in enclosed and open environments are different. The Arnhem Lead Study (Brunekreef et al (1981)(133) reported the following deposition velocities for lead:

$Vg = 1.3 \times 10^{-2}$ m s^{-1} (outdoors)
$Vg = 3.3 \times 10^{-4}$ m s^{-1} (indoors)

As Hamilton and Revitt (1987)(134) note, lead is present in air as submicron particles and the deposition velocity is determined by Brownian motion and eddy diffusion. Higher deposition velocities are expected in the more turbulent outdoor atmosphere. This fact may also be applicable to carbon particles whose size in the ambient atmosphere is likewise submicron. Thus, if carbon particles are responsible for soiling, the deposition velocity and ultimate rates of soiling may be expected to be greater in an ambient exposed location than in an enclosed area at the same airborne PEC level.

6.4 Elemental analysis of deposited matter on exposure materials

At the end of the exposure programmes for both the Hatfield tunnel and the nine-site project reported in Chapters Five and Six, samples of the deposited matter on the exposed materials were brushed off their surfaces and such samples were analysed using the elemental analyser, as described in Appendix B. In all, deposited samples from five sites were analysed and the results are given in Table 6.6. In addition, a sample of wood and tile was exposed at busy road routes (East India Dock Road and York Road) where the number of vehicles per day passing the site is in the order of over 50,000 vehicles.

An example of the experimental scheme used in the East India Dock Road is given in Figure 6.20. The materials were displayed approximately 4 metres above ground level for a period of three months, smoke shade levels are recorded at this site and the daily average smoke level during the exposure period was 75 $\mu g\ m^{-3}$. The inlet funnel to the smoke shade apparatus is apparent from the second window to the left of the column.

Figure 6.21 shows the exposed materials located at York Road 5 m above ground level at the end of their three month exposure period, during which time the daily average smoke shade level was 58 $\mu g\ m^{-3}$.

Figure 6.20 The experimental scheme used to display materials of tile and wood at a site on the East India Dock Road, London.

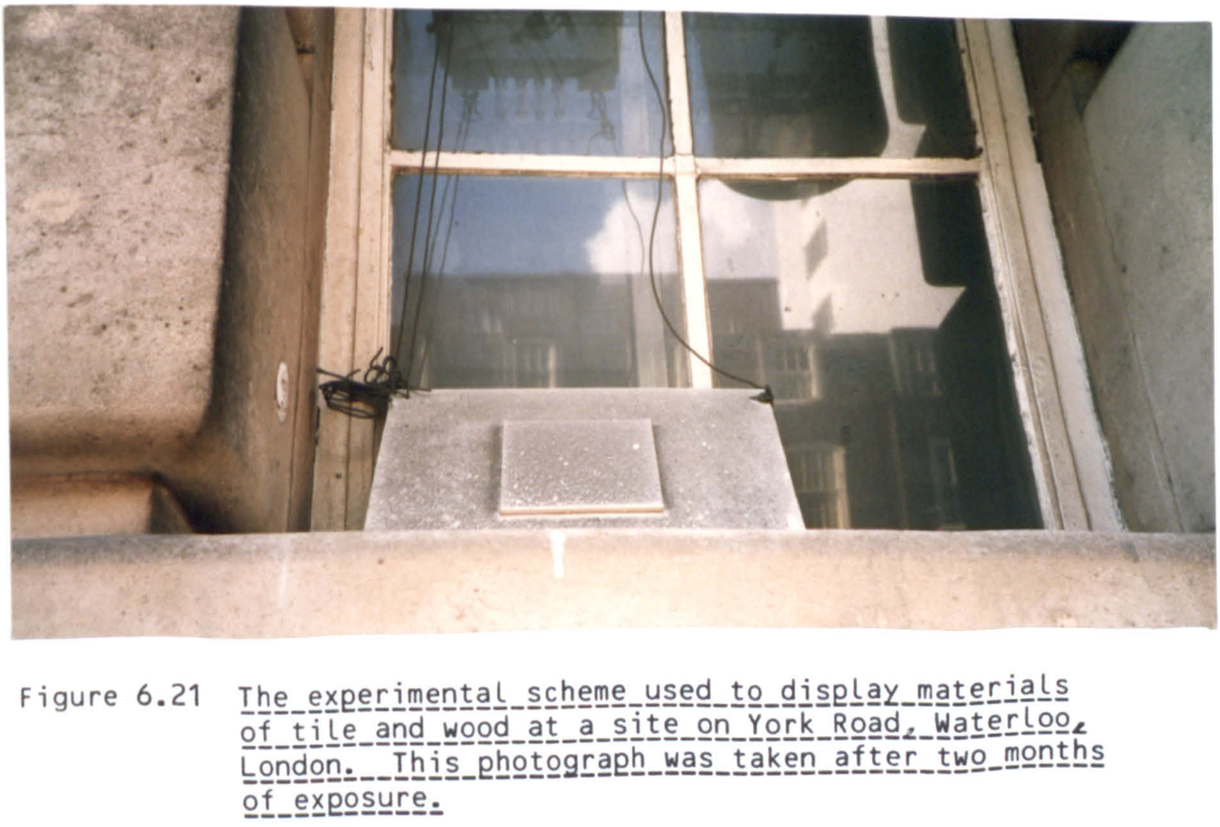


Figure 6.21 The experimental scheme used to display materials of tile and wood at a site on York Road, Waterloo, London. This photograph was taken after two months of exposure.

Table 6.6 Measurements of the % total, elemental carbon and ash recorded for samples of deposited matter removed from exposed materials at a variety of sites with different smoke levels

	Location	Total Carbon %	Elemental Carbon %	Ash %	Average smoke level ($\mu g\ m^{-3}$)
Closed environment action of rainfall absent	Hatfield tunnel	12.44	4.1	62.82	247
	Dartford tunnel	18.31	6.1	60.49	not recorded
open environment action of rainfall present	East India Dock Rd	18.54	6.2	61.72	75
	York Road, SE1	18.74	6.2	59.08	58
	Tottenham College, N18	17.69	5.8	66.32	15
	Hatfield tunnel ambient	44.6	14.8	28.7	247
	Urban street dust(68)	-	0.51	-	-

The high ash content of over 60% for the samples of deposited matter analysed, indicates that a high level of resuspended road dust and soil derived particles were present. As indicated in Section 2.3.2, the particles created by the wear of the road are usually greater than 2 µm in diameter and composed of quartz, calcite, talc, feldspar, gypsum, hematite, magnatite, plus some silica, calcium, aluminium and iron compounds.

Some zinc particles may also be present as a result of the corrosion of the galvanized safety barriers. However, the majority of such particles are much lighter in colour than those emanating as a result of fuel combustion and may not contribute significantly to the darkening of exposed surfaces. Also, despite resuspended road dust and soil derived debris being deposited on to exposed surfaces, such particles may be removed with rainfall because they are usually larger and more water soluble than those which are vehicularly derived. The presence of resuspended and vehicularly derived particles and their probable different removal mechanisms from a surface, may be a factor in explaining the fluctuating soiling results in Chapter Six and the comparatively low levels of total carbon recorded for the deposited matter.

CHAPTER SEVEN

THE ECONOMIC COSTS OF BUILDING SOILING IN THE UK

7.1 The need for cost-benefit analysis and some of the associated difficulties

The direct soiling costs of air pollution result from an increased requirement for washing of both interiors and exteriors of buildings, laundering and cleaning of materials, painting of buildings and washing of motor vehicles. However, there are also other intangible factors which should be considered. For example, in a heavily polluted environment the standards of cleanliness may be allowed to deteriorate. If these conditions are improved, the gain may be one of amenity rather than economic, or some combination of the two. There is also a depressing psychological effect on people who must work to eliminate the dirt which air pollution leaves on their furniture and clothes. This same depressing effect of air pollution may have an adverse influence on working efficiency and on a person's relationship with others.

Policy makers need to know how much damage both environmentally and economically a source of pollution is causing before they can decide if there is any rationale for control measures to be implemented. Unfortunately, it is not possible to translate all air pollution effects into economic terms. For example, a harmful smoke affecting the general health may be represented as a "loss" on the assumption that it increases costs for care and treatment. But it is not so easy to express the physical and psychological effects in terms of money.

It is obvious, therefore, that many different factors and conditions must be taken into account when considering the economic and social aspects of air pollution.

7.1.1 Externalties and Environmental Quality

The need for cost benefit analysis (CBA) in studies on environmental quality arises because markets do not function perfectly in the real world and because they do not force firms to internalise all of their costs. Classical economic theory leads to the conclusion that prices will act as reliable indicators of the value set by society on the goods or services available. Thus, in theory, market forces should ensure that resources are utilised in an optimal fashion for the prevailing pattern of wealth distribution. However, in the environmental field the polluter and the polluted usually lack knowledge of the true nature and extent of the pollution effects and therefore set no meaningful value to them. Also, the structure of the market may be such that there is no direct link between the polluter and the polluted. The expenditure by polluters on pollution control may not bring them any direct benefit and by increasing such costs may put them at a great economic disadvantage in relation to competitors (especially within the industrial field). The beneficiaries from their control are under no obligation to reward them and there is therefore no direct economic incentive to incur expenditure. Thus, social pressure or regulation are the only forces that can operate in this situation in the short term.

When there is a divergence between social and private costs, there arises an 'external diseconomy' or, alternatively, known as an 'externality'. The effects in terms of changes in patterns of expenditure, consumption and general levels of amenity resulting from a decision to change the level of air pollution can be best appreciated by building a simple model such as given in Figure 7.1.(135) It is useful when examining the effects of pollution on the environment to assess the qualitative consequences that could be envisaged to result through some change in ambient pollution level. This enables us to structure our thinking and to follow through the second and higher consequences arising as a result of postulated changes in the pollution level. However, it should be remembered that what is beneficial to one section of the community may not be beneficial to others. For example, pollution control equipment installed in a factory to decrease atmospheric emissions uses energy and resources in their manufacture, labour in their manufacture and installation and energy in their operation. The main apparent beneficiaries are our appreciation of clean air, improved health in the long term and the reduced probability of environmental collapse. To make use of such a model as a decision aid, it is vital to have factual information on the different costs and benefits, with particular attention to the transfers between different sectors of the economy, showing what benefits and disbenefits will accrue and to whom and what the net overall effect will be. There is also a need to define the geographical constraint of the model - is it local or regionally based? or is a global approach more appropriate? Having established such constraints one can then turn ones attention to the problems of measurement.

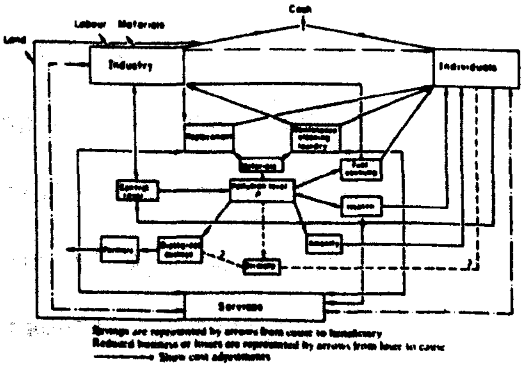


Figure 7.1 Transfer model (Pollution Decreasing)(135)

7.1.2 Evaluating the costs and benefits of environmental quality control

Like many private businesses, governments are increasingly adopting programming, planning and budgeting systems influenced by cost-benefit considerations to facilitate their management decision making.

With studies of environmental quality there are four general categories of cost that are relevant in cost-benefit studies according to Jones (1973)(135):

(i) cost of control or avoidance of environmental damage;

(ii) the directly measurable economic costs of damage, such as soiling or loss of output due to illness resulting from air pollution;

(iii) the indirect measurable costs where monetary values are not usually applied but where market values can be inferred from suitable proxies. Examples include losses in leisure time, loss of amenity due to noise or pollution;

(iv) unmeasurable costs where no market values are readily ascribable, such as the costs of suffering, premature death, the destruction of a forest or historic treasures such as St Paul's Cathedral in London.

Such categories are not distinct and often overlap. Benefits from improvement in environmental quality arise either from decreases in the costs listed in (ii) to (iv) or from the creation of additional utility as in time saving or increased amenity. It is not usually practicable or sensible to talk in terms of absolute costs and benefits since the complete abolition of all pollution or nuisance is prohibitively costly. The relevant parameter is the change in costs and benefits in relation to proposed changes in environmental quality.

When considering the costs of control or avoidance of damage, one needs to look at the specific activities leading to the effects and how these could be improved; for example, the cost of scrubbers or low sulphur fuels to reduce sulphur dioxide air pollution. Each cost has to be determined as a function of the degree of environmental improvement obtained and care needed to ensure that the control route that is adopted is the cheapest and to watch for step changes in best-options.

The directly measurable economic costs of damage may appear simple to determine but seldom are in practice, especially with the more diffuse effects. For example, as Jones(136) illustrates, corrosion caused by a pollutant can be measured in the laboratory or ambient air environment, but the costs of corrosion arise in many ways. Extra expenditure may be spent in using corrosion resistant or specially treated materials or maintenance by cleaning and painting may be increased, or the materials may be allowed to corrode and replacement becomes more frequent, or the item susceptible to damage may be specially housed to protect it from the environment. The cost of each of these alternatives if actually employed needs to be determined from knowledge of the ambient environmental conditions and the distribution of susceptible materials, neither of which may be known with any great degree of reliability. Although some of these problems are reduced where localised effects are concerned, it is still very difficult to determine how much corrosion or paint damage is due to pollution and how much to poor surface treatment and normal weathering by sun and moisture. As Seeley(137) notes, apart from climatic and environmental effects, paint work may deteriorate earlier than could be expected because of the poor standard of workmanship or the use of incorrect paints or the mixing of incompatible ones, or the excessive thinning of paints, or as a result of painting carried out in unsuitable conditions, or inadequate preparatory work on the surface to be painted. Indirect cost is another category where economists' views may also differ widely. For example, the value of time saving is usually equated to average salary where the time saved is business time and can be assumed to be put to productive use. However, the value of the saving really depends on the use to which the time is put. If the saving makes the difference between catching or missing a train with a possible long wait, it may be more valuable than if the time is distributed over a number of activities with no observable change of output. Numerous other examples use the inference of value from market proxies. Minimum notional values for housewives' services (which may be lost through illness) can be assessed by arguing that their families must value their services at least as highly as those of the average working woman, otherwise she would work. Alternatively, the costs of replacing all the services by paid labour might be taken. The use of property values as a general means of measuring disutility associated with living in a particular environment is further considered in Section 7.2.2.

The final class of costs incurred from poor environment relates to the incommensurables such as suffering and premature death. These typify things that no individual can value rationally even if they can appreciate the degree of disutility. To be able to express health improvement benefits in monetary terms may be difficult, even unpleasant, but the procedure makes it unavoidable.

It should be remembered that no society behaves as if life is priceless. As Pearce(138) notes, if we did so, our health service would receive all the money it needed and thus there would be no shortage of kidney dialysis machines and no long operation lists. Some attempts have been made in America to determine what people would be prepared to pay for a change in the probability of death over a defined time period and to extrapolate this data to gain a current valuation of life. This area is known as risk assessment and risk management and involves identifying "an acceptable level of risk". Pearce (138) quotes the range of single year benefits for the USA ranged from about $250,000 to $1 million for each life lost and the variation in the value used explains much of the variation in the results obtained. Such values were not arbitrary but were derived from the valuations that individuals in risky occupations appear to place on their lives by accepting compensation for more risky work. However, such workers accept those risks 'voluntarily' whereas few of us 'voluntarily' expose ourselves to the risk of air pollution.

Pearce (138) has also evaluated the methodology by which economists can estimate the value of historic treasures, such as the Acropolis in Athens, and the damage done to them by air pollution. He suggests the process of valuation should be 'inverted' and we should ask ourselves what we have to do to prevent air pollution damage. Assuming we are not to coat the Acropolis in plastic or remove parts of it for protection, that cost will be given by the cost of reducing pollution to levels which will not harm the monuments in question. Simple techniques exist for expressing such a cost in annual terms and we can then ask ourselves 'since it cost x million pounds to protect the Acropolis each year, do we value it at more than x million pounds per year?' If the answer is 'yes' then there is an automatic economic rationale for outright protection through abatement schemes, but if the answer is hesitant, reference to the other benefits such protection would bring health and aesthetic benefits. These may be directly quantifiable and if they come to y million pounds, the question can be rephrased 'do we value the Acropolis more than x - y million pounds a year?' In this way, the framework of CBA has been used to guide our thinking, which is valuable in itself. Indeed the issue of cost explains why we have not already implemented a vast pollution control programme to protect such monuments.

However, general experience indicates that what people say they would do and what they will do differ widely so that the results of such enquiries need to be treated with considerable scepticism. This has recently been partially demonstrated by the introduction of admission prices to enter famous National Museums and Cathedrals such as the Victoria and Albert Museum and Ely Cathedral. Various reports (139)(140) state that since the introduction of a £2 admission fee to the Victoria and Albert Museum, attendance has dropped by 50%. Similarly, with Ely Cathedral an admission charge of £1.50 has been introduced to help with its upkeep; prior to this admission was free with an average donation of 32 pence per visitor.

7.1.3 The value of CBA

There is a tacit assumption that whilst there are difficulties in finding the right values to attach to costs, these 'right' values actually exist. However, this will not be the case and there can be considerable doubt as to whether a particular cost should or should not be included. The market values attached to the environment have no unique correctness. Each different distribution of wealth in society will give a different market equilibrium and a different set of values.(141) A further problem also arises because democratic decision is based on the principle of one man, one vote. Thus, in a referendum everyone has an equal say but with Parliamentary rule the system is likely to be biased away from the national average.

Similarly, CBA biases a decision towards the wealthier members of society compared with the referendum.(142)

Despite the validity of such criticisms, it is hard to envisage how decisions made in the absence of factual information, can be better than those made with data, albeit uncertain. The fact that some items remain unquantifiable is only of importance if one has a subjective reason to believe that they greatly exceed all other items. Here it may then not be worthwhile undertaking a CBA since the decision is necessarily subjective, although the results of the redistributional effects resulting from decisions may still be useful.

It has been argued that decisions have to be made concerning environmental quality and that it is the cost of environmental damage and its avoidance and the subsequent benefits of environmental improvement that should be analysed if such decisions are to be objective. These costs and benefits should be analysed in relation to changes in quality and it is very important that the proper constraints and framework are used.

The determination of the costs of environmental damage is far from easy even in apparently obvious cases such as damage by corrosion or soiling, and when social disutility is involved the costs are never absolute nor do they have permanence. Decisions at the end of the day will be 'political', the result of many differing pressures within society, ad hoc events and so forth. Also, attention must always be given to the changing values of society and the temporal relevance of pollution costs to the decisions in hand. Despite such inherent problems, CBA can provide a valuable input into policy formulation and into decisions on control or avoidance of damage. It can be used to test proposed changes in the environment as well as assisting in future investment in research and development. Providing the cost-benefit analyst does not try to become the decision-taker and acknowledges that there are other value systems besides those of economic efficiency, there can be no real dispute between the decision-takers, planners and analyst. For it is the task of society, through the Government, to decide what criteria it wants used to formulate decisions on environmental quality. The importance of assigning costs to environmental damage was illustrated by Sawyer and Pitz(143) who have shown that the inclusion of soiling costs would alter some of the major conclusions of the National Research Council study on the impacts of diesel-powered light-duty vehicles.(144) Results which argue against going from a 0.6 g mile^{-1} to a 0.2 g mile^{-1} particulate emission standard are reversed if soiling costs are included. If it is accepted that in general society wishes to decrease pollution and to keep it at a minimum, it is part of the duty of the cost-benefit analyst to provide objective figures to the decision-makers on the costs and benefits of environmental damage and control. In times of recession it has become evident that the economic rationale for control is not centred on traditional areas of concern such as health but on other benefits that air pollution control may bring such as decreased maintenance costs on materials and structures, etc. Although as previously stated the evaluation of such costs is not simple, it is less emotive to define and investigate than would be an investigation on the cost and incidence of human cancer in relation to air pollution effects. In the remainder of this chapter, previously used techniques adopted to assign soiling costs are reviewed and the techniques that have been used in this research are introduced and the findings given. The benefits of reducing soiling and removing its effects are explored in Chapter Eight.

7.2 Past studies on the cost of air pollution with special attention to soiling costs

7.2.1.1 Introduction

The economic loss due to air pollution is real. It can cause damage to building materials such as paint, stone, metal, etc., while the excessive shortening of the life and soiling of home furniture and clothes is familiar to those living and working in urban areas. The blighting and subsequent reduction of large sections of urban areas is well known, causing loss to the property owner and to the community through loss of taxes. Trying to assign a monetary value for such losses is difficult.

However, even estimates of direct cost belie their apparent simplicity; for example, the owners of property in polluted areas do not necessarily observe the standards of maintenance which could exist without pollution; residents in 'smoky' towns may accept lower standards of cleanliness. Thus, there is a cost of pollution which is not reflected in actual expenditure and, even if actual expenditure could be measured accurately, it would not be a true estimate. However, it is still worthwhile attempting to assess damage costs if it is accepted that the order of magnitude, not high precision, is acceptable. For, ideally, one should measure all damage costs by measuring pollution levels over the whole country (or area concerned) and applying statistical techniques. In practice, this is not often possible due to lack of data and other financial considerations.

The only comprehensive study of the costs of air pollution in the UK since the Beaver report (145) was undertaken between 1969 and 1972 by the Programme Analysis Unit (PAU)(146) which was a joint unit of the Department of Trade and Industry and the Atomic Energy Authority. Basically the concept used was to envisage a situation where the whole country could be divided simply into either 'clean' areas or 'polluted' areas, reflecting two levels of air pollution (high and low). Then, the total national expenditure on the item under study such as laundry, painting exteriors, etc. may be formulated as: the unit expenditure (i.e. per person, household) in clean areas multiplied by the number of units, plus the unit expenditure in polluted areas multiplied by the number of units. Thus:

$$(\text{total cost}) = n_c e_c + n_p e_p$$

Assuming that the higher cost in polluted areas is solely due to air pollution, this extra cost (marginal cost) to the nation resulting from the presence of areas more polluted than the 'clean' areas may be expressed as the Total Cost at two levels of pollution minus the Total Cost at the lower level of pollution.

So

$$(\text{extra Cost}) = (n_c e_c + n_p e_p) - (n_c + n_p)e_c$$

Often information on unit expenditure is not available, but information on another variable which can be expected to change in the same way and which bears a close relation to it may be available, for example, the frequency of repainting or cleaning. Likewise, the number of units affected in both areas may be unknown, but it is assumed that the ratio of the number of affected units in 'clean' as compared with polluted area is the same as the ratio of the total number of units in both areas. Thus, PAU were able to develop formulae to enable adequate damage costs to be computed. Some of these costings and those from other authors are illustrated in Sections 7.2.1.2 - 7.2.1.5.

7.2.1.2 Laundry and Household goods soiling costs

Another affected area is the frequency of laundering and household cleaning. Here the primary effect is one of soiling which leads to increased frequency of cleaning. As well as the cost of extra labour and material resulting from this, the life of material may be shortened by the extra washing, especially if carried out incorrectly. Finally, chemical degradation can take place.

In the PAU report (1972)(146) the usage of cleaning materials by families in various regions of the country was correlated with the average pollution levels (smoke) in those regions. In the Family Expenditure Survey, expenditure on cleaning materials is broken down into two parts; soap and detergents and other cleaning materials. A correlation coefficient of - 0.43 was obtained between expenditure on soaps and detergents and pollution levels, i.e. the dirtier the air the less spent on detergents, etc. The correlation coefficient for 'other cleaning' materials was - 0.69 and finally the correlation for total expenditure on cleaning materials was - 0.78. It was recognised that two factors were being ignored which could alter the figures, size of disposable incomes and family size. The analysis was repeated allowing for these factors. Negative correlations were still found, but of smaller size and only the correlation with "other cleaning materials" was significant (coefficient = - 0.68).

In order to check whether these conclusions accorded with the experience of commercial firms, an approach was made to a large soap powder manufacturer, who supplied figures showing sales of soaps of varying types in regions in the U.K. Significant coefficients of - 0.53 and 0.61 were obtained for soap powder and heavy soaps respectively.

However, there are many statistical shortcomings with such a survey as well as factors for which no allowance was made and which could distort the correlations. Differences between areas of hard and soft water can obviously affect the amount of soap needed for cleaning purposes. Social preferences between regions, for example in the use of cheap soap bars in some areas and the use of expensive biological detergents in others for carrying out the same cleaning task would also affect the amount spent per family. Nonetheless, the evidence seems to suggest that higher pollution levels are reflected in higher acceptance of pollution, which may not affect household expenditure but certainly affect regional image and perception of opportunity.

The final figures from PAU(146) give a mean value for the extra cost of labour and materials (assuming equal standards of cleanliness in clean and polluted areas) of £12.5M per annum. The extra cost of housewives' services on the same assumption would be £150M per annum. These are both largely social costs not appearing in GNP, though some small proportion in local regions will certainly be real enough.

In another study, Ridker(147) conducted comparative urban studies to determine the relation between per capita soiling costs and air pollution level for 144 cities in the US. Soiling damage costs were approximated by per capita expenditures on laundry and dry cleaning services. Ridker found that no discernible patterns between soiling costs and the suspended particulate levels were detected, whether the effects of climate, per capita income, and price differentials were controlled for or not. The problem often encountered in identifying the soiling damages, as noted by Ridker, is that cleaning and maintenance operations are often undertaken on a rigid schedule which is independent of the location of the operation. This is especially true for commercial and industrial buildings. Furthermore, non-pollution factors which could not be controlled for may be important in explaining the cleaning and maintenance procedures.

However, a study by Booz Allen and Hamilton, Inc(148) offers the needed data base for the purpose of developing the soiling physical damage functions. Sophisticated and rigorous statistical survey techniques were employed by the researchers. The Renjerdel area around Philadelphia, Pennsylvania was used as the data gathering area. Frequency of cleaning by the residents was determined by a carefully developed questionnaire, into cleaning operations and a set of self-fererent statements on cleaning attitudes. Among the 27 cleaning and maintenance operations, the study shows that 11 were somewhat sensitive to air-suspended particulate levels. Because of the lack of information for evaluating the costs, subsequent use of their data by other researchers has only used certain tasks which they originally found to be pollution sensitive. For example, Watson and Jaksch(149) used eight of the tasks identified by the Booz Allen and Hamilton study. They regressed the frequencies of performance for households conducting the tasks against socioeconomic characteristics, attitudes towards cleanliness and household pollution levels. They found that the frequency of cleaning was not significantly different across households having different socioeconomic characteristics, attitudes and pollution levels. In other words, while regional variations may exist, attitudes and activities within regions are common in the range of social groups.

According to Watson's and Jaksch's results three implications may be drawn for estimating changes in consumer welfare:

(i) households do not attempt to adjust to a dirtier environment by changing their outlays or habits, but there is a welfare loss incurred by the households exposed to a dirtier environment. This loss is the lower utility of having to live in a more polluted environment;

(ii) since cleaning frequencies do not change, it is not necessary to assign households to different classes on the basis of cleaning behaviour in order to estimate changes in consumer's welfare;

(iii) even though the regression analysis indicates no difference in behaviour, it is necessary to classify households by their initial pollution levels. As households in more polluted areas face higher unit prices for cleanliness. They stand, therefore, to gain more from a reduction of air pollution towards the levels required by Federal standards.

In their opinion other studies estimating the impacts of air pollution on household cleaning costs suffer two shortcomings. One is that none, except Ridker, corrected for attitudes towards cleanliness. Tastes for cleanliness affect behaviour. Households with meticulous tastes could clean more frequently and even react more strongly to pollution than lackadaisical households, everything else held constant. Their analysis attempts to classify households according to cleanliness tastes and uses this information in estimating cleaning frequencies and cleaning costs. A second shortcoming is that all of the existing studies have overlooked a relatively important methodological issue.

Their approach is to estimate the demand for household cleanliness and not merely the changed frequency of household cleaning as affected by pollution, the latter being the approach taken in other existing studies. For the frequency relationship is only one input into the correct specification of the household demand function for cleanliness. An important outcome of their approach is that costs can occur when pollution increases even though the frequency of cleaning and therefore total cleaning expenditure does not change so their estimates are likely to be higher than existing studies.

7.2.1.3 Window cleaning costs

In most places where people live and/or work, dirt deposited on windows has eventually to be removed. The actual process of cleaning means that some cost is incurred and this cost is increased by factors which are likely to increase the level of dirt deposited.

In the PAU report (1972)(146) window cleaning firms were contacted in order to gain an idea of how important air pollution was, in relation to frequency of window cleaning. Once again it was found that the effects of air pollution were swamped by other factors. Even though the levels of dirt deposition have fallen considerably in London, there has been no adjustment to the frequency with which windows are cleaned. From Table 7.1below it can be seen that the areas in which buildings are situated does make some difference to the frequency with which its windows are cleaned.(146) It might well be true that these three categories correspond to high, medium and low pollution, but one point still remains; the fact that these cleaning schedules have been in operation continuously for over 25 years, yet, smoke levels had at that time been falling during these years (PAU, 1972).(146)

Table 7.1 The recommended window cleaning frequencies for government buildings.(147)

LOCATION	GROUND FLOOR WINDOWS	ALL OTHER WINDOWS	ROOF LIGHTS
London Postal area and smoky industrial areas of large cities	every 3 wks	every 6 wks	every 6 mths
Semi-industrial towns	every month	every 2 mths	every 6 mths
Non-industrial towns	twice every 3 months	every 3 mths	every 12 mths

The schedule in Table 7.1 makes no distinction between different types or functions of buildings. Under the "British Council Code of Practice CP.153, Part 1, 1969"(150) the frequency with which windows are cleaned is determined not by the level of dirt in the atmosphere, but by the type of building, i.e. whether it is a shop, bank, hospital. This suggests that the determining factor in the cleaning of buildings might be the acceptable standard of cleanliness, rather than simple level of dirt deposition. Thus, dirt levels could fall, yet because people demand a higher standard of cleanliness the frequency of cleaning may not fall much, or may even increase.

Also, it can be seen from the Table 7.1 greater cleaning frequencies are recommended for ground floor as compared with upper floor windows. This may be due to the recognition of the fact that pollution affects the first few feet from ground level far more severely than above, but this is not the only factor involved. It is more likely to be that ground floor windows, especially in main streets, are generally "show windows" where dirty windows are bad publicity. Also traffic pollution is not only the cause of soiling of ground floor windows - people brushing past and touching glass shop windows, mud and dust thrown up by the traffic - all contribute in making windows dirty.

The conclusions reached on the effects of air pollution on window cleaning are not untypical of the effects of the cleaning industry generally, viz. it is the public's taste that determines the frequency with which windows are cleaned, rather than the actual level of dirt deposition; air pollution is only one of the factors that contributes to the deposits which have to be cleaned from windows. Of the total cost of cleaning windows, the removal of the deposit is a less significant part than size and nature of the glass and accessibility of the windows.

7.2.1.4 Painting Costs

The first function of paint (at least externally) is to protect the substrate. Its intrinsic cost is low in relation to the cost of surface preparation and application. The second function is to provide a decorative finish to buildings. Painting is often a relatively cheap way of introducing an interesting and pleasing appearance to buildings, emphasising planes or lines that add to the attractiveness of the design and camouflaging those features which are unsightly.

Given these purposes of painting for decoration, it can be seen that repainting is not just carried out in order to keep the paint film intact. Thus repainting is often done to freshen up the appearance when the old coating has merely lost its "face" and perhaps picked up dirt especially in a non-uniform manner, or when a major change of colour is desired.

The PAU report states paint manufacturers believe that levels of air pollution found in the UK had little effect on paint life and that one of the most common causes of premature paint film deterioration was poor surface preparation leading to breaking of the paint film and attack on the substrate.

Habit has played a large part in "freezing" repainting frequencies, and a 3-5 year cycle is regarded in many places as "standard practice" irrespective of the state of the paintwork. Financial considerations were also important; in times of credit squeeze, repainting and routine maintenance were almost always the first expenditure to be put off. This was not always a wise move, since it could mean a higher expenditure on labour later on if the surface had deteriorated significantly.

In general, the frequency of internal painting was believed to be determined by the "need for a change" and the presence of scuffing and chipping produced by personal contact. Changes in fashion and personal taste were also important factors.

The PAU survey failed to detect any difference in frequency of repainting which could reasonably be ascribed to differences in levels of air pollution. If soiling had been a significant factor, this could have been concealed by a greater frequency of washing down. The real national cost is therefore believed to be very small. However, accepting that air pollution does have a damaging effect on paint at least as far as exteriors are concerned, the results could be explained in one or both of two ways:

(a) any effect due to differences in levels of air pollution is small and completely swamped by other more decisive factors such as surface preparation, sunlight or financial situation;

(b) standards of upkeep of paintwork are lower in the more polluted areas, and so the repainting which would have been done had the higher standards in the less polluted areas been applied, was delayed.

It is possible and even likely that both influences were at work. The extra national cost which would be incurred if "polluted" areas adopted the same standards of repainting as "clean" areas is £6.3M p.a. This is primarily a social cost, though some real costs may be covered by the estimate.

Beaver(145) reported that evidence from local authorities suggested that houses in "polluted" areas required painting almost twice as frequently as those in "clean" areas. This was confirmed by evidence from firms owning multiple stores. Beaver(145) used the assumption that 50% of the buildings are in "polluted" areas and that the standards of appearance were everywhere equal to those maintained in the "clean" areas. From this he estimated that the additional national cost of painting amounted to some £30M p.a. Clearly this figure includes both economic and social costs. If PAU estimates are recalculated using Beaver's figures for total paint consumption and proportion of buildings in "polluted" areas, the national cost is about £17M p.a. Then taking into account that the annual average concentrations of smoke in 1972 had decreased by half since 1954, agreement between the two estimates is good, even when allowing for the rate of inflation.

The studies of Michelson and Tourin (1966)(151) in the USA appear to give very high values for the excessive costs incurred in external maintenance of houses. Their study of Steubenville and Uniontown Ohio gave a figure equivalent to expenditure in excess of \$65 per household for a 180 $\mu g\ m^{-3}$ change in mean particulate level. However, the pollution levels experienced in the UK are much lower, the labour costs are 50% down and the majority of US properties covered were of clap-board finish which must involve two to five times as much maintenance as the average UK residence. These factors would reduce the household cost to an equivalent of about 50p per residence in the UK for a change from conurbation to non-conurbation conditions or roughly £5M - £15M p.a. which is of the same order of magnitude as reported in the PAU study.

The methodology of Michelson and Tourin (1966)(151) is based on the hypothesis that significant soiling due to air pollution may be reflected in shortened time intervals between successive cleaning and maintenance operations. Their studies in the Upper Ohio River Valley and Washington D.C. established a positive relationship between frequency of cleaning operations and the levels of air pollution in both studies. However, the problems with the sample survey design and the lack of a statistically reliable technique cast doubt on the reliability of their findings. Thus, examples of their data as plotted out in Figure 7.2 of the relationship between soiling costs and TSP levels in the atmosphere must be viewed with caution.

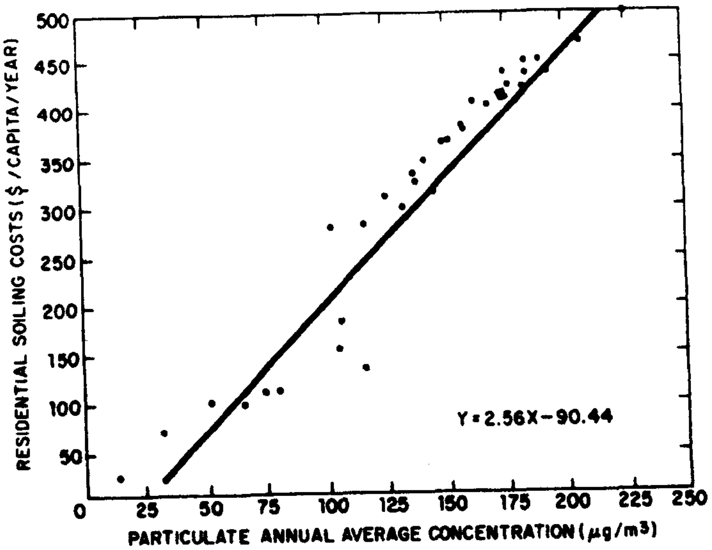


Figure 7.2 Annual average particulate concentration versus residential soiling costs.(151)

7.2.1.5 Building soiling costs

Apart from soiling by smoke, stone can be chemically attacked by acidic gases such as sulphur dioxide. No one would suggest that air pollution is the only factor which causes the degradation of building materials, but it certainly accelerates the process. At the same time, buildings are cleaned in places where there is very little air pollution to remove moss, bird droppings, etc., but it appears that the level of air pollution is the most significant factor in the deposition of dirt on to buildings and hence should be the most important element in the cost of cleaning buildings.

It is a striking fact that in recent years there has been a sharp increase in the number of buildings cleaned. The PAU report noted that the amount spent on the cleaning of buildings has increased almost exponentially since the mid-1950s. They noted while London and the South East did most of the cleaning, it was not alone in the fashion for clean buildings. Many buildings in Midland and Northern cities had also been cleaned; whilst the Clearing Banks have cleaned some of their provincial premises more than once in the last fifteen years.(146)

In the PAU report, information was provided by a leading stone-cleaning firm on their turnover and estimate of market share. From this PAU estimated that the total market in the cleaning of buildings could be greater than £1.5M per annum in 1972. However, this is a small fraction of what expenditure would be if we reached the state of equilibrium on exterior cleaning of buildings. If this were the case, PAU suggests the national expenditure would be in the order of £10M to £20M per annum.

Stone cleaning firms say that to maintain a reasonable and consistent standard of cleanliness the identical building would probably have to be cleaned every seven years in a dirty atmosphere and every ten years in a clean atmosphere. PAU suggests that the mean extra national cost which would be incurred if "polluted" areas adopted the same standards of cleaning building exteriors as "clean" areas is £1.5M per annum. This was then thought to be more a social than an economic cost since it assumes uniform standards of cleaning throughout the country.

Since the 1972 PAU report, only two other studies apart from this, have attempted to estimate the cost of soiling for a given area. In 1986, a TNO report(51) estimated that the total cost of soiling in the Netherlands is about £250 million per annum. Also, Sawyer and Pitz(143) have produced the only known estimate to date of the order of costs which could be attributable to soiling by diesel emissions. They have estimated the costs for California which would result from a dieselisation of 20% of light duty vehicles. Depending on the assumed cost of baseline particulate soiling and the relative soiling parameter for diesel particulate chosen (used a soiling index of 5), the costs fall in the range of $220M to $2,700M annually with a best estimate of the annual welfare loss of $800M. These figures relate to the cost to California domestic households. Costs associated with the soiling of public and commercial buildings are not included.

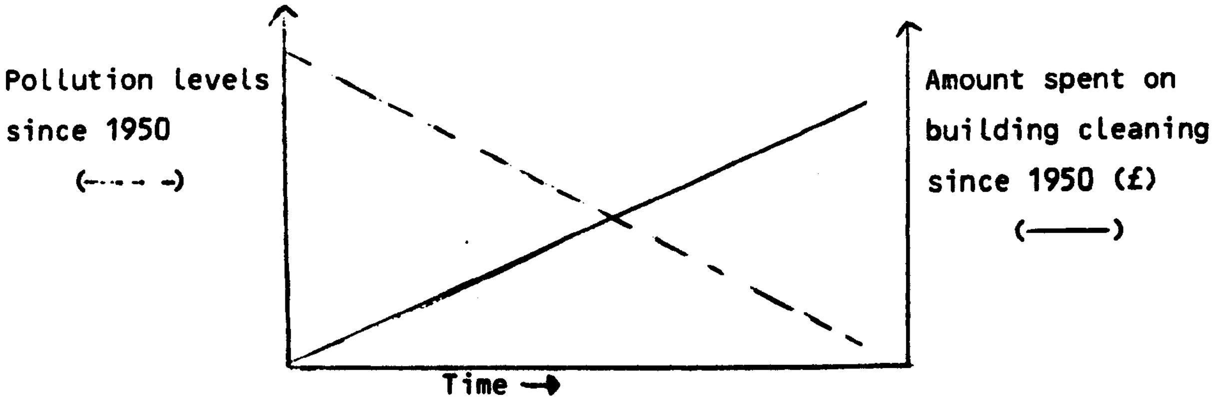
Thus, although there are numerous estimates of the total national costs of air pollution, very little work has been done on the costs of building soiling. For example, one of the first studies carried out on the partial cost of smoke nuisance to the residents of Pittsburgh in 1913(152) quotes the various areas of costs as illustrated in Table 7.2.

Table 7.2 The itemised bill of partial cost of the smoke nuisance to the people of Pittsburgh (1913)(152)

1.	Cost to the Smoke Maker	
	a) Imperfect Combustion	$ 1,520,740
2.	Cost to the Individual	
	a) Laundry Bills	1,500,000
	b) Dry Cleaning Bills	750,000
3.	Cost to the Household	
	a) Exterior Painting	330,000
	b) Sheet Metal Work	1,008,000
	c) Cleaning and Renewing Wallpaper	550,000
	d) Cleaning and Renewing Lace Curtains	360,000
	e) Artificial Lighting	84,000
4.	Cost to Wholesale and Retail Stores	
	a) Merchandise	1,650,000
	b) Extra Precautions	450,000
	c) Cleaning	750,000
	d) Artificial Lighting	650,000
	e) Department Stores	175,000
5.	Cost to Quasi-Public Buildings	
	a) Office Buildings	90,000
	b) Hotels	20,000
	c) Hospitals	55,000
	Total:	$9,944,740

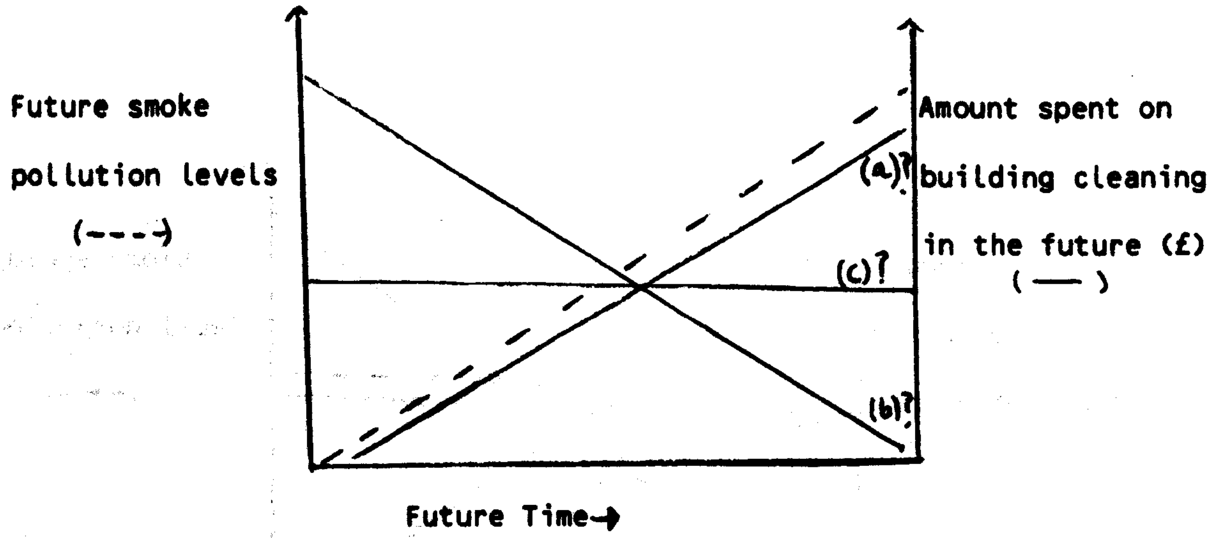
It may be that building soiling has been previously considered as a disposable part of the urban environment and that black smoke and soiled buildings were regarded as a sign of prosperity. Thus, building soiling was not considered as a nuisance though interior soiling was noticed and regarded as a disamenity and thus complaints were more noted about interior rather than exterior building soiling. Similarly the cost of corrosion on metal work was recorded, presumably because once corrosion had occurred the metal work would have to be replaced to resume its function, unlike buildings which, despite being soiled, could still be used without any immediate expenditure occurring. Now, it is often felt that regular inspection and maintenance of the building fabric is cheaper and may help to prolong the longevity of the fabric. Indeed public attitudes towards cleaning and pollution are an important factor to be considered. People may not have bothered to clean buildings in earlier times when smoke levels were greater than they are now, because they felt re-soiling would occur too quickly and that they would not be getting value for money. For example, Parker (1955)(153) quotes that buildings in Pall Mall were painted cream in colour and that even before the paint was dry the surfaces had collected numerous black specks and that within two years such buildings had lost their 'exterior freshness' and were distinctly soiled. However, today there is every reason to believe that as time progresses this trend towards cleaner buildings will continue. People's tastes are changing and it is unlikely that they will ever again tolerate dirty buildings. If a graph is plotted showing levels of pollution - especially smoke and expenditure on cleaning buildings, it is found that as air pollution has fallen, expenditure on the cleaning of buildings has risen. Whilst soiling was rapid in the periods of heavy smoke pollution, cleaning was a pointless activity. Clearly buildings now stay clean long enough for owners to think the expense (and accrued benefits) worthwhile. Once the accumulations of historical dirt have been removed and the fashion established it would be expected that assuming further drops in pollution levels occur, cleaning frequencies will, in the long term, also decrease. This tendency will, of course, be influenced by the extent to which standards of cleanliness change. Indeed in any research involved with future trends, one must take into account changing social attituds so that decisions are based on the standards that will be applicable when the results of such decisions are realised. Such factors are illustrated hypothetically in Figures 7.3 - 7.5. Figure 7.3, simply represents the situation which has occurred since the 1950s, the level of smoke in the UK has decreased since this time, yet, the expenditure on building cleaning has increased. Figure 7.4 illustrates three hypothetical trends which may occur on the frequency of building cleaning if the level of smoke in the UK rose in the future above its present level. Figure 7.5. illustrates three hypothetical trends which may occur in the future to the rate of building cleaning if the level of smoke in the UK remained at its present level. It is assumed in Figures 7.4 and 7.5. that the future economic climate is the same as currently experienced.

Figure 7.3: A hypothetical situation showing the relationship between smoke level and the amount spent on building cleaning with time



Air pollution has fallen yet the amount spent on building cleaning has increased.

Figure 7.4 A hypothetical situation showing three possible relationships between an increase in smoke levels and the amount spent on building cleaning in the future.*1



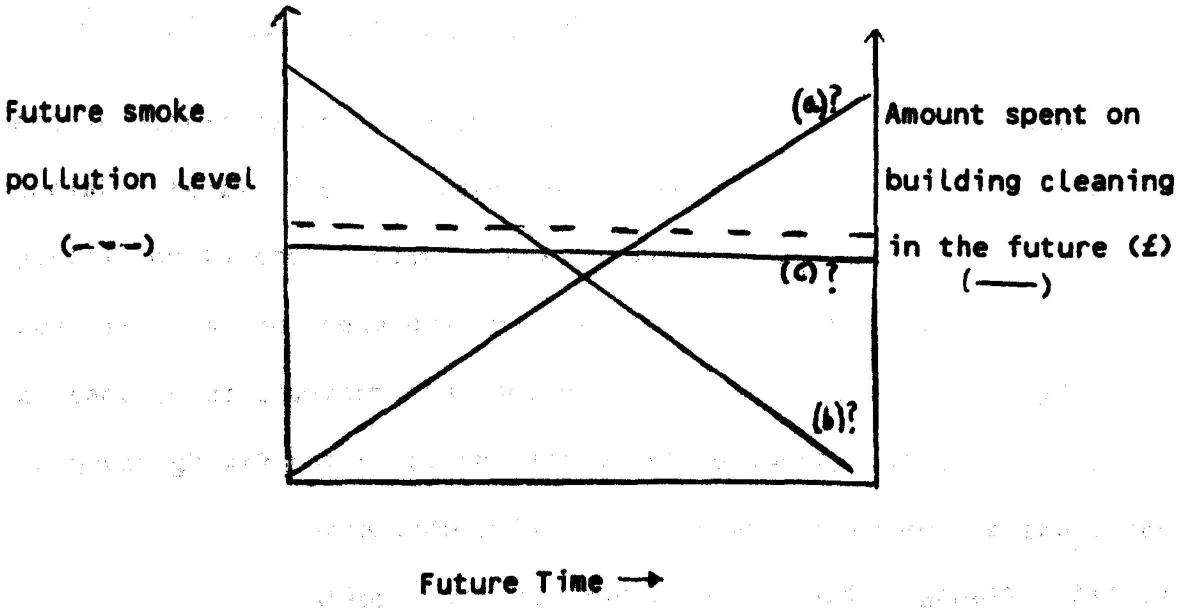
*1 If smoke pollution levels increased in the future, would the money spent on cleaning:

(a) increase as people's tolerance of soiled buildings is now lower than previously observed?

(b) decrease as people do not consider that buildings are staying clean long enough to justify such an expenditure?

(c) stay at current level as decisions for building cleaning etc. is done on a regular pre-set repeated cycle and thus is unaffected by pollution levels.

Figure 7.5 <u>A hypothetical situation showing two possible trends in the relationship between future smoke levels and expenditure on building cleaning in the future.</u>*2



*2 if pollution level stays the same in the future, will expenditure on cleaning:

(a) increase as standards of 'cleanliness' for buildings further increase?

(b) decrease as the need for cleaning remains the same and standards for 'cleanliness' are laxed and the law of diminishing returns is reached

(c) stays constant.

The current and future trends on the amount spent on stone cleaning per annum within the United Kingdom as identified from this research is given in Section 7.4 and represents the only available figures which have attempted to assign an estimate of such costs since the PAU report in 1972. Initially, it had been intended to estimate the public attitude towards soiling and the cleaning of buildings. However, as will be illustrated in Section 7.3 obtaining such estimates is very difficult and the results may be dubious. So the costs reported in Section 7.4 represent the direct cost of stone building soiling alone. Some of the social costs of air pollution are, however, illustrated in the following Section 7.2.2.

7.2.2. The social costs of air pollution

Another category of elements involved in any study of the economic and social effects of particulate matter in the atmosphere are those pertaining to social costs, some of which it may be possible to quantify. Among these are the questions of aesthetics, individual perception of environmental deterioration and the influence of pollution on urban growth patterns, on real estate property values and the type and location of recreation activities. Also, included are the effects on social organisation, such as independent suburban growth. All of these elements tend to be less easily identified and evaluated than direct economic costs.

The interesting problem of general utility loss due to local variations in the environment has frequently been examined by studying the variation of property values. Air pollution studies of this type have been mounted by Ridker(147) who studied property values as a function of SO_2 levels in St Louis and also the effect of the introduction of a new source of pollution on property values in an affected area compared with unaffected controls. In the PAU study (146) estate agents were asked their views on factors affecting property values. Only 10% of respondents mentioned pollution and all these rated it lowly in comparison with other factors affecting property value. The impact of smoke control regulations on the price of properties was considered to be small with roughly a 1% average enhancement of value in heavily polluted areas compared with half this in relatively clean areas. The lag between the introduction of improved environment and equilibration of property values was found to be approximately 2 years. These figures, crude though they were, were closely in line with those derived by Ridker when all were normalised to a roughly comparable basis.

A third general category of social costs which under most circumstances do not have a direct quantitative economic cost, but which might very well have a significant influence nonetheless; for example, the effect of visibility, not only upon human activities, but upon perception and philosophical outlook and the overall psychological impact of a deteriorating environment on a community. These elements are even more difficult to identify and relate than those listed above, but nevertheless may be equally significant in the long run.

7.3 The link between particulate matter pollution and public concern

7.3.1 Previous studies on public attitudes and concern on environmental problems.

Various American studies have indicated a relationship between particulate pollution levels (used as an index of air pollution), and the extent of public concern over the problem. A 1963 study conducted in the St Louis metropolitan region found a direct linear relationship between the proportion of the community's population which stated that air pollution was a nuisance and the annual mean concentration of particulate air pollution within that area (154) The relationship which was formed from data within the St Louis area, whose annual concentration ranged from 50 to 200 $\mu g\ m^{-3}$ was derived as:

$$y = 0.3\ x - 14$$

where y = population fraction (%) concerned.

x = annual geometric mean particle concentration ($\mu g\ m^{-3}$)

It is considered that the reaction to suspended particulates as a nuisance probably occurs at peak concentrations and not necessarily at the levels representing the annual means. Such a relationship can provide a useful guide of how the nuisance effect of air pollution relates to concentration. For example, nearly 10% of the study population considered air pollution a nuisance in areas where the annual geometric suspended particulate level was 80 $\mu g\ m^{-3}$. At this level of pollution, 30% of the study population was 'aware of' air pollution. In areas where the geometric annual mean was 120 $\mu g\ m^{-3}$, 20% were 'bothered by' and 50% were 'aware of' air pollution. Likewise where the level was 160 $\mu g\ m^{-3}$, 33% were 'bothered by' and 75% were 'aware of' air pollution.(152)

Although data from other studies do not readily lend themselves to quantitative formulation, they generally do support the relationship reported by the St Louis study. (154) For example, in 1972 a survey was carried out on behalf of the Department of Transport for the whole of England which aimed to assess the attitudes of the general public to road traffic nuisance.(155) The survey found nine disturbances caused by traffic, as given in Table 7.3.

Table 7.3 <u>The main categories of traffic induced disturbance.</u>(155)

Pedestrian/vehicle conflict
Parking outside the home
Vibration
Noise as experienced at home
Noise as experienced when out
Dust and dirt in the home
Fumes as experienced at home
Fumes as experienced when out
Visual intrusion

Nearly half of the 5,686 households interviewed stated that 'things get dirty very quickly here, for example, window ledges or curtains or bookshelves, or washing on the line'. However, not all interviewed could attribute the dirt to the traffic and when asked to consider only the dirt caused by traffic, 36% said they were bothered about it and 7% very much. Figure 7.6 shows the relationship between annoyance with respect to dirt and dust and fumes in the home as a function of peak hour traffic flow outside the home. Unfortunately, the origin and nature of the deposited matter was not elucidated from the survey.

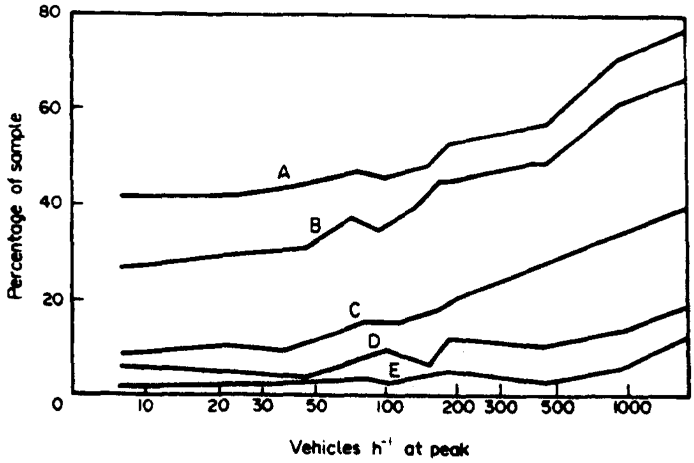


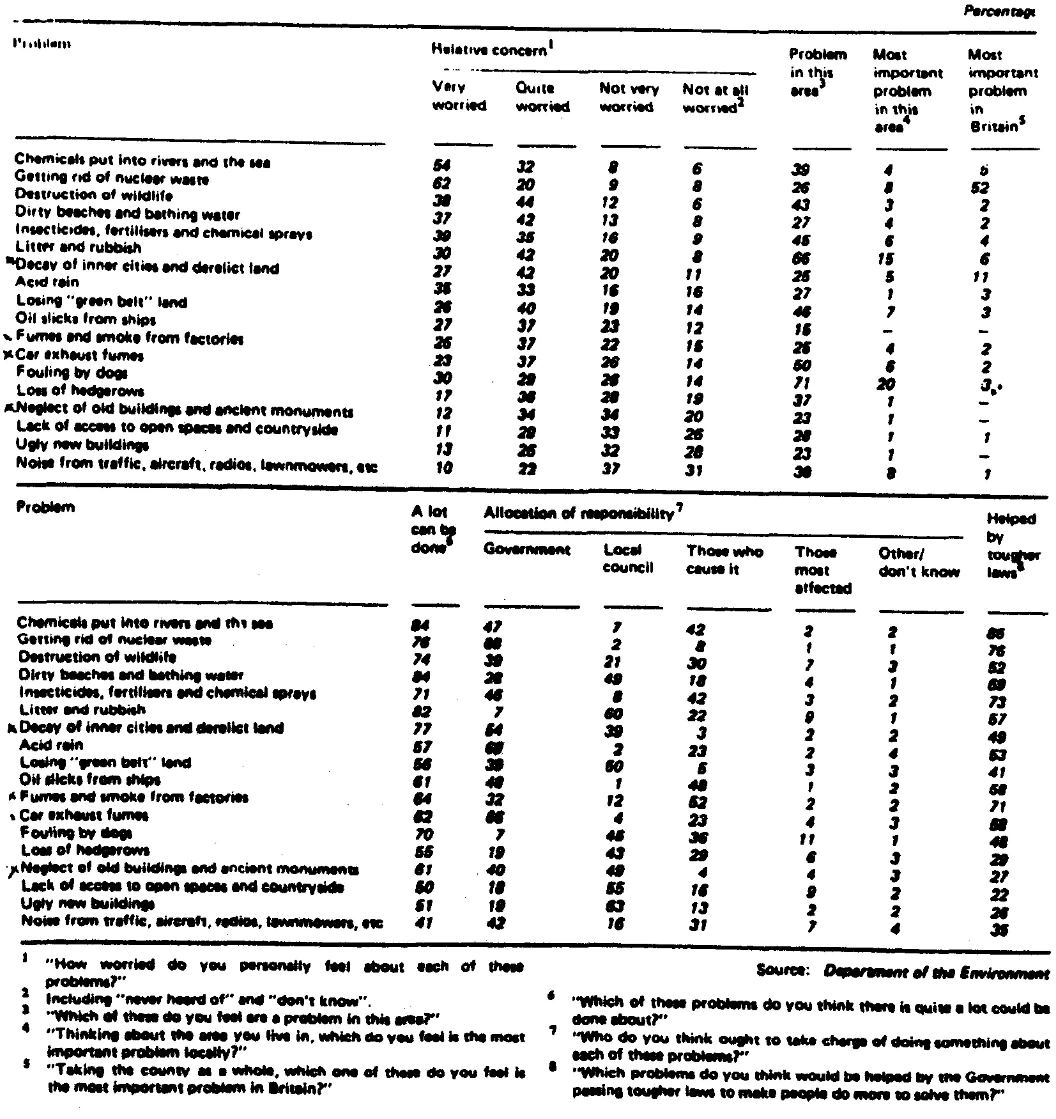
Figure 7.6. The relationship between public disturbance due to dust and dirt or fumes in the home and peak hour traffic flow outside the home. A - finds things get dirty quickly; B - disturbed by dust and dirt; C - seriously disturbed by dust and dirt; D - notice fumes; E - seriously disturbed by fumes.

However, circumstantial evidence from the survey such as the soiling of curtains, etc. implies that they have been blackened by a carbonaceous deposit rather than a lighter siliceous deposit and thus vehicular exhaust smoke rather than road dust deposits may be more responsible in soiling certain household items than the latter. Other public-opinion surveys considering the environmental impact of traffic find public concern concentrated on perceived health effects and soiling and that legislation on the smoke emission limits for diesel engines was based on the fact that it was the visibility of such emissions that caused public annoyance.(12) Clearly, there is a discrepancy here in that the legislation appears not to reflect present public concern over the environmental impact of traffic.

Indeed, in recent years the level of public concern over environmental issues has increasingly emerged. In 1986, the Department of the

Environment commissioned a survey to investigate public attitudes towards a number of environmental problems.(156) When asked to say what they considered the most important problems facing the country today, over 8% of the public included environmental problems among the most important problems the Government should be dealing with. The survey also focussed on public attitudes to eighteen environmental problems and asked the respondents how concerned they were about each of them, the allocation of responsibility for solving such problems, the public's willingness to pay for environmental improvements, etc. Some of these results are illustrated in Table 7.4 and Figure 7.7.

Table 7.4 Attitudes towards environmental problems in England and Wales (1986)(156)



Percentage

Problem	Relative concern[1]				Problem in this area[3]	Most important problem in this area[4]	Most important problem in Britain[5]
	Very worried	Quite worried	Not very worried	Not at all worried[2]			
Chemicals put into rivers and the sea	54	32	8	6	39	4	5
Getting rid of nuclear waste	62	20	9	8	26	8	52
Destruction of wildlife	38	44	12	6	43	3	2
Dirty beaches and bathing water	37	42	13	8	27	4	2
Insecticides, fertilisers and chemical sprays	39	35	16	9	45	6	4
Litter and rubbish	30	42	20	8	66	15	6
Decay of inner cities and derelict land	27	42	20	11	26	5	11
Acid rain	35	33	16	16	27	1	3
Losing "green belt" land	26	40	19	14	46	7	3
Oil slicks from ships	27	37	23	12	16	–	–
Fumes and smoke from factories	26	37	22	15	25	4	2
Car exhaust fumes	23	37	26	14	50	6	2
Fouling by dogs	30	29	26	14	71	20	3
Loss of hedgerows	17	36	28	19	37	1	–
Neglect of old buildings and ancient monuments	12	34	34	20	23	1	–
Lack of access to open spaces and countryside	11	29	33	26	28	1	1
Ugly new buildings	13	26	32	28	23	1	–
Noise from traffic, aircraft, radios, lawnmowers, etc	10	22	37	31	38	8	1

Problem	A lot can be done[6]	Allocation of responsibility[7]					Helped by tougher laws[8]
		Government	Local council	Those who cause it	Those most affected	Other/ don't know	
Chemicals put into rivers and the sea	84	47	7	42	2	2	86
Getting rid of nuclear waste	76	88	2	8	1	1	76
Destruction of wildlife	74	39	21	30	7	3	52
Dirty beaches and bathing water	84	28	49	18	4	1	69
Insecticides, fertilisers and chemical sprays	71	46	8	42	3	2	73
Litter and rubbish	82	7	60	22	9	1	57
Decay of inner cities and derelict land	77	54	39	3	2	2	49
Acid rain	57	69	2	23	2	4	63
Losing "green belt" land	56	39	60	5	3	3	41
Oil slicks from ships	61	48	1	48	1	2	58
Fumes and smoke from factories	64	32	12	52	2	2	71
Car exhaust fumes	62	66	4	23	4	3	88
Fouling by dogs	70	7	46	36	11	1	48
Loss of hedgerows	55	19	43	29	6	3	29
Neglect of old buildings and ancient monuments	61	40	49	4	4	3	27
Lack of access to open spaces and countryside	60	18	55	16	9	2	22
Ugly new buildings	51	19	63	13	2	2	26
Noise from traffic, aircraft, radios, lawnmowers, etc	41	42	16	31	7	4	35

Source: *Department of the Environment*

[1] "How worried do you personally feel about each of these problems?"

[2] Including "never heard of" and "don't know".

[3] "Which of these do you feel are a problem in this area?"

[4] "Thinking about the area you live in, which do you feel is the most important problem locally?"

[5] "Taking the county as a whole, which one of these do you feel is the most important problem in Britain?"

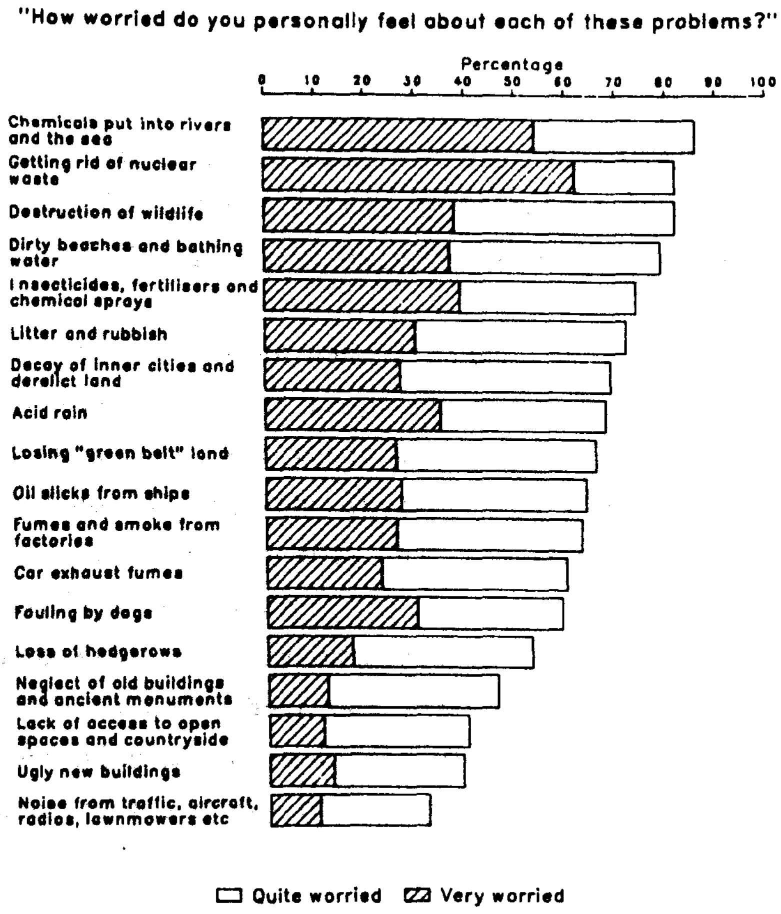
[6] "Which of these problems do you think there is quite a lot could be done about?"

[7] "Who do you think ought to take charge of doing something about each of these problems?"

[8] "Which problems do you think would be helped by the Government passing tougher laws to make people do more to solve them?"

Some of these results, which may be applicable to building soiling, its sources and effects, have been highlighted in the above table. With respect to inner city decay and derelict land, it was somewhat surprisingly seen as the second most important problem in Britain after getting rid of nuclear waste. Although the causes and remedies of it were not further probed, the soiling of buildings may be an important contributing factor in adding to the appearance and psychological effect of the decay within a city. The benefits of cleaning buildings is further elucidated in Chapter Eight and the public's view on the allocation of responsibility given in Table 7.7 for certain environmental problems is further examined.

Figure 7.7 Relative concern about different environmental problems. (156)



7.3.2 A pilot study of public attitudes towards building soiling

As mentioned in 7.2.1.5 a study was carried out within the confines of this research to assess public attitudes on building soiling and cleaning. An initial pilot survey was carried out in this research on thirty members of the British public and twenty foreign tourists visiting the country over the summer of 1986. The approach used here was to seek the response from thirty attitude statements which were read to the respondents and who were then asked to choose a response which best reflected their answer to the statement from the range of strongly disagree, disagree, agree, strongly agree or don't know. No mention was made as to the reason why the research was being carried out and thus any bias on the connection between air pollution and other possible sources of soiling was not introduced.

Examples of some of the attitude statements used in this pilot survey are illustrated below in Table 7.5.

Table 7.5 Examples of some of the attitude statements used in a pilot survey to examine public attitudes on building soiling and cleaning.

Old buildings look better when cleaned
Clean buildings show that people have pride in the place
Buildings should reflect their age
Dirty buildings destroy the character of the area
Too many dirty buildings show that the country is going downhill
Clean buildings are false
Building owners have a responsibility to keep buildings clean
Dirty buildings have their own character
I would not mind paying a little to help with cleaning costs
A poor country has dirty buildings.

From the results of this pilot survey, it seemed apparent that the wording of such statements may not have been entirely appropriate for examining public attitudes. Whilst interviewing members of the public, it was perceived by the interviewer that the public were somewhat sceptical of the statements being read and perhaps wondering if it was investigating their own personal standards of hygiene and cleanliness. Thus, for example, the responses to the first two questions in Table 7.5 prompted a virtually 100% strongly agree reply! Interestingly enough, when asked whether they 'would not mind paying a little to help with cleaning costs', the response time rate was a lot slower than was observed with the former two questions mentioned. Again, reiterating the point made in Section 7.1.2, that despite feeling strongly towards an environmental issue, personal(voluntary) payment towards alleviating it may not be as strong.

Analysis of the tourists' responses did slightly vary according to nationality. For example most Europeans, especially Germans, felt strongly that 'too many dirty buildings were a sign that the country was going downhill' and that 'clean buildings show that people have pride in the place'. Many later noted that more buildings had been cleaned in London since their previous visit (on average four years) and that also it was a sign of an economic recovery from the recession. With respect to the American tourists, their reaction to building cleaning in general was more that 'buildings should reflect their age' for their expected impressions of London's buildings were based on Dickens and Sherlock Holmes novels, and thus some were quite disappointed that there were not too many dirt encrusted buildings about! Indeed, one such tourist remarked he had initially missed a few famous buildings in London thinking they were comparatively new and therefore not of interest to him. (only later did he realise they had been cleaned and thus merited being photographed!)

As a result of this survey it was felt that assessing public attitudes on soiling and building cleaning was problematic and should properly be the focus of a research programme in its own right. Consequently the research then focussed on obtaining the direct stone soiling costs for the United Kingdom by two routes. One method (described in the following section) aimed at assessing the value of the UK stone cleaning market. The second route was to identify the customers of stone cleaning companies and assess how much was spent annually on stone cleaning between these various factions. These results are given in Chapter 8.

7.4 The characteristics and value of the stone cleaning industry in the United Kingdom in 1986/87.

7.4.1 Introduction

As is shown in Appendix D, a questionnaire was designed in this project which sought to explore:

(i) the principal customers of the industry and the motivation for building cleaning; (Questions 1-6)

(ii) the cost of cleaning by various methods, the recommended cleaning frequency for a given variety of urban locations and the factors responsible for any noted difference in frequency; (Questions 7-11)

(iii) the major areas of the country where cleaning occurs, the amount of the market share held by companies and their turnover for 1986/87, with estimates of the value of the annual stone cleaning market. (Questions 12-17).

The questionnaire and covering letter was initially sent to the 85 companies which were members of the Stone Federation (part of the Builders Employment Confederation) which advertised a stone cleaning service.(157) Some 18% of these returned the questionnaire stating that the amount of stone cleaning work they undertook was negligible or that they sub-contracted their stone cleaning. In all a 37% postal response was achieved from the Stone Federation members. However, many of the responses stated that there were a large number of non-Federation members (which they called 'cowboys') which did stone cleaning. Indeed, a further 450 companies were identified by checking all the Yellow Pages directories for the United Kingdom under stone cleaning services. The questionnaire was then subsequently sent to all these companies. In all an 11% postal response rate was achieved from these companies. However, the results and trends from both the registered and unregistered companies were virtually identical. Thus, the results given below represent the merged findings from the survey.

7.4.2 The Industry's Clientele

By far the majority of the respondents stated that more than 60% of their work came from the private sector; a commonly quoted ratio was 80:20 private to public sector distribution. However, it was noticeable that more companies serving Scotland and the North of England quoted the public sector as their most frequent customer.

The categories and proportion of customers served within the private and public sectors respectively as shown in Figure 7.8 and 7.9. Some examples of the type of customers served by the stone cleaning industry are presented in Figure 7.10 (a)-(d).

Figure 7.8 The categories and proportion of customers served within the private sector. *Companies in Scotland and the North of England generally stated a greater proportion of domestic housing share than is represented by the mean response of replies.

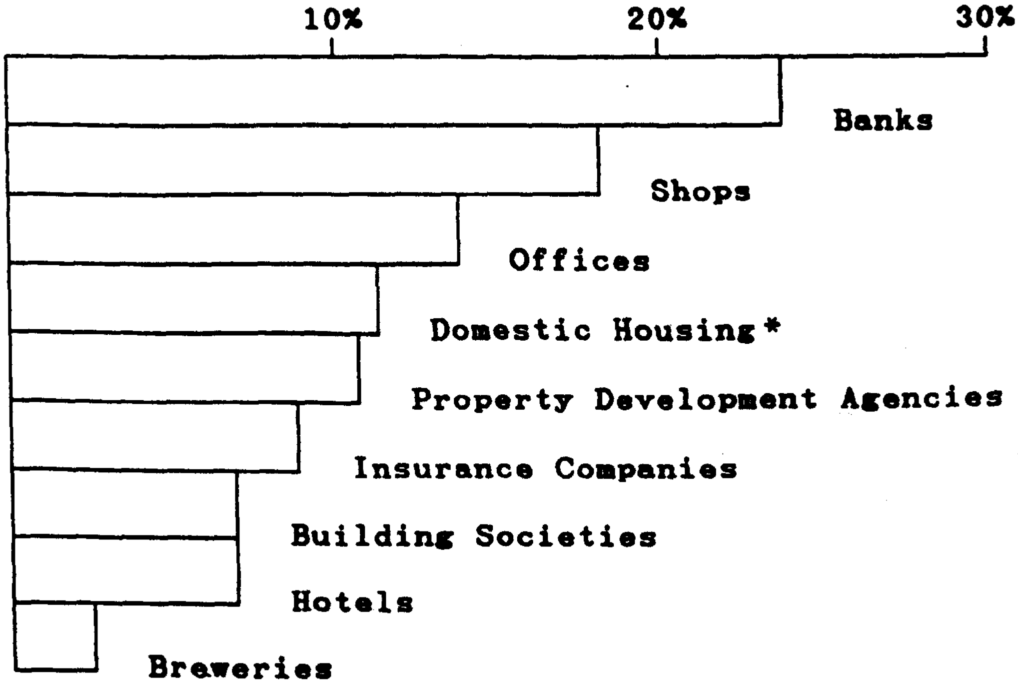


Figure 7.9 The categories and proportions of customers within the public sector.

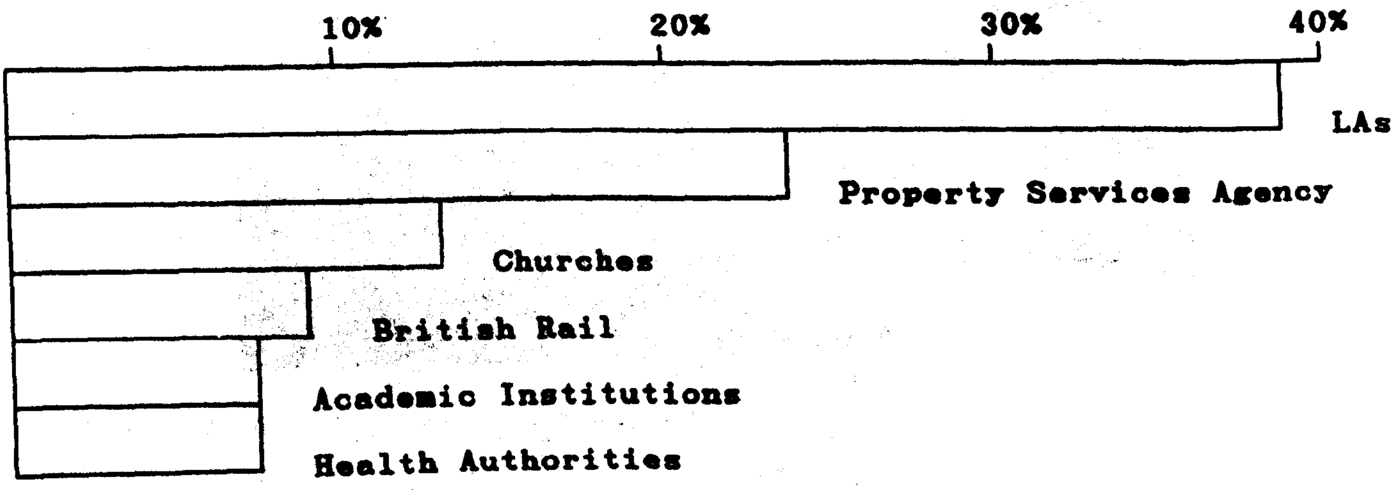


Figure 7.10 (a)-(d) Examples of the customers served by the stone cleaning industry

Figure 7.10(a) The Britannia Adelphi Hotel in Liverpool after cleaning

Figure 7.10(b) The Prince of Wales Theatre in London during cleaning

Figure 7.10(c) A shopping pedestrianised zone in the centre of Liverpool, which serves as a good visual example of before and after cleaning

Figure 7.10(d) Nelson's Column in Trafalgar Square, London in the process of being cleaned to remove all sources of deposited matter on it

7.4.3 Reasons for cleaning

The principal reasons for having a building cleaned according to Stone Cleaning Companies were as follows:

29%	to protect the building fabric
20%	to improve appearance
19%	to increase property value
11%	to enable a detailed structural survey to be undertaken
8%	to increase trade
2%	to improve 'social' environment
2%	to deter vandalism and grafitti

According to the replies from a majority of the cleaning companies there is little difference in the motivation for cleaning buildings between the public and private sectors, although the response to a further question suggested one variant - 68% of the private sector choose to have only the front of the building cleaned against 44% of the public sector. This discrepancy seems to indicate a desire on the part of the private sector to keep up appearances, with the public sector more concerned with the fabric of the building.

Property owners may decide to clean only the front facade for either economic or aesthetic reasons, but some authorities also identified the front of the buildings as being most soiled - a fact which offers some circumstantial evidence for the vehicular source of the soiling problem.

7.4.4 Cleaning prices, cleaning frequency and future trends

Cleaning companies were asked to quote a per m^2 price to clean a stone facade using a range of methods. The costs, exclusive of scaffolding, are shown in Table 7.6.

When asked to price the cleaning of a 550 m^2 c.1850s Portland stone building,20 m in height and with a simple facade, prices quoted ranged from £900 - £11,000 (excluding scaffolding). However, over 50% of the quotes fell between £1500 and £2000. This appears to indicate a competitive market, a fact borne out by the majority of replies, which fell close to the typical prices given in Table 7.6.

Table 7.6 <u>The range in prices for different stone cleaning techniques (1987).</u>

Method	Range of prices m^2	Typical cost m^2
Water clean	£1 - 20	£2 - 3
Degresses & water clean	£2 - 12	£3 - 4
Dry abrasive	£2 - 14	£5 - 6
Wet abrasive	£2 - 20	£6 - 7
Use of sealant after cleaning	£1 - 4	£2 - 3

In answer to a question on the frequency of cleaning recommended for a Portland stone building in a major city, over 46% of replies gave a time varying from 5-10 years. For buildings in a town the time span was 10-15 years and for country locations it jumped to every 60 years. Such a wide variation between urban and rural environments suggests a main source of building soiling is traffic pollution a reason quoted by 42% of companies in answer to this question. Industrial emissions were given by another 17% as important contributory factors, whilst 23% mentioned grit and dirt 'dustfall'.

Over 75% of respondents predicted an increase in trade for the future, especially from the domestic housing sector. Many felt also that the 'sandblasting mania in the North of England' was in decline - partly because of its dangers in unskilled hands to both buildings and health.

In its place there appears to be an increase in chemical cleaning methods. (Perhaps no less of a danger in unskilled hands).

Not surprisingly, many companies, especially a high proportion of Stone Federation members, voiced concern over the growth of the so-called 'cowboy' element within the market. They are blamed for bringing discredit on the work of reputable companies as well as doing irrevocable damage to many buildings.

Overall, the sector appears to be very busy, but there is continuing competitive tendering, and over 72% of the companies responding to the survey see price increases being restricted to the annual inflation rate, or even less, during the next five years.

7.4.5 The value of the stone cleaning market for the UK in 1986/87

Only 21% of respondents attempted to assess the annual value of the UK cleaning market putting it between £5M-£100M. Not all companies were prepared to give their annual turnover, and others were not able to estimate it for stone cleaning activities alone where these were only a small part - less than 15% - of their turnover, stone cleaning frequently being undertaken as a part of a major rehabilitation or restoration project.

However, on the data available through the survey, it was possible to calculate an average turnover figure of £135,000 for each of the 535 companies operating in the UK, giving a total annual market value of £74 million. Total company turnover would of course be much higher as this figure represents only that portion of business attributable to stone cleaning. On this basis the stone cleaning market has increased rapidly since 1973 when it was valued at less than £2m a year by the Programme Analysis Unit.

The market for stone cleaning is not evenly spread throughout the country but appears to be most active in London (60% of the companies work in this area). However, cities such as Liverpool, Manchester, Bristol, Sheffield, Glasgow and Edinburgh were also frequently mentioned. Figure 7.11 gives the distribution of the companies identified who undertake stone cleaning according to county borders in 1987. It is interesting to note that in general stone cleaning companies are most densely located in :

(i) areas where there are many companies' headquarters, for example, London;

(ii) areas which are famous for their architectural heritage and thus tourism, such as Bath in Avon, York in Yorkshire and Edinburgh;

(iii) areas where there has been concern about inner city regeneration and various governmental and council attempts to alleviate such problems, for example, Liverpool, Manchester and Glasgow. This newly emerging area of business for stone cleaning companies is more fully illustrated in the following sections of Chapter Eight.

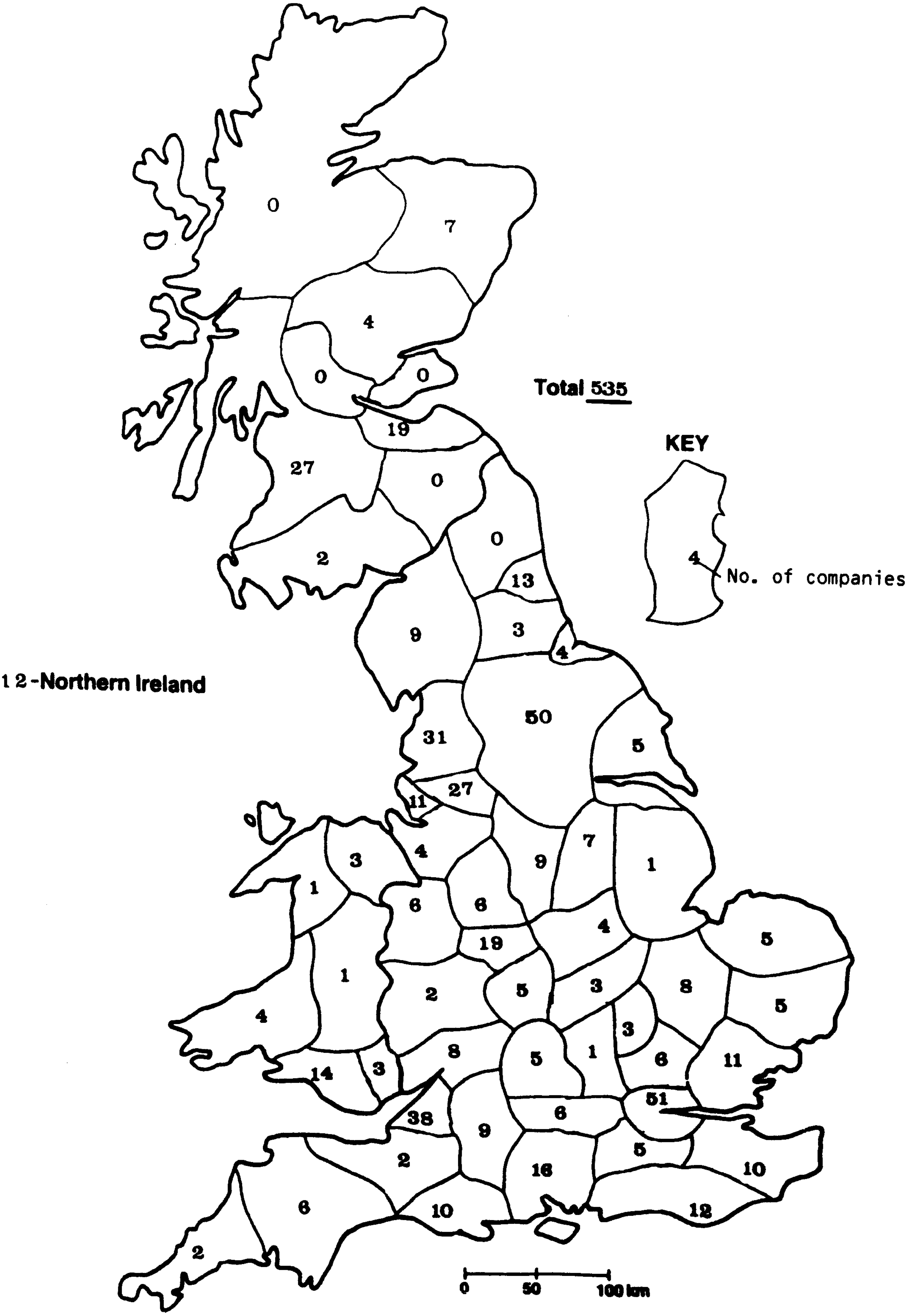


Figure 7.11. The distribution of companies undertaking stone cleaning according to county borders (1987)

Thus to conclude this section, an estimate of the size of the stone cleaning market has been derived from a postal questionnaire, based on the response of the average turnover per annum of the 535 stone cleaning companies operating in the UK in 1987, a figure of £74 million was calculated. Considering the previous estimate by PAU (146) fifteen years before, the value of the stone cleaning market was £2 million.

Between 1972 and 1987, the average annual rate of inflation has increased at the rate of 11.6% per annum. (158) Thus, if the value of £2M of the stone cleaning market in 1972 had increased by inflation alone at the rate of 11.6% per year, the value of the stone cleaning industry would be valued at £10.3 million in 1987. Clearly, the value of £74M in 1987 derived from this research, shows the extent as to which the value of the stone cleaning industry has increased since 1972, even when figures have been adjusted for the annual rate of inflation.

As already stated, the stone cleaning market is predicting just as busy a future over the next five years with an increase in trade, especially from the domestic housing market, although the industry does not expect the price in cleaning to rise by more than the rate of inflation over the same period. Thus, perhaps the trend over the next five years, if smoke pollution levels stay constant, might be that of line (a) in Figure 7.5. Also perhaps, the cost of building cleaning is now becoming more of an economic one rather than a social cost as PAU reported.(146)

Furthermore, if the £74 million quoted represents only 15% of the average turnover of such cleaning companies, because the remainder results from restoration work as faults become apparent after the building has been cleaned - the total value of the stone cleaning and restoration industry is in the order of £500 million per annum. Of course, not all of this total is due to the deleterious effects of air pollution on stone; for natural weathering occurs, cleaning may also be done to remove moss and lichen growth, pigeon droppings and graffiti. However, even if the latter groups were responsible for half of the industry's turnover, the cost of air pollution damage to stone in the UK would be in the order of £250 million per annum. This figure is likely to be an underestimate of the damage, for, as illustrated the domestic housing sector accounts for a very small proportion of the industry's clientele. Usually the public prefer to employ general builders to repair stonework and fabric defects, rather than using an often larger specialist company. Plus, many may "do it themselves" or not at all, thus the size of the market underestimates the cost (i.e. pollution as an externality).

Despite the fact that windows, paintwork are also soiled, buildings have been one of the easier estimates of soiling costs to obtain. For as shown in Section 7.2.1.3, the cleaning of windows and costing is difficult to obtain for often it is done on a fixed cycle which can be based on a subjective assessment of the owner's standard of cleanliness and not correlated with other environmental factors. Plus, the operation may be carried out by employees of the company as part of their general maintenance duties and thus quantification of such an economic cost is very difficult to assess. Also, estimates of the turnover of the paint industry are not useful in estimating exterior painting material costs because the paints can be used for both interior and exterior painting.

The use of house prices as an index of the social cost of air pollution were not considered as a useful guide here partly because, as PAU reported in 1972,(146) when estate agents were asked, less than 10% mentioned pollution and even then it was rated very low in comparison with other factors affecting property values. It was felt here that the presence of elevated levels of ambient air pollution would have very little influence on the price of the property or the decision of the buyer. For it seems that potential buyers are so keen to buy a property, before the price of it further increases beyond their reach, that adverse environmental factors are not currently deemed as a very important consideration in affecting the price of the property or their decision to purchase it. (Especially given the dramatic increase in house prices predominantly in the South-east of England where domestic properties were increasing on average £1000 per month during 1987)

Thus, building soiling costs are easier to estimate because the sum of the cost for cleaning a building usually costs thousands of pounds and requires the deployment of specialist outside companies. So the company having its building cleaned usually keeps a record of such a comparatively large maintenance cost and the stone cleaning company's turnover is virtually specific to work carried out on the exterior stonework of buildings. However, as is illustrated in the following chapter, the frequency of building cleaning may often not be related to environmental factors but dictated by socio-economic factors and/or the attainment of a public image by the building owners. Although evidence is presented which may indicate that cleaning is now also done more for maintenance and 'good house-keeping' practices rather than solely for aesthetic reasons.

CHAPTER EIGHT

THE POSSIBLE BENEFITS OBTAINED FROM STONE CLEANING AND ALLEVIATING SOILING RATES

8.1.1 Introduction: The reasons why buildings are cleaned

As has already been noted, policy makers need to know not only the economic damage costs of a source of pollution, but also the type of benefits that may accrue as a result of decreasing pollution levels before they can decide if there is any rationale for control measures to be enforced. Thus, having attempted an estimate of the value of the stone cleaning market in the previous chapter, the purpose of this one is to estimate and identify the range of benefits that may be gained as a result of building cleaning. Also, a second route of identifying the costs of stone soiling is examined and compared with the former route of using stone cleaning companies' turnover results.

According to the British Standard Code(159) for cleaning and surface repair of buildings, there are two main reasons why buildings are cleaned ; aesthetics and maintenance; though in practice, cleaning a building for aesthetic reasons may reveal the need for maintenance. With aesthetic reasons, one or more of the following may apply even where maintenance is not required:

(i) to reveal the nature, colour or details of an existing building;

(ii) to unify the appearance of a building which has been altered, extended or repaired;

(iii) to facilitate the choice of suitable materials for a proposed extension or for repairs;

(iv) to reflect more light on to other buildings;

(v) to promote personal or civic pride.

For maintenance reasons it may prove necessary to clean the building either :

(i) to remove harmful deposits from the fabric, or

(ii) to expose defects in order to establish the extent and nature of repairs needed.

However, in the context of this research it was necessary to find out the precise reasons why stone cleaning was generally undertaken. For example, was it because the soiled building was considered an aesthetic blight and bad for a company's image, or was it because the deposited matter was considered to affect adversely and damage the building fabric? As well as attempting to gain insight into the frequency of stone cleaning, the survey also assessed the amount spent per annum by a variety of representative organisations and the benefits they felt they obtained as a result of having their building cleaned. A copy of the covering letter and questionnaire devised to obtain some answers to the above questions is given in Appendix D and the results obtained and major findings discussed in the following Section 8.1.2.

8.1.2 An in-depth survey of the attitude of the stone cleaning industry's customers on cleaning

8.1.2.1 Methodology

Having ascertained the stone cleaning industry's market characteristics and proportion of customers from within the private and public sectors (as given in Section 7.4.2 and illustrated in Figures 7.8 and 7.9), it was then possible to question such clients on their opinion and reasons for undertaking stone cleaning. Thus, the questionnaire given in Appendix D was sent to a representative sample of such organisations. In all a total of 750 questionnaires were sent (in August 1987) to the three main types of customers who have their buildings cleaned. The three groups represented :

(i) the 450 councils in England and Wales which included the County, District, Borough, City, Metropolitan and London Boroughs as well as development corporations. An excellent response rate of 63% was obtained.

(ii) 120 questionnaires were sent out to the national banks, building societies, insurance companies and property development organisations. A 15% response rate was obtained with some personal interviews undertaken such as with the chief surveyors of the four major clearing banks in the UK.

(iii) 200 questionnaires were despatched to national high street chain stores, theatres, embassies, hotels and breweries. In all a 20% response rate was achieved.

Thus, the councils represented the main fraction of the public sector of the market, although others such as the Property Service Agency were also personally interviewed. Other representatives within this sector such as churches, academic institutions, etc. were discounted from the findings given here because of the small and thus unrepresentative number of replies. For reasons that will become apparent later, the private sector has been divided into two main groups such as large financial organisations and retailing shops, hotels, etc. The replies of the questionnaires were then coded and analysed using the computer package SPSSX.(160)

8.1.2.2 Reasons for and frequency of cleaning

When asked to rank the reasons given for cleaning a building, a strongly similar pattern was observed for all three groups. As is illustrated in Figure 8.1, the first three reasons for all groups are the same, in that the primary reason for cleaning is that of aesthetics and enhancement of the building's appearance. However, it should be noted that the second reason - that of protecting the building fabric from decay - follows closely behind and indeed the third reason of identifying faults is also connected with the care and maintenance of the building fabric. If these latter two reasons are combined together as the stone cleaning industry suggests they should be, then the maintenance of building fabric is observed as the most important reason for undertaking stone cleaning and agrees with the results given in Section 7.4.2 of why stone cleaning companies consider why buildings should be cleaned. It is also interesting to note the councils' response for the reason 'protecting from decay' is not so high as the other two groups. This difference in emphasis by the councils on the benefits of protecting from decay will also be highlighted when the results of the question 'do you consider the deposited material on buildings harmful to the fabric' is analysed in Section 8.1.2.3.

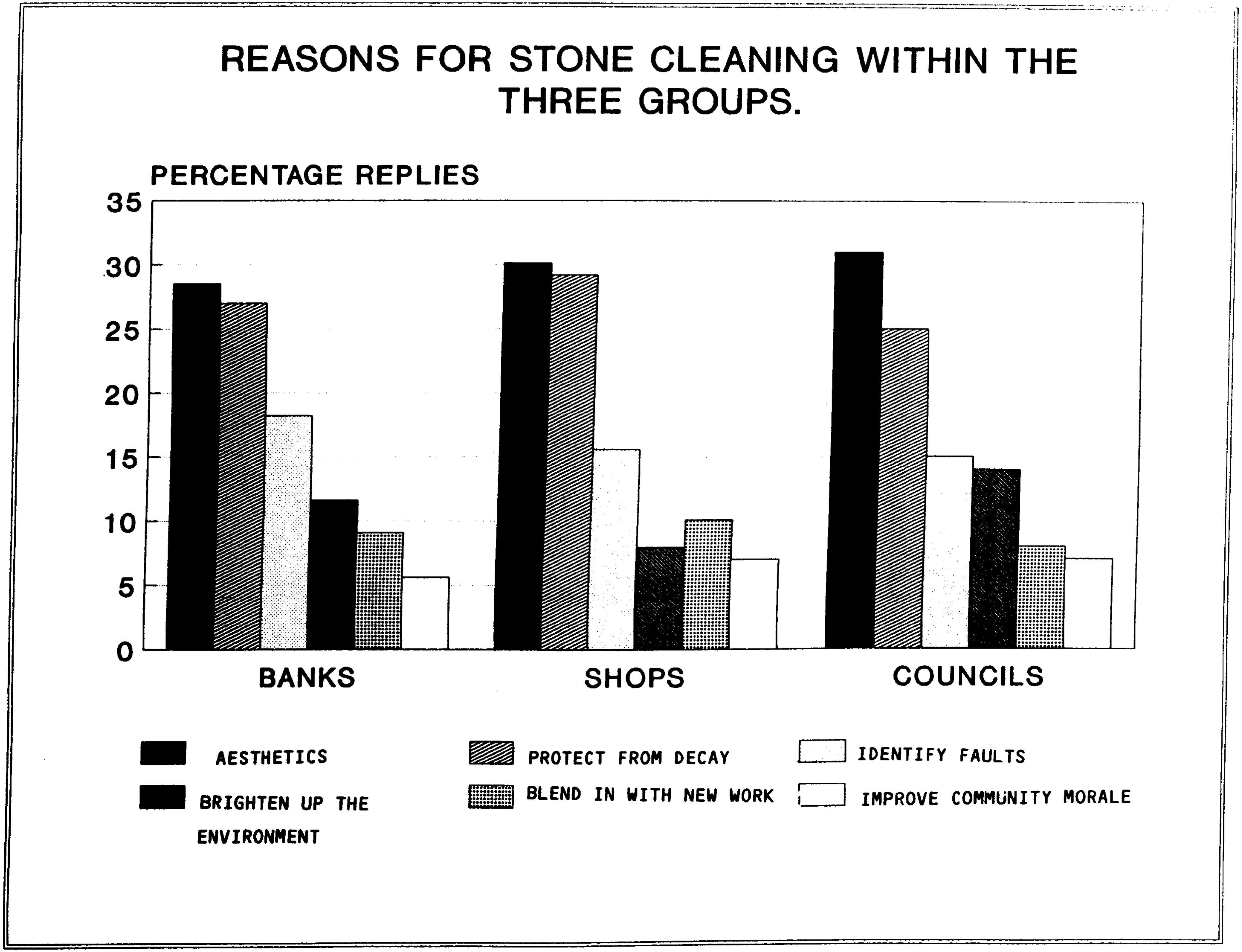


Figure 8.1 The main reasons for having a building cleaned according to the three groups of customers

The results of how often the three groups cleaned their windows is given in Table 8.1. Perhaps not surprisingly the two groups whose livelihood and economic survival depends on attracting business and customers cleaned their windows more frequently than councils. For it was felt that by maintaining an attractive and clean external appearance the customer's attraction to enter the company's premises etc. would be enhanced. Plus, the economic constraints to undertake such cleaning are generally more severe for councils than the other groups.

Table 8.1 The frequency of window cleaning according to the three groups classified below

Frequency of window cleaning	BANKS (%)	SHOPS, etc (%)	COUNCILS(%)
once a month	56	43	13
every 2 months	11	7	14
" 3 "	6	21	16
" 4 "	-	7	4
" 6 "	-	-	7
" 12 "	-	-	1
" 13 "	-	-	1
No fixed frequency	27	22	44

This same trend is repeated for the frequency of undertaking outside painting within the three groups, as is illustrated in Table 8.2.

Table 8.2 The frequency of exterior painting according to the three classified groups

Frequency of outside painting	BANKS (%)	SHOPS, etc (%)	COUNCILS (%)
every year	-	-	1
" 2 years	6	-	1
" 3 "	44	14	2
" 4 "	11	50	13
" 5 "	33	14	45
" 6 "	-	-	6
" 7 "	-	7	2
No fixed frequency	6	15	30

These results are in general agreement with those found by Seeley(137) who observed that in 1985 the external painting cycles within the private sector were in the range of every two to five years, with the majority in the three to four year range. Howevever, as can be seen from Table 8.3 the existence of a policy of frequent and regular cleaning for stone cleaning by the three groups may be still in its infancy, for in each group over 50% of respondents said stone cleaning was not done on a regular basis, with only 6% of the councils having any temporal policy at all. Here again, the findings suggest that the economic constraints on councils are tight and that the competition for limited council resources is often great. Thus cleaning cannot afford to be done as part of a maintenance practice but is, unfortunately, only done when it is necessary for vital repairs to be carried out (though this may be more expensive in the long run). However, a further question was asked in order to see how often the three groups would advocate carrying out painting and stone cleaning in the absence of economic constraints, etc. these results are given in Tables 8.4 and 8.5 respectively.

Table 8.3 <u>The frequency of stone cleaning according to the three groups</u>

Frequency of stone cleaning (years)	BANKS (%)	SHOPS etc. (%)	COUNCILS (%)
less than every 4 years	6	4	-
5-9 "	23	9	1
10-14 "	12	8	2
15-19 "	6	8	0.5
20-24 "	-	-	-
25-29 "	-	-	0.5
30-34 "	-	6	-
35-39 "	-	-	-
40-44 "	-	-	1
No fixed frequency	53	65	94

Table 8.4 <u>The ideal frequency for exterior painting according to the three groups</u>

Ideal exterior painting frequency	BANKS (%)	SHOPS, etc (%)	COUNCILS (%)
every year	12	14	3
" 2 years	10	-	30
" 3 "	50	22	25
" 4 "	6	20	20
" 5 "	22	37	-
" 6 "	-	-	1
" 7 "	-	-	1
" 10 "	-	-	1
Don't know	-	7	19

The extent to which financial constraints may be operating in affecting the frequency of painting and stone cleaning can be partially revealed by examining the current frequencies of such operations with the ideal frequencies given by the three groups. For example, with the current painting policy of banks over 74% paint within 5 years, yet in an ideal situation 100% would paint within 5 years. Similarly, for shops currently 78% paint within every 5 years yet ideally 93% would like to do so. For the councils, 62% paint within every 5 years, yet ideally 78% would like to paint within this time period. Thus, even within organisations whose economic constraints are less tight than those of the councils, there is evidence that it is not always financially possible to paint and clean the building as often as the owners would like. During the survey, it was learnt that with respect to banks each bank manager is responsible for the painting of their own branch. However, the money for this comes from his branch's own profit and thus in wishing to maximise the branch's profits (in comparison with other branches). Managers only authorise painting as often as their head office advocates.

Table 8.5 <u>The ideal frequency for stone cleaning according to the three groups</u>

Ideal stone cleaning frequency	BANKS (%)	SHOPS, etc.(%)	COUNCILS (%)
every year	6	20	-
4-9 years	28	13	6
10-14 "	30	15	12
15-19	7	23	9
20-24	-	-	8
25-29	-	7	8
30-34	-	-	1
35-39	-	-	-
40-44	-	-	2
45-49	-	-	-
50-54	-	-	1
Don't know	6	-	27
as and when necessary	17	22	26

In general, it can then be seen that all three groups seem to be prevented from painting or stone cleaning as often as they would advocate due to economic constraints. The public sector usually has tighter economic circumstances than those from the private sector, as can be seen from the frequency with which windows, paintwork or stone are cleaned. It appears that a stone cleaning policy within all three groups is not as apparent as are the window and painting policies and as is reflected in Table 8.5, there still exists an uncertainty about the value of stone cleaning and how often it should be done. This may be a reflection of the trend observed by Seeley(137) in that the requirement and necessity of a regular painting cycle was absent in the early 1980s and only when the cost of the neglected paintwork was realised did a trend towards more frequent and regular painting by large groups of property owners become apparent. For example, Seeley quotes a city council which decided it could cut spending by extending the 5-year painting cycle normally applied to its houses to 11 years. Ostensibly, this was a policy which could have saved a great deal of money but the result was such extensive damage to external joinery that some 20% of it had to be replaced at six times the cost that would have been incurred had sensible painting cycles been followed.

Perhaps this may be the same for stone cleaning. At some point owners will realise that it may be more economically beneficial to inspect and perhaps then clean stonework on a more regular basis and that this policy may ultimately prevent any decay or faults from further developing. This policy may well be an example, perhaps, of the proverb 'a stitch in time saves nine'. It appears that at the moment only banks have a regular integrated maintenance policy, in that exterior paintwork is usually repainted within a four year cycle. Since this requires the use of scaffolding, the inconvenience to the public and cost of scaffolding can be minimised if stone cleaning is also carried out within the same period. As one bank surveyor noted "if you're paying £28,000 to have the scaffolding and paintwork done, a further £2,000 to have the stonework cleaned is not a significant added cost". Thus, as reflected in Table 8.3, this bank's newly adopted philosophy produces the benefits of a regular, fixed stone cleaning cycle. It was also noted that there is an increasing contractual obligation. Building leases are now beginning to state that some of the buildings must be cleaned within every ten years. Banks also noted that their building premises were also financial asssets and thus their maintenance and longevity should be considered as well as financial expenditure minimised and this was felt to be best achieved by adopting a regular integrated maintenance policy. However, amongst the councils one surveyor noted that soot represented 'ignorance as bliss' for there were so many other financial and labour pressures on council surveyors, that no knowing about the state of the stonework was a temporary relief on their workload.

8.1.2.3 The sources and effects of the deposited matter on the building fabric

When the groups were asked whether they thought the deposited matter on the buildings was detrimental to the building fabric, the views varied according to location. For example rural areas considered that the main source of the deposited matter on their buildings was moss and lichen and that their effect was minimal. However, the results given in Figure 8.2 represent the overall findings for cities and urban areas.

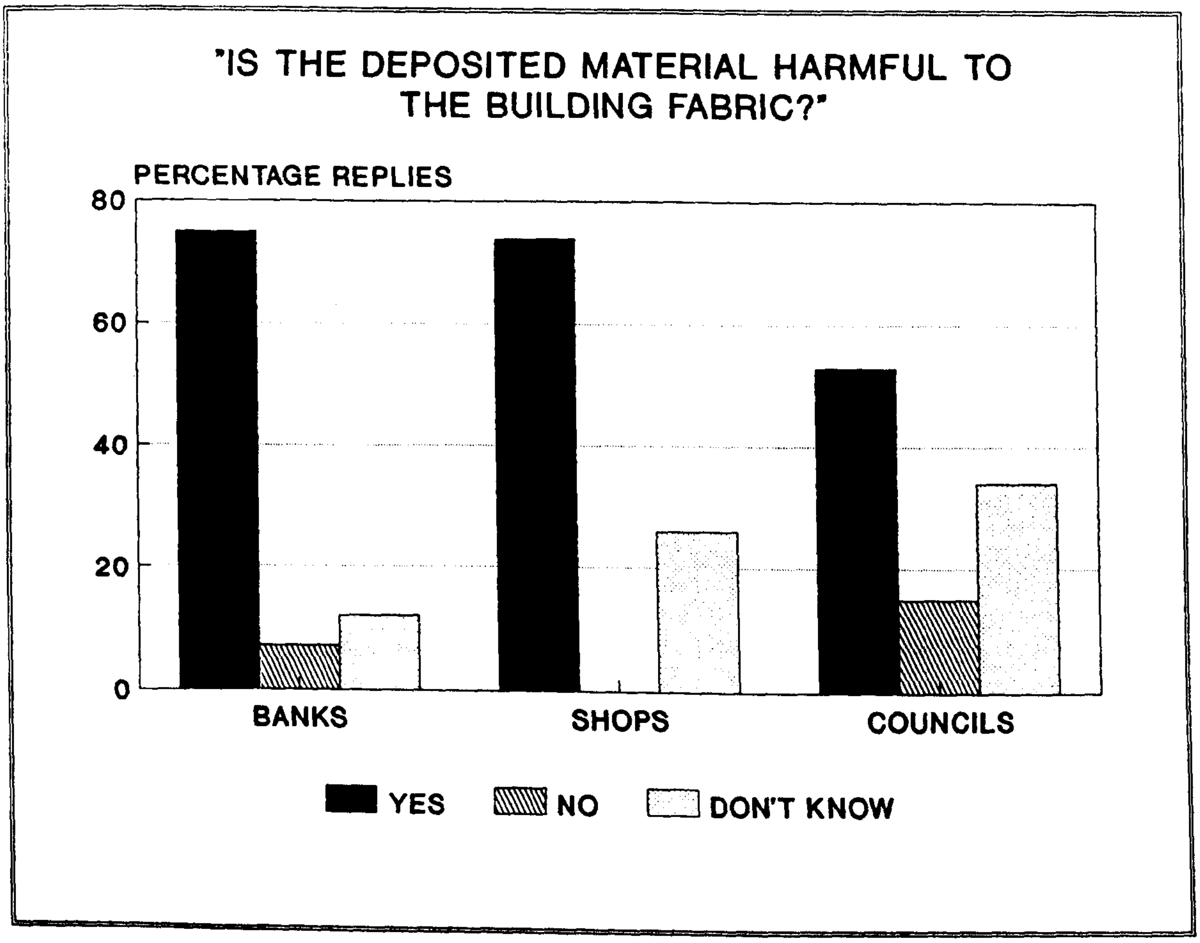


Figure 8.2 Replies to the question 'Is the deposited material on buildings harmful to the fabric?'

As illustrated above, the banks and shop groups felt more strongly that such deposited material was damaging to the fabric than did the council's (75%, 74%, 52% respectively replied 'yes'). Again, the doubts about the merits of stone cleaning protecting the building fabric were reflected with the councils showing the greatest doubt about cleaning compared with the bank and shop groups (12%, 26%, 34% respectively replied 'don't know'). In all cases, less than 11% in each group stated that it was not detrimental to the fabric, 6% of banks replied that it was not damaging and similarly 0% of the shop-type group. Finally, it should be noted here that numerous replies, especially those from the councils, asked to be sent a copy of the results of this study on stone cleaning, suggesting that they genuinely 'don't know' but are willing to consider any reports written on the subject.

The sources of the deposited matter, according to the three groups are given in Table 8.6. Perhaps somewhat surprisingly, all three groups named vehicles within the top three sources of the deposited matter on buildings. Indeed, the traditional sources of polluting domestic smoke and power stations, only featured in the councils' replies and even then were ranked eighth and ninth in the order of their replies. Interestingly, the banks named vehicles as the greatest contributor of the deposited matter and by a large margin in comparison with the other sources thought to be responsible. It may be because, as has previously been illustrated, banks are the only group which have a serious stone cleaning policy and thus have had more experience at identifying the potential sources of the deposited matter. This is partly reflected in the ranking by all three groups of 'past pollution' as the source of the deposited matter. This reply is ranked last by the bank and shop groups - perhaps, because they have already removed such sources. However, this response is ranked fifth out of the 22 replies given by the councils suggesting that this source may not yet have been removed from some of their building facades.

The nuisance from bird droppings was voiced in all three groups. Indeed there is an increasing tendency to use wire mesh around ornate architectural features; this is mainly to prevent birds from damaging and defacating on buildings. The wire mesh also serves as a safety function, in that any falling masonry should be entrapped within it and thus not fall to the ground.

Table 8.6 Sources of the deposited matter on buildings as identified by the three groups

CHOICE	BANKS	(%)	SHOPS etc	(%)	COUNCIL	(%)
1st	vehicles	36	air pollution	19	industry	18
2nd	acid rain	14	industry	15	air pollution	15
3rd	industry	10	vehicles	15	vehicles	14
4th	dust	10	dust	12	birds	8
5th	birds	6	acid rain	10	past pollution	6
6th	plants	5	birds	6	plants	6
7th	air polln.	3	seaspray	5	soot	6
8th	smoke	3	plants	4	acid rain	4
9th	soot	3	climate	4	seaspray	4
10th	climate	3	sulphur	4	climate	3
12th	past polln.	3	past polln.	4	dust	3
13th					coal fires	3
14th					sulphur	2
15th					power stations	2
16th					carbon	2
17th					vandals	1
18th					smoke	1
19th					sulphur oxides	0.4
20th					weather	0.4
21st					acid smuts	0.4
22nd					bacteria	0.4
23rd					agriculture	0.4

8.1.2.4 The building's location and importance and the effect on cleaning frequency

The groups were asked two questions to elucidate how much of the stone cleaning was carried out mainly for an aesthetic reason. The first question was 'does the frequency differ with the location and importance/use of the building and if so why?' These results are given in Table 8.7.

Table 8.7 Replies to the question 'does the frequency of cleaning differ according to building's importance and location and why?'

Does frequency differ?	BANKS (%)	SHOPS (%)	COUNCILS (%)
YES	67	50	23
NO	33	50	77
IF YES, WHY DOES IT DIFFER?			
Type of environmental exposure	50	21	5
A listed building	-	7	2
Near the sea	11	-	4
Type of material	-	7	1
Important public building	6	-	8
Politics	-	-	4
Missing answer	33	57	76

The second question posed was 'when cleaning a building, how often is only the front cleaned and why?' The answer to this question is illustrated in Table 8.8.

Table 8.8 Response to the question 'how often is just the front of the building cleaned and why?'

only the front cleaned?	BANKS (%)	SHOPS (%)	COUNCILS (%)
YES	39	54	21
NO	61	46	79
IF YES, WHY?			
cost	6	-	12
dirtiest at front	8	21	4
visible part seen	12	-	6
different material at front	18	8	6
architectural features	-	-	2
missing answer	56	71	74

The response to the above questions, generally show that perhaps banks and the shop groups are more generally concerned with the aesthetic appearance of the building than are the councils. Banks and shops clean the front only in 54% and 39% of the cases compared with 21% for councils. Perhaps this is correct if the main purpose of the councils is to provide services for the public and care for their needs, rather than provide buildings and working environments which are aesthetically attractive. However, it was noted that the rear of the building was often built in different (often cheaper) materials from the front and that the most ornate architectural features were obviously displayed at the front of the building and so there was more reason to clean the front than the rear. It is interesting to note that all groups stated that it was the front that was more noticably soiled than the rear and thus needed a clean more than the rear. This may present some circumstantial evidence that it could be vehicularly derived matter that is more responsible for soiling than other general urban sources.

8.1.2.5 The benefits of stone cleaning

The groups were asked to rank seven potential benefits of cleaning a building into the most important and least important reasons why they cleaned a building. These results are given in Table 8.9.

Table 8.9 The ranked reasons of the most and least important benefits of cleaning a building according to the three groups

		MOST IMPORTANT	(%)	LEAST IMPORTANT	(%)
BANKS	1st	prolongs life of fabric	32	decreases vandalism	26
	2nd	improves visual env.	20	promotes civic pride	24
	3rd	attracts business	20	changes image of co.	20
	4th	decreases vandalism	7	attracts business	11
	5th	changes image of company	7	demonstrates co. action	9
	6th	promotes civic pride	5	improved visual env.	7
	7th	demonstrates co. action	5	prolongs life of fabric	2
SHOPS	1st	prolongs life of fabric	29	promotes civic pride	24
	2nd	demonstrates co. action	19	changes image of co.	24
	3rd	attracts business	17	decreases vandalism	22
	4th	improved visual env.	17	attracts business	10
	5th	decreases vandalism	10	demonstrates co. action	10
	6th	promotes civic pride	7	improved visual env.	7
	7th	changes image of co.	2	prolongs life of fabric	2
COUNCILS	1st	improved visual env.	26	demonstrates council action	23
	2nd	prolongs life of fabric	25	attracts business activity	21
	3rd	decreases vandalism and graffiti	14	decreases vandalism and graffiti	18
	4th	promotes civic pride	12	promotes civic pride	17
	5th	changes image of town	12	changes image of town	10
	6th	demonstrates council action	7	prolongs life of fabric	7
	7th	attracts business activity	6	improved visual environment	5

The results given in Table 8.9 do show some of the different attitudes between the value of stone cleaning within the private and public sectors. Ideally, on Table 8.9 the most important reason for cleaning should match the least important reason for cleaning. These figures do not match exactly, perhaps reflecting the difficulty of ranking such benefits which often may be inter-related. However, a general match pattern was achieved. Banks and shops in general do not clean for aesthetic reasons and thus one would not expect response to promoting civic pride to be ranked that highly in their most important benefits for undertaking cleaning. Thus factors such as prolonging the life of the building fabric and attracting business are considered as some of the most important benefits. It seems that these two groups are 'content' with how they are perceived by the public.

It is interesting to note that a decrease in vandalism and graffiti is considered quite an important benefit resulting from stone cleaning. As noted by one council reply "if people live in a hell-hole they voice their concern and anger at doing so. After a building has been cleaned, there is a noticeable drop in vandalism and graffiti in the immediate surrounding area". This may be because people within that area feel that something is being done to improve their ambient environment and that action is being taken over their grievances. The council's view that cleaning 'attracts business activity into the area' was surprisingly ranked last as the most important benefit of cleaning. As will be more fully exemplified in Section 8.3, this appears to be a different view from the present philosophy of governmental and other agencies currently implementing action on restoring certain inner city areas within Britain.

The groups were also asked whether they had received any type of public reaction as a result of stone cleaning. The results of this question are shown in Table 8.10.

Table 8.10 Type of public reaction received after a building was cleaned

Received public reaction	BANKS (%)	SHOPS (%)	COUNCILS (%)
YES	39	14	35
NO	61	86	65
IF YES, WHAT TYPE ?			
PRAISE	33	-	65
NEWSPAPER, MEDIA PUBLICITY	6	-	18
CRITICISM	-	-	7
REQUESTS TO DO OTHER BUILDINGS	-	-	2
MISSING	71	93	8

As is seen in Table 8.10, there is generally a small response by the general public after a building has been cleaned. However, when present this response is generally favourable and is often a request for other cleaning to be carried out. Although, the councils did note that criticism was occasionally voiced after cleaning and such criticism usually implied that money spent on cleaning should have been allocated to another (more deserving) cause. This perhaps shows that cleaning undertaken by councils may also be politically sensitive, in that it must not appear to waste money. This may be yet another reason why councils are less ready, or able, to clean their stonework than are the other two groups.

When asked what buildings they would or would not clean again most said they would clean all stone buildings again, although about 10% stated they would not consider cleaning concrete again.

8.1.3 The amount spent per annum on stone cleaning within the three groups

For reasons of confidentiality as guaranteed to the respondents, the amount spent on stone cleaning by specific individual organisations cannot be revealed. However, the general groups and the amount spent are given in Table 8.11. Because a 100% response rate was not obtained from the companies approached and because the question had not always been answered, the figures only provide estimates. This is particularly true for chain store shops. In-depth interviews were conducted, especially within the bank sector and these confirmed that the amounts spent were realistic. Council estimates are based on an average for all the councils. For example, many recorded a zero expenditure on stone cleaning for the year, yet others mentioned sums in the range of over a quarter of a million pounds spent in that year. Indeed, it did seem that figures from the councils were either very large or negligible (i.e. less than £1,000). This suggests that money for stone cleaning was rarely allocated on a regular annual basis, and so "stone cleaning blitzes" occurred when other monies were unexpectedly obtained or allocated to that council department, for as some replies noted, when there were political reasons for suddenly doing so.

Table 8.11 The amount spent per annum by the three groups

On average:	4 big banks spend about £5M each per annum on stone cleaning	=	20
	other banks, building societies, insurance companies	=	10
	private housing	=	3
	the 455 councils in England and Wales spend on average £44,000 each per annum	=	20
	private sector shops	=	27
	TOTAL	=	80M

This estimate of £80 million pounds spent on stone cleaning within the private and public sector, compares very closely with that derived of the value of the stone cleaning market of £74 million. (as shown in Section 7.4.4). This value of £80 million has been given as evidence in the House of Lords Select Committee on pollution from diesel vehicles.(2) The amount spent by private home owners on stone cleaning could not feasibly be evaluated here and thus estimates based on stone cleaning companies had to be used. It is felt that both estimates probably represent the minimum amount that is spent per annum on stone cleaning within the UK.

8.1.4 The socio-economic and other difficulties faced when evaluating the costs of building soiling

The results of this survey show that buildings are cleaned for a variety of reasons but they may not always be cleaned when such cleaning is required due to economic constraints within an organisation.

An attempt was made to see if there was an association between the frequency of window cleaning, painting or stone cleaning and the area of the country from which the reply came, based on a classification of general coastal, rural, urban, industrial, suburban and city location. One might have expected that rural and suburban locations had a lower frequency of cleaning than would a city or industrial location. However, there was no evidence of a general trend for any of the locations except for replies from coastal areas which did show a slight increase in painting frequency compared with the other groups. Realistically, this absence of a trend may not be so surprising. For example, if a council is based in a prosperous rural area the amount spent on stone cleaning and general maintenance may be greater than that of a busy industrial city, although the level of air pollution and need for cleaning and maintenance is greater in the city. This may be a reflection of the fact that the budget of a city council is under greater competition from the various departments than is that of the rural council. Thus, despite air pollution levels and the need for building maintenance being greater in the city, cleaning, etc. cannot be carried out on the ideally needed frequency due to greater economic constraints. For this reason, the association between air pollution levels and cleaning frequencies is not observed.

It may also be that many people responsible for buildings, especially those from the public sector, remain uncertain of the value of stone cleaning and its effect on prolonging the life of the building's fabric and thus are somewhat wary as to whether stone cleaning is the latest maintenance gimmick. This was illustrated in Figure 8.2. As is evident by such replies and the doubts of other building specialists, more research must be carried out within this field to establish if soiled deposits on buildings are truly detrimental to the fabric or merely an aesthetic blight. For example, scientific research needs to assess whether the carbon deposit can act as a catalyst which converts acidic gases and into acidic liquids which can then begin to accelerate the natural erosion rate of the building.

Only when the results of such work are established can building owners decide whether it is really necessary to clean their buildings or not. Indeed, if there was strong evidence to suggest it was harmful to the building fabric, those responsible for cleaning, but under tight economic constraints, could then objectively justify their reason and need for cleaning the building fabric. However, if the evidence was to the contrary then decisions to undertake stone cleaning can only be based on the subjective and aesthetic tastes of those responsible. It would then be interesting to note the value of the stone cleaning market and whether people would still clean their buildings at the same rate for predominantly aesthetic reasons alone.

Finally, another reason why stone cleaning may not be as popular in the various sectors is the fact that in the 1970s many buildings were irrevocably damaged due to stone cleaning. In this period, the Government sponsored a campaign entitled 'operation spring clean' in which grants were available for a limited period to have buildings cleaned. Towards the end of the grant period, many building owners had a grant for cleaning to be done but there was a shortage of cleaning specialists available to undertake such a demand. Thus many 'cowboy' cleaning companies with very little practical expertise were set up in this time and employed by such grant holders. Inevitably, some of these companies damaged many architecturally important buildings. Far more than any air pollution was thought to do. Thus the practise of stone cleaning lost some of its popularity at this time. Perhaps this fear is still slightly evident amongst the councils who are in charge of public buildings and thus wish to protect them as best as possible. As described in Section 7.4.3, stone federation members are now increasingly concerned that the growth in the 'cowboy' trade is rising and they fear that their work will be discredited by the public who have seen the results of the 'cowboy'. The survey revealed a strong feeling that steps should be taken to regulate this growth.

8.2 Some of the sociological and intangible benefits of stone cleaning (or the potential disbenefits of soiling)

8.2.1 Stone cleaning in Urban Regeneration Schemes

The recently published 'Action for Cities'(161) pamphlet produced by the Government states that its aim is to help cities meet the challenge of change and to build confidence in them as places in which to live, work and invest. This is done by

- creating the right framework for action;
- offering help for rebuilding
- raising skills and encouraging enterprise;
- making cities better places in which to live.

Cities exist for a purpose. The purpose may vary, but every city needs a firm economic foundation if it is to flourish and must be a pleasant place in which to live. Places that are good to be in, will attract new enterprise and will possess entrepreneurial drive. The wealth-creating power of product development is one of the forces needed to drive urban improvements, but the quality and responsiveness of the townscape is itself an important factor in attracting new business and energetic people.

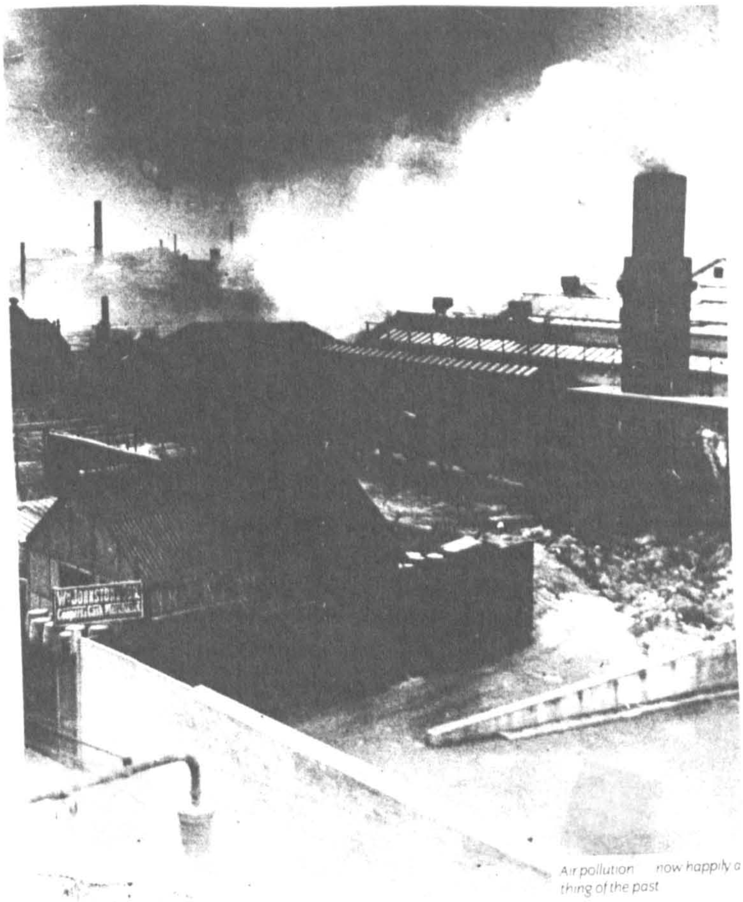
The role of stone cleaning in such cities may play a beneficial role in helping make such places better to live in. For example, to the east of Glasgow city centre the Scottish Development Agency (SDA) is co-ordinating contributions from central and local Government and private investors to rejuvenate an area covering 1618 hectares. This project, known as GEAR (Glasgow Eastern Area Renewal), was set up in 1976 and is aimed directly at a part of the city where every social indicator of economic distress - employment, health, housing - is well below the average.

The environmental improvements have been dramatic and the numerous delegations and important visitors to the area are impressed,(162) for they see sand-blasted tenements and modernised flats, new houses, blooming shrub beds, numerous small factories and the multi-million pound sports complexes within the project area.

Indeed, numerous other newspaper reports and television documentaries note that stone cleaning has been done as part of the campaign to revitalise inner-city areas and attract new businesses within them. For example, Sir Trevor Jones, the Alliance Leader of the Liverpool Council, recently stated "we have taken steps to clean up the city centre as part of the need to improve the image of the city to the outside world to begin to attract more investment and jobs."(163)

However, as Richard Colwell, director of area projects with the SDA stated "it's not just about cleaning up buildings and improving the physical environment, it's about finding people a job so that they can contribute to society rather than being apart from it. Such changing of the economic scene is outside the trends of the urban regeneration people like myself."(164) The act of cleaning buildings is an intangible factor in perhaps initiating some facets of city revival. The photographs of recently cleaned buildings are certainly viewed as a positive attribute in advertising the area to future investors, etc. as is witnessed in the array of publicity material produced. This is illustrated in Figures 8.3 and 8.4.

The role of stone cleaning in inner city decay regeneration schemes is also enforced from the information gained as a result of identifying the major areas of the country where stone cleaners were situated and often worked and illustrated in Figure 7.11. Thus as stated in Section 7.4.4 much work is carried out in cities such as Liverpool and Glasgow as well as certain areas of London such as the Docklands. The presence of a large number of cleaning companies around cities such as Bristol



Air pollution now happily a thing of the past

Figure 8.3 The improvement of the environment is often advertised in publicity brochures advertising a city's regeneration.(160)

The stone cleaned People's Palace a treasure-trove rich in the history of the East End

Figure 8.4 Such photographs of important town buildings that have been recently cleaned, commonly feature in publicity brochures sent out to prospective companies, etc.(160)

and Bath reflects the fact that they are tourist centres made famous, in part, by their architecture. Thus, to maintain the tourist trade the external building appearance is deemed to be an important factor.

8.2.2 The role of stone cleaning and restoring buildings in conservation

The role of cleaning and restoring previously derelict old buildings has several important functions. For example, many people are nostalgic and like to see things that preserve their links with the past and that give them a cultural or heritage link with the area. Buildings may be conserved for such reasons alone. However, as often experienced in the real world, other more 'objective' reasons need to be found for justifying their retention. Such reasons may be that it may be cheaper to restore and maintain a building than would it cost to demolish it and build anew. Thus, increasingly new uses have been found for old buildings. The Albert Dock scheme in Liverpool is a classic example of such factors at work. As is shown in Figure 8.5, the Dock warehouses have been converted into a tourist centre comprising shops, museums, etc. Residents of the area see a new role for buildings which had previously been neglected and appreciate that action is being taken on the visual environment and employment prospects in the area. Similarly, they may feel happy to see the buildings where they once worked or lived nearby, being used again and value that their their link in the past is being preserved. Similarly, Figure 8.6 shows a previously abandoned carpet warehouse in Glasgow that has successfully been converted into a prestigious office complex.

Thus by stone cleaning and restoration of buildings, cultural, historical and aesthetic values may be maintained and/or enhanced. The community needs the visual assurance of continuity of place, the idea of

Figure 8.5 The Albert Dock, Liverpool. The Merseyside Development Corporation is converting these outstanding listed buildings to provide a new focus for tourism.(160)

(Source: 'Action for Cities')

Figure 8.6 Doges Palace in Glasgow built in the nineteenth century as a carpet warehouse, has now been successfully cleaned and restored into office premises for the electronics and high technology field.

identity both at national and local levels is psychologically important to us all. There may be economic benefits, such as through tourism in historic towns and cities, but there are also savings in time, energy and finance by the recycling of sound building structures. However, the creative use of conservation through control of environmental change does require a long term political commitment as well as the economic will to carry out such a change. Perhaps, only time will tell, how successful the current philosophy on inner city regeneration is/has been.

8.3 A provisional cost-benefit analysis of building soiling with the UK

8.3.1 The current limitations inherent in undertaking a CBA of building soiling resulting from a specific pollution source

A comprehensive cost-benefit analysis of building soiling in the UK cannot as yet be fully achieved within the UK for a variety of reasons. These include the following :

(i) the cost of building soiling has only been estimated on the basis of the costs of soiling for certain members of the private and public sectors. Thus, for example, the cost to houseowners has only been marginally addressed;

(ii) the social cost of soiling has not been estimated, although it undoubtedly exists, as is suggested by the fact that economic constraints can prevent cleaning from being carried out, even though organisations wished to undertake it;

(iii) the social and direct costs may also not be fully evaluated, because many building owners felt that evidence of the detrimental effects of soiling had not been truly validated. Thus preventing them from making an objective decision as to whether or not cleaning should be undertaken;

(iv) the source of the deposited matter on the buildings in urban areas has not yet fully been proven experimentally, although theoretical studies do indicate that diesel derived smoke emissions may be the major source responsible for such soiling. Thus, calculations on the cost of mitigating the source or sources of this deposited matter can only be speculated upon;

(v) even if it were proven that diesel exhaust emissions were largely responsible for such soiling, the technology to control such emissions either through modification of engine design, use of fuel additives to suppress smoke formation, or catalytic traps to catch such particles before they are emitted into the atmosphere are not yet technologically proven. However, at the moment the use of catalytic traps is appearing as the most realistic option in curbing exhaust particulate emissions. In addition, it should be noted that the additional benefits of the reduced risk to health, albedo, etc. from curtailing such emissions (if they really exist) have not been evaluated here;

(vi) the precise nature and evaluation of benefits that may accrue as a result of stone cleaning and through decreasing the rate of building soiling difficult to quantify. However, it may be assumed that if currently £74 million is spent per annum on stone cleaning within certain sectors of the private and public sectors, £74 million of benefit must be accrued. Much of this sum is spent by private business concerns, which have as their objective profit maximisation; it can be imagined that it is unlikely that they would waste their money on building cleaning if they did not gain an equal or greater financial return from it. However, as has been shown, there may also be intangible benefits from stone cleaning, such as raising community morale decreasing vandalism and graffiti, helping to regenerate cities which had previously suffered inner city decay. Such factors are difficult to quantify in strict economic terms and no attempt has been made to estimate them here.

8.3.2 An initial attempt to assess the costs and benefits of building soiling and its prevention within the UK

Having thus explained the uncertainties currently experienced in estimating the costs of building soiling and the benefits of cleaning or reducing the rate of building soiling, it should be noted that the cost-benefit analysis presented here is based on the assumption that all diesel vehicles with the exception of private diesel cars (which currently represent less than 4% of this market) are fitted with an exhaust particulate trap which costs in the region of £100 per vehicle.

This estimate has been derived from discussion with individuals in the motor industry and catalyst trap trade,(165)(166) although it must be noted that such a device is not yet commercially available and the price may subsequently fluctuate above or below this price.

Using Department of Transport figures(167) on the number of diesel vehicles on the road, excluding private cars, in 1985, a figure of 2,410,000 is derived as seen from Table 8.12. This figure assumes that all buses, coaches, taxis, light and heavy goods vehicles use diesel fuel.

Table 8.12 Vehicles in use in 1985 (in thousands)(167)

Year	Private cars[1]	Motor cycles	Buses and coaches	Taxis	Light goods vehicles[1]	Heavy goods vehicles[12]	Other vehicles[3]	Total vehicles
1960	5,717	1,796	79	14	565	641	628	9,439
1965	8,901	1,612	81	15	880	736	713	12,938
1970	11,328	1,048	78	25	1,120	683	668	14,950
1975	13,517	1,161	80	32	1,337	688	706	17,501
1980	14,772	1,372	71	39	1,461	575	920	19,210
1983	15,543	1,290	68	46	1,615	565	1,090	20,217
1984	16,055	1,225	67	49	1,666	576	1,135	20,773
* 1985	16,453	1,148	67	53	1,708	582	1,156	21,167

Multiplying this figure by £100 for the cost of a particulate trap for each of these vehicles, a total cost of £241 million is obtained. Assuming the cost of building stone cleaning is in the region of £74-80 million per annum, it can be calculated that the cost of recuperating the £241 million on particulate traps would be redeemed within a period of 4 to 5 years. Indeed, if the cost of soiling on windows, painting and the intangible benefits that may be gained from decreasing the frequency of soiling and its other adverse effects are taken into account the time taken to redeem the initial outlay on the cost of fitting particulate traps would be further decreased. However, as was described in Section 7.1.1, that which is beneficial to one section of the community may not be beneficial to others, and the net effect of a decrease in the level of pollution is the release of resources of labour, materials, with an equivalent release of cash which should enable the resources to be diverted to more beneficial activities within the community.

For example, if there was a decline in soiling rates some of those currently employed within the stone cleaning industry may find themselves unemployed due to the decrease in demand for cleaning. Likewise, with the paint industry and painters and the supply trade to such industries may also feel this knock-on effect. Thus the suppliers of scaffolding, machinery and chemicals to the stone cleaning industry may also suffer economically as a result of any decrease in soiling rates. However, companies which currently spend money on stone cleaning may then have to spend less on cleaning than they currently do and so such monies saved could be diverted elsewhere within such organisations who may need this money more.

However, other options apart from catalytic traps and other such mechanical devices which involve a direct expenditure by the vehicle owners are often mooted when considering how vehicular derived pollution may be abated. Such schemes may include an added tax on vehicle fuel to cover the environmental damage it is believed to cause, or the better planning of road transport schemes which may prevent traffic congestion or involve the re-routing of certain 'undesirable' vehicles. In addition, some authorities have argued for the improvement of the public transport system which aims to discourage the widespread use of privately owned vehicles, which are deemed responsible for adding to traffic congestion. Finally, a change in fuel use itself to more 'environmentally friendly' fuels (such as replacing diesel fuel with methanol) has also been considered. However, as yet such schemes are not usually rigorously assessed as viable solutions in decreasing the environmental effects of vehicular derived exhaust. Thus, at the moment, the only real apparent option may be that of curtailing diesel particulate exhaust by the use of a particulate trap, although even this device has as yet to prove its effectiveness with on-road diesel vehicles. The conclusion that much groundwork still remains to be done before a thorough cost-benefit study on decreasing the building soiling rates, cannot be avoided.

CHAPTER NINE

MAIN RESEARCH FINDINGS AND SUGGESTIONS FOR FUTURE RESEARCH

CHAPTER TWO

1. It was noted that natural sources of particulate matter exceed anthropogenic emissions on a mass basis. However, anthropogenic sources are deemed to have a greater impact on urban air quality than naturally produced particulate matter because of their disproportionate distribution and smaller size.

2. The soiling potential and effect on air quality by anthropogenic sources of particulate matter were assessed. The impact of both industrial and non-industrial fugitive particulate emissions on air quality was considered to be mainly localised. This is because of their comparatively large diameter (on average $> 10\ \mu m$) which implies such emissions settle a short distance from the source. The soiling potential of such emissions was also deemed as limited, because they usually contain more siliceous than carbonaceous material. Also, such emissions may have larger amounts of water-soluble material than other sources of anthropogenic emissions (e.g. combustion-derived sources). It is more likely that such fugitive emissions will be dissolved with rainfall and removed from any surfaces on which they have deposited, unlike particulate combustion derived sources.

3. Anthropogenic sources of particulate matter from fuel combustion were considered to have the greatest overall impact on urban air quality and soiling potential. Although fuel can be combusted without the production of particulate matter, it was explained that the conditions to achieve such a stoichiometric reaction do not usually exist because

of operation conditions and the kinetic nature of the system. Thus, emissions of such particulate matter occurs. The soiling potential of fuel emissions is greater than previous sources discussed because often these emissions are coated with tarry viscous materials which aid in the adherence of such particles on to a surface. This greater adherence ability implies that such particles are less likely to be removed from surfaces by meteorological conditions. Also the small size of these particles (typically < 1 μm) means they are more likely to remain suspended within the ambient air and affect air quality than larger size particles which have a greater sedimentation velocity and thus lower residence time within the atmosphere.

4. Industrial and other transportational sources of particulate matter were concluded as having a smaller soiling potential than combustion derived sources, because of their larger size (usually > 10 μm) and smaller carbonaceous content. However, it was noted that such emissions may produce a soiling effect if they are deposited on to surfaces which are sheltered from rainfall and/or are in association with particles than are adhesive in nature.

5. The methods by which airborne particulate matter is analysed were introduced. It was noted that the British smoke shade sampler has a 14 μm cut-off point for particulate matter. However, because that method measures the staining capacity of the air, the gravimetric technique was considered more useful if a determination of the total amount of particulate matter in the ambient air was required. The gravimetric method measures the mass of particulate matter collected in a known volume of air, the staining capacity is not recorded and the cut-off point for the material samples is approximately 45 μm in diameter. The use of size-selective methods was assessed and some studies quoted whose

results have shown that it is particles whose diameter is less than 2 μm which have the greatest soiling potential within the ambient air.

6. The relationship between the British smoke shade and gravimetric methods was assessed and found to vary according to seasons and location of measuring apparatus, as well as to the contribution to the atmospheric aerosol by vehicular sources.

7. The levels and sources of smoke in the UK were examined, using data on the type and amount of fuel consumed within the UK (from 1971 to 1986) and the particulate emission factor (% by mass) of the fuel type. The relative soiling factor for each fuel was also calculated by multiplying the quantity of smoke emitted by the relative soiling factor for a given fuel. The results for the UK (from 1971 to 1986) show that the percentage contribution of dark smoke emitted from diesel appears to be increasing by approximately 1% per annum, whilst coal's contribution is decreasing by 1% per annum. In 1986, coal combustion was responsible for 61% of the total mass of dark smoke emitted in the UK and diesel's contribution was 29%. Yet, an emission inventory of dark smoke in London showed that in urban areas the relative contribution to dark smoke production from diesel was in the range of 60% and coal's contribution was approximately 15%. Thus, diesel dark smoke production may be in the order of four times as great as that from coal in an urban area such as London.

8. Areas requiring further research noted in this chapter were the contribution from other vehicular contaminant sources (e.g. such as from body work and engine wear) to ambient particulate matter. The size of such particles and their emission factors has not as yet been studied in sufficient detail for their contribution to airborne particulate matter

to be fully evaluated. Likewise, work on emission inventories of dark smoke and smoke has been very limited and is still in its infancy. Thus the emission factors quoted and currently used, need to be further investigated to check their current validity.

CHAPTER THREE

1. The major forms of carbon in atmospheric particulates were considered to be graphitic carbon and organic material. It was noted that primary organic carbon had few or no light-absorptive properties unlike the graphitic form (which is only produced from combustion processes). The absence of a standard terminology in naming the 'graphitic' component was noted as an area deserving attention so that measurements of this component can be more easily facilitated by workers in this field.

2. Examination of the chemical properties of PEC noted that its structure was similar to graphite in that it has a π- electron system and very large surface areas. Since each exposed carbon atom at the surface can use its extra valence electron to bind other atoms, such forms of carbon have strong adsorption properties. However, the sheets of carbon in PEC are distorted and disoriented unlike graphite and contain some oxygen and hydrogen impurities. Such defects may be responsible for the observed catalytic activity of elemental carbon particles. Although it was noted that the impact of such carbon-catalysed reactions have not yet been well studied it was mooted that if the soiling of buildings was mainly attributable to PEC, then soiling may not only be a nuisance in terms of an aesthetic blight, but may also be involved in enhancing the rate of fabric erosion by catalytically facilitating the conversion of acidic gases into acidic liquids with the

presence of rainfall.

3. The multimodal size distributions of black carbons issuing from a variety of combustion sources were compared. Automotive traffic was noted as producing large amounts of nucleation mode material of approximate size 0.1 μm. Most of this material was soot and other organic compounds. After coagulation and dilution within the carbon atmosphere, the nucleation mode material contributes to the accumulation mode which for carbon was about 0.5 μm. A coarse mode of several microns was also observed which was thought to be attributable to the deposition of fine particles on the walls of the exhaust system and a subsequent entrainment in the issuing gases. The composition of some black carbons was examined and it was noted that some fuel sources produce relatively pure sources of PEC whilst others produce a soot which is less than 50% PEC, the rest often being organic matter. For example, the percentage elemental carbon content for furnace black soot, from a domestic coal fire and soot from a small diesel engine were 98, 0.36 and 51% respectively.

4. Examination of the atmospheric life cycle of PEC noted that because it is inert at ordinary temperatures, hygrophobic and insoluble in any solvent, chemical removal mechanisms from the atmosphere do not exist for PEC. Thus, physical removal mechanisms such as wet or dry deposition were the only possible removal systems that operated for atmospheric PEC. In considering dry deposition removal processes for PEC, it was noted that for particles 1 μm in diameter their deposition was determined by aerodynamic processes such as sedimentation. However, the movement of particles less than 0.2 μm in diameter is controlled by Brownian motion. Indeed, it was noted that dry deposition fluxes for PEC are probably larger in urban than rural areas because there are

larger concentrations of such particles in urban areas. Also, Brownian motion is more pronounced in smaller sized particles which increases the occurrence of collisions with other particles and the opportunity to form agglomerates. Thus, such processes rapidly decrease the number, concentration and increases the mean size, so that the residence time of PEC in an urban atmosphere is in the order of hours compared with a residence time of several days in the upper troposphere.

Precipitation scavenging is considered to be the predominant removal for PEC under most conditions, although it was noted that the exact way in which PEC is incorporated into rainfall depends upon the size and the hygroscopicity of the PEC containing particles. For example, accumulation-mode PEC which is coated with hygroscopic substances has an atmospheric residence time in the order of days, whilst if hygrophobic it has a longer residence time because the processes of nucleation scavenging and diffusion to hydrometeors are less efficient in such circumstances.

5. An emission inventory of PEC from combustion sources for fuel use in the UK from 1971 to 1986 and for London in 1980 were derived. Diesel fuel combustion was observed to be responsible both on a national and urban (London) level for over 90% of the PEC emissions on a mass basis. Ambient concentrations of PEC were also reported for a variety of locations, the average urban level of PEC was observed to be in the range of 2-16 $\mu g\ m^{-3}$. The relationship between PEC and smoke shade levels was noted and two theoretical models which predict airborne PEC concentrations were introduced.

CHAPTER FOUR

1. It was noted that very few material damage functions exist for particulate matter, despite much qualitative evidence that such air pollutants can cause damage to materials. Some damage functions that have been reported noted that change in reflectance was proportional to the square root of the dose of the particulate matter. Damage functions curves predicted from such relationships were shown and it was noted that the results of the damage functions obtained from this research (reported in Chapter Six) were different. The difference in ability of materials to remain soiled/retain grime was reported and supports the results given in Chapter Six that different materials soil at different rates due to differences in the aerodynamic properties of their surfaces.

2. Work on dry deposition of particulate matter carried out in London was reported and such results were similar to those reported in Chapter Six, in that the build-up of dust does not continue indefinitely and that dry removal mechanisms operate to remove deposited matter from a surface. Differences in the soiling characteristic between rooftop and roadside sites were noticed, although there were similar gloss readings at the rooftop and roadside sites, the daytime measurements of the roadside site had the greatest percentage decrease, suggesting vehicular pollution may be an important contributory factor responsible for this decrease. Coarse particulate matter (mainly from resuspended surface dust) was noted as an additional roadside contribution which affected the percentage coverage more than the reflectance value. Dry deposition studies carried out in America reported that 99% of the volume and 63% of the soiling of glass was caused by 39 particles with a diameter of greater than 10 μm. However, it was noted that despite the deposited

particle mass being dominated by particles greater than 10 um in diameter, this does not necessarily imply that such particles are also responsible for the soiling change of the surface on to which they are usually (temporarily) deposited. As previously noted soiling is a long-term process and the presence of larger particles on to a surface may cause 'dustiness' which is temporary as it is usually removed by meteorological action, whereas soiling particulate matter is less likely to be removed by the action of rainfall, wind, etc. Also, the current definition of soiling appears inappropriate as is discussed in the conclusions of Chapter Six.

3. The two theoretical models derived by Haynie(112) and Lanting(121) were introduced and assessed in terms of the parameters used in their formulation. A generalised formulation for describing soiling rate in terms of a soiling potential was introduced. However, it was realised that the deposition of aerosols from the ambient atmosphere on materials is a complex phenomenon and predicted models must of necessity simplify the situation.

4. The role of rainfall on building facades was examined to lead to an understanding of how soiling patterns on facades arise.

CHAPTER FIVE

1. An introduction of how the measurement of soiling rates for wood and tile exposed in a road traffic tunnel was given. Measurements of total carbon were recorded during some of the exposure period and were found to be in close agreement to the theoretically derived values of Bailey and Clayton(39) and Edwards et al.(89)

2. Soiling in the tunnel was modelled by the equation:

$$R = 100\ e^{-K\ t}$$

where $K = 1.92\ yr^{-1}$ for wood, correlation coefficient = 0.96

where $K = 1.87\ yr^{-1}$ for tile, correlation coefficient = 0.96

The models of Haynie(192) and Lanting(121) were also compared to the experimentally derived rates. Haynie's value of K = 1.73 yr^{-1} which slightly underestimated the actual experimentally derived rate, whilst Lanting's value of K = 3.7 yr^{-1} overestimated the experimental rate.

3. Two other empirical models were fitted to the experimentally derived data points, although these gave acceptable correlation coefficients (in the range of 0.93-0.96), a survey of the trends shown by their residuals revealed that these models fitted less well than those provided by the exponential model.

4. The economic considerations of soiling with road traffic tunnels were considered, for the walls of tunnels are used to reflect light to aid in visibility within it. If the walls are soiled this reflectance will be diminished and extra electricity will have to be provided to compensate for this decrease in reflectance.

CHAPTER SIX

1. Results from the measurements of soiling rates for exposed and sheltered wood and tile from a daily measurement programme (111 days) at a suburban location were given. Correlation coefficients were calculated for the exposed and sheltered materials with rain. Only one material - the exposed wood with rainfall - was significant at the 5% level of confidence. However, the correlation coefficients of the materials with rain are greater for the exposed than sheltered materials, where the action of rainfall on the latter is assumed to be more restricted. Thus suggesting that rainfall may partially remove (the larger) particles from the surface.

2. The experimentally derived soiling constants for the exposed and sheltered materials ranged from 0.5 to 0.8 yr^{-1}, whilst the predicted values from Haynie and Lanting were 0.25 and 0.37 yr^{-1} respectively. The results from this daily programme agree with the findings detailed in the following section, which reports short and longer term soiling rates for a variety of sites and materials. Soiling rates calculated over longer term exposure periods produced a lower soiling constant than those derived over short-term exposure periods and these former constants are usually closer to the values predicted by the theoretical models of Haynie and Lanting. Again, reiterating the point that soiling is a long-term process and if the soiling rates are to be calculated, data is needed which is collected over such a time scale.

3. A comparison of the soiling constants derived for exposed wood at the Enfield site from the daily and long-term exposure programmes gave three different soiling constants:

The daily programme produced a value of 0.7 yr^{-1};
The first 0.2 years of the long-term exposure programme produced a value of 2.0 yr^{-1};
The 0.2 years - end of the long-term exposure programme - produced a value of 0.4 yr^{-1}.

It was concluded that this latter value of 0.4 yr^{-1} best describes the soiling propensity and rate for this site, given that soiling is a long-term process.

4. Samples of white-painted wood generally soiled the most, then followed tile and cotton, glass soiled the least of all the materials. Horizontal orientations of these materials soiled more than the vertical

ones, though samples of glass exposed did not always follow this trend. The differences between such rates in soiling were considered with respect to the aerodynamic properties of the surface.

5. Carbon analysis of samples of the deposited matter collected on surfaces during the exposure programmes was undertaken. On average such samples comprise about 5% elemental carbon and had an ash content of 60%. This high ash content indicates that a high level of resuspended road dust and soil derived particles were present in the deposited matter. However, although such particles were present on the surface at the time the elemental analysis was recorded, this does not imply that such particles are permanently present on the surface and therefore act as a soiling agent. As previously discussed, the size and chemical composition of such particles usually prevent them being permanently adhered to a surface.

6. Although soiling has been defined by the EPA as "What is undone by cleaning",(4) the results of this research would suggest that this term needs a more concise definition. As shown from the experimental results in this chapter, rainfall may partially clean a surface covered with deposited particulate matter but the particles are those which give rise to predominantly to a temporary dustiness and not long-term soiling effect. Thus perhaps a more precise definition of soiling would be: "What is not undone by meteorological factors but only by manual processes".

CHAPTER SEVEN

1. The value of cost-benefit analysis in studies of environmental quality was confirmed. It is required because markets cannot deal with 'free goods' and because they do not force the polluters to internalise all of their costs. The directly measurable economic costs of damage may appear simple to determine but seldom are in practice, especially with the more diffuse effects, for example, costs such as suffering and premature death incurred as a result of poor environmental quality. However, it was noted that market values attached to the environment have not unique correctness and that each different distribution of wealth in society will give a different market equilibrium and a different set of values.

2. Previous studies which have attempted to assign the cost of soiling were reviewed. For example, the cost of laundry and household goods and window cleaning showed that such cleaning and maintenance operations are often undertaken on a rigid schedule which is independent of the location of the operation. Non-pollution factors which could not be controlled may be important in explaining such cleaning and maintenance procedures. It was noted that very few studies had corrected for attitudes towards cleanliness. Thus, households with meticulous tastes could clean more frequently and even react more strongly to pollution than lackadaisical households, everything else held constant. This attitude was also applicable to household painting costs.

3. A review of the few limited studies on building soiling noted that as a consequence of the lower smoke atmospheric pollution levels experienced in cities during the past thirty years, the practice of

stone cleaning had become more frequent. Indeed, it was noted that the value of the stone cleaning market in the UK was valued at £2M in 1972 and in 1987 the value was £74M. Allowing for inflation, the value of the 1972 stone cleaning market would have been worth £10.3M in 1987. Thus, there has been a real increase of some £64M.

4. An in-depth survey of stone cleaning companies in the UK yielded much information with respect to the prices of cleaning and the techniques used, the types of customer and their reason for cleaning. The stone cleaning companies recommended frequency of cleaning and their views on the benefits of cleaning and sources of deposited matter on the buildings were noted. Their replies yielded much circumstantial evidence to support the hypothesis that vehicular derived pollution was a significant contributor to the deposited matter on soiled building facades.

CHAPTER EIGHT

1. A survey of customers of the stone cleaning companies yielded much information on the perceived benefits of stone cleaning. Although most of the respondents ranked reasons of aesthetics as the primary reason for undertaking stone cleaning, a strong benefit of cleaning was that of protecting the building fabric from further decay. It was also noted that within the public sector, stone cleaning may have other sociological benefits such as decreasing the amount of vandalism and graffiti.

2. The amount spent on stone cleaning by representative organisations within the private and public sector gave an average value of £80M per annum within the UK. This figure is in very close agreement to the value of the stone cleaning industry as identified by such companies' turnover and as

reported in Chapter Seven.

3. The results of this survey also showed that buildings were not always cleaned due to economic constraints within their organisations. This was especially applicable for organisations within the public sector. However, it was noted that when stone cleaning is undertaken by the latter it is often for political-sociological reasons such as part of the restoration of cities in need of urban regeneration. Case studies of such examples were reviewed.

4. A provisional cost-benefit analysis of building soiling within the UK was attempted, though reference was made to the limitations of its findings. For example, it was assumed that DERV emissions were largely responsible for soiling. If the technology were fully developed to curtail such emissions from HGVs the cost would be in the order of £240M. Thus, it would take at least five years to recuperate this expenditure in terms of a decreasing amount of money spent on stone cleaning during this time.

5. Finally, it should be noted that if diesel emissions are later proven to be responsible for the majority of building soiling and legislative measures are not enforced to curtail such emissions, the rate of building soiling in the future may increase. As is shown in Table 2.4, diesel fuel consumption within the UK is increasing. This is because in comparison with petrol vehicles diesel has a better fuel efficiency and is cheaper in price. Thus, as is seen from Figures 9.1 and 9.2 the market share of both diesel driven HGVs and cars is expected to rise in the UK. DERV emissions may also increase in the future as the quality of the fuel decreases by lowering its cetane number to meet its increasing demand. However, such forecasts depend upon fiscal and

legislative action as well as further environmental research on the effects of such emissions. For example, the projected estimates for diesel growth in West Germany may now not follow the trend given in Figures 9.1 and 9.2. The evidence here suggests that diesel emissions may be more detrimental to the environment than petrol exhaust emissions

Figure 9.1 Estimated proportion of diesel cars within France, West Germany, USA and UK from 1975-2000

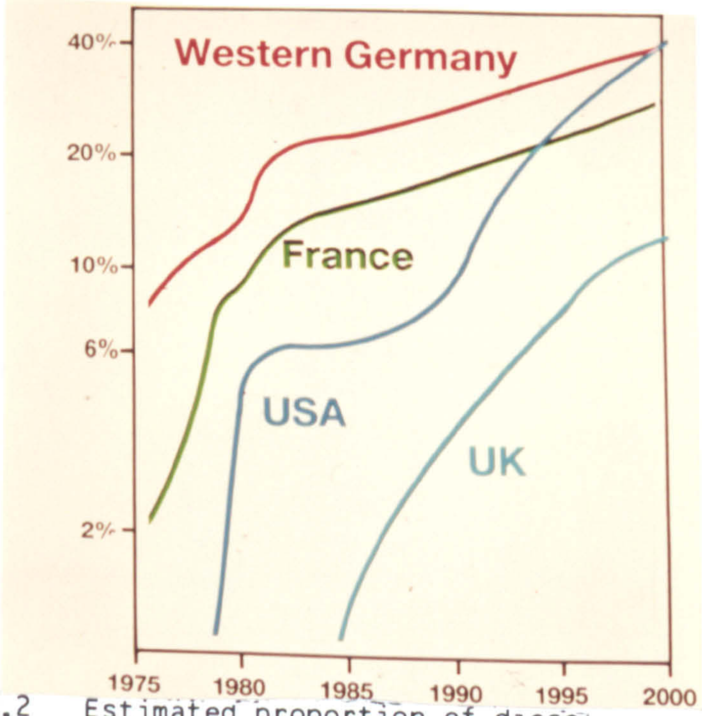
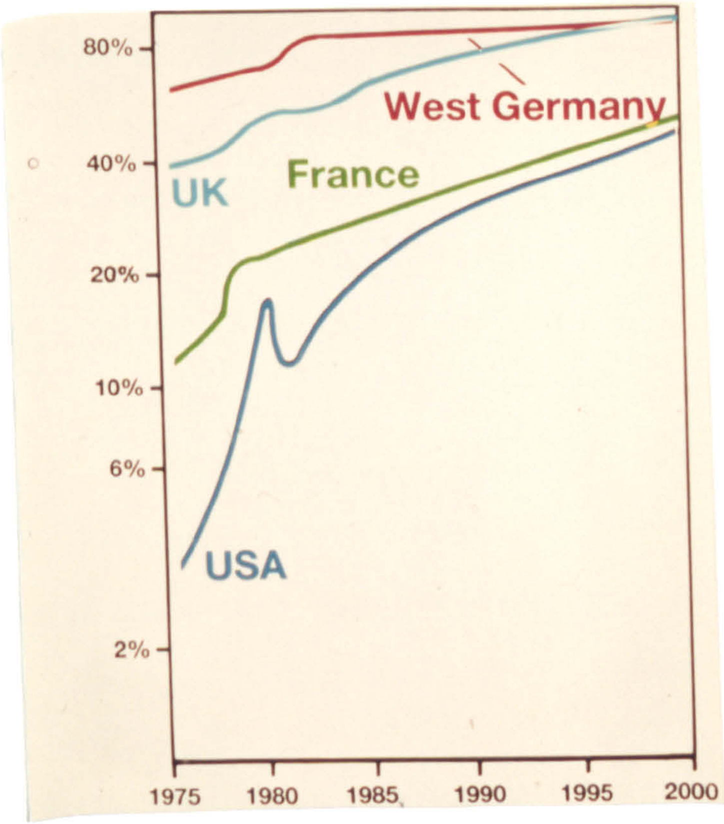


Figure 9.2 Estimated proportion of diesel HGVs within France, West Germany, USA and UK from 1975-2000



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This thesis is dedicated to my niece Rebecca-Clare and her new brother/sister due to be born in February 1989 in the hope that they may grow up in a world where environmental issues are given the respect and attention they rightly deserve.

APPENDIX A

The measurement of soiling and retention strength of cotton fabric after eighteen months of exposure

Introduction

The role of air pollutants in the deterioration of cotton fabrics has received limited attention in outdoor exposure programmes.
Race (1949)(168) found from an experiment conducted in Leeds that exposed cotton yarn suffered greater strength loss during winter months than during the summer, despite the higher sunlight intensity during that period. He attributed this to the threefold increase in coal consumption, together with a high incidence of calm, foggy days that resulted in a higher atmospheric acidity in the winter.

The primary method of sample evaluation is by measurement of the retention breaking strength. The breaking strength of the samples of cotton (pillowcases) exposed in the nine-site exposure programme, were tested at the end of the exposure period using a tensometer. Three samples were tested for both the weft (width) and warp (length) of each of the nine samples. This was done because such materials are aniostrophic - (i.e. have different directional strengths).

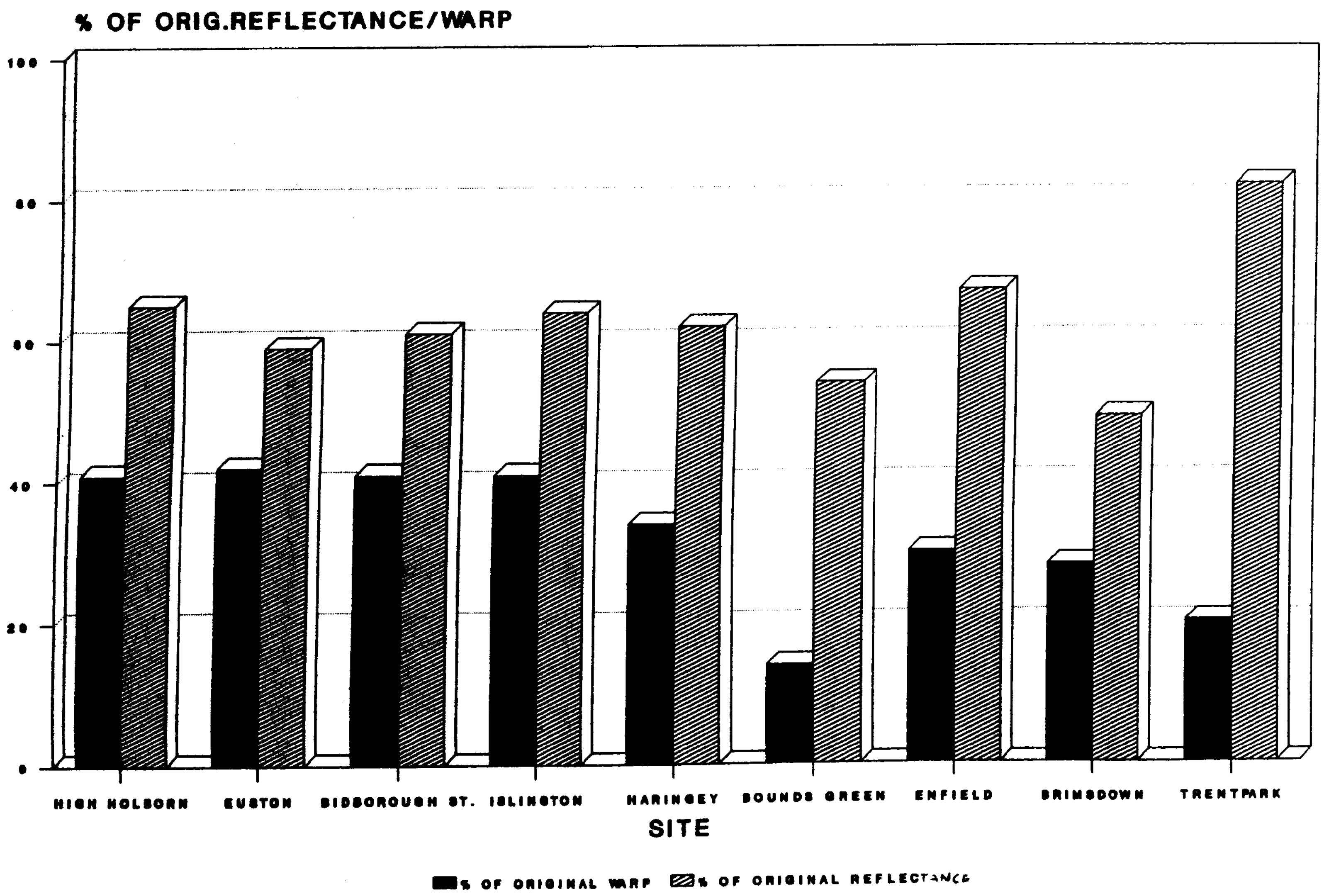
Method:

The samples were cut into 10 cm by 3 cm strips and the results of the breaking strength tests recorded. The retention strength of the warp is usually quoted in such studies and for new unexposed cotton pillowcases the warp is usually in the range of 310 newtons. Below in Table A.1 the average retention strength of the weft and warp and the percentage of original warp strength is given, together with the percentage decrease of original reflectance after nearly eighteen months of exposure. The average concentrations of smoke and sulphur dioxide recorded in $\mu g\ m^{-3}$ are also given for each site.

Table A.1 The retention strength and % of original reflectance for cotton samples exposed at a variety of nine locations in London

Site	No. of days of exposure	Average ambient level of Smoke	Average ambient level of Sulphur dioxide	Retention strength of weft	Retention strength of warp	% of original warp strength	% of original reflectance H = Horizontal V = Vertical
		(in $\mu g\ m^{-3}$)		(in Newtons)			
High Holborn	526	21	57	76	128	41	65H 62V
Euston	595	48	47	124	133	42	59H 54V
Bidborough St.	512	19	40	102	129	41	61H 61V
Islington	595	18	39	103	129	41	64H 55V
Haringey	552	13	41	71	107	34	62H 64V
Bounds Green	519	19	-	40	44	14	54H 50V
Enfield	559	18	45	61	93	30	67H 61V
Brimsdown	541	23	-	48	89	28	49H 51V
Trent Park	565	7	-	89	62	20	82H 76V
Average and Standard Deviation		20.6 ± 10.6	44.8 ± 6.7	79 ± 20.0	101 ± 30.4	32 ± 9.6	63H 59V ± 8.6 ± 7.6

FIGURE A.1 THE RELATIONSHIP BETWEEN % OF ORIGINAL REFLECTANCE AND % OF WARP STRENGTH



COTTON SAMPLES AFTER 18 MONTHS EXPOSURE

From the results displayed in Table A.1 and Figure A.1, there appears to be no real general relationship between smoke and sulphur dioxide levels and the effect on retention breaking strength or reflectance. For example. the Euston site had the highest smoke level and one of the highest sulphur dioxide levels. yet its retention strength was one of the highest recorded. Likewise, the Trent Park site had the lowest level of smoke recorded, yet its retention strength was the lowest, although its soiling rate was the lowest. Perhaps no general pattern is emerging between pollutant levels and the effect on cotton because the range in pollutant levels is not sufficiently great for an obvious pattern to emerge. As is shown in Table A.1. the mean smoke level was 20.6 $\mu g\, m^{-3}$ for the nine sites with a S.D. of ± 11. Likewise for sulphur dioxide, despite levels being only available for 6 of the 9 sites the level was 44.8 $\mu g\, m^{-3}$ with a S.D. of ± 7.

However, it should be remembered that pollution may not be the only factor responsible for the deterioration of exposed cotton samples. Indeed, it may be that other pollutants not recorded here may be more effective deteriorating agents than the smoke and sulphur dioxide levels recorded here. Also, biological damage may also be partly responsible for the decrease in retention strength observed here. Indeed, the samples from Trent Park and Enfield were noted as having mildew. Unfortunately, cellulose fluidity determinations were not made on these samples. This test works on the principle that unexposed cotton fabric is composed of relatively large molecules and when dissolved in a suitable reagent yields a solution of low fluidity. When the average size of these molecules has been reduced by chemically induced degradation (accelerated depolymerization caused by sunlight, contamination, etc.) the fluidity increases and is accompanied by a loss of breaking strength of the fabric. However, biologically damaged samples do not show this reduction in average molecular size and despite a reduction in strength, the fluidity of the dissolved sample is very similar to that of the undamaged sample.

Despite such limitations, some general observations can be noted:

(i) between 500-600 days exposure, cotton samples displayed in locations where smoke values ranged from 7-48 $\mu g\ m^{-3}$ and sulphur dioxide approximately from 41-57 $\mu g\ m^{-3}$, the retention of the weft was 79 Newtons ±26. Assuming that unexposed cotton has a retention strength of 310 Newtons in the warp direction, after exposure the average retention strength recorded here was 32% ±10 of the original;

(ii) the average decrease in the percentage of original reflectance for the cotton samples exposed in the horizontal direction was 63% ±9 and for the vertical direction 59% ±8.

Finally, it is worth considering the economic aspects of air pollution induced deterioration. Brysson et al (1967)(169) assumed that a fabric article retains serviceability up to the point where it retains 33% of its original strength. Results from this study show that this point is reached before 600 days of exposure. Though as mentioned above, not all of the deterioration in strength is attributable to the effects of air pollution alone. Biological action may also play a part in the degradation of such exposed materials. Indeed, it may be that biological action is a more important degradating agent in rural areas than air pollutants. Since in urban areas where higher levels of air pollutants are observed, the presence of potentially biologically damaging species to cotton are absent, because of their intolerance to high levels of air pollution.

Electrostatic Precipitator:

An electrostatic precipitator was used to collect a sample of the ambient aerosol within the Hatfield tunnel. This is because analysis of the PEC content of the aerosols deposited on glass fibre filters has inherent operational difficulties. For example, during the combustion of the filter, it melts and this can entrap the deposited particles and prevent their combustion. Also, false readings may occur which are due to the release of gases produced during the melting of the glass fibre filter.(37)

The electrostatic precipitator used was a 'Bendix' model 573. A high voltage potential (12 kV. d.c) is maintained across the plates of a capacitor with the air to be sampled flowing between the capacitor plates. The ionizing potential formed from the elctrostatic field creates ions in the gas stream. These ions then collide with particles and charge them. Such charged particles migrate under the influence of the electrostatic field to the collecting electrode. The device has been reported to be virtually 100% efficient for a wide range of particle sizes at flow rates of up to 85 litre min^{-1}.

Indeed, high voltage electrostatic precipitators are used more widely in industry than other types of high efficiency particulate matter collector. The instrument can be fitted with a cyclone, which allows particles of 5 μm or smaller in diameter to be sampled. The cyclone was not used when sampling in the Hatfield tunnel, thus the ash and elemental carbon content may be expected to be higher/lower than samples taken with the cyclone on, for reasons mentioned in Section 2.4.2 and it was not used because it was felt necessary to know the overall content of the ambient aerosol so that comparisons with the content of the deposited materials on the samples were more valid.

APPENDIX B

At the end of the sampling period the deposited particles were scraped off the aluminium walls of the precipitator's cylinder into a platinum sample boat and dried out overnight in a dessicator. This latter procedure was also done for the deposited matter present on the exposed materials, described in Section 6.4.

Elemental Analysis:

The measurement of the carbon content of the afore-mentioned samples were carried out using a Perkin Elmer C.N.H. elemental analyser. The model type 240C can accurately determine the carbon (as CO_2), hydrogen (as H_2O) and nitrogen content of organic compounds. Usually over 1 mg of the sample is needed for the analysis. Combustion occurs in pure oxygen and the products formed as a result of this are analysed automatically by the use of a thermal conductivity analyser and showed the results produced from the analysis. Sensitivity factors, analytical results and blanks are computed in weight per cent using an Epxm Microvitec Cub Computer, model 1431 MS and printed using an Epxm terminal printer of MX 30 range.

The carbon result is the fraction of the carbon in the mass inserted into the analyser. As mentioned in Section 3.5, elemental carbon is not more than $\frac{1}{3}$ of the total carbon. Thus the results obtained from the analysis of the samples measured total carbon only. Thus these results were divided by a third to give the values of elemental carbon quoted in Section 6.4.

APPENDIX C

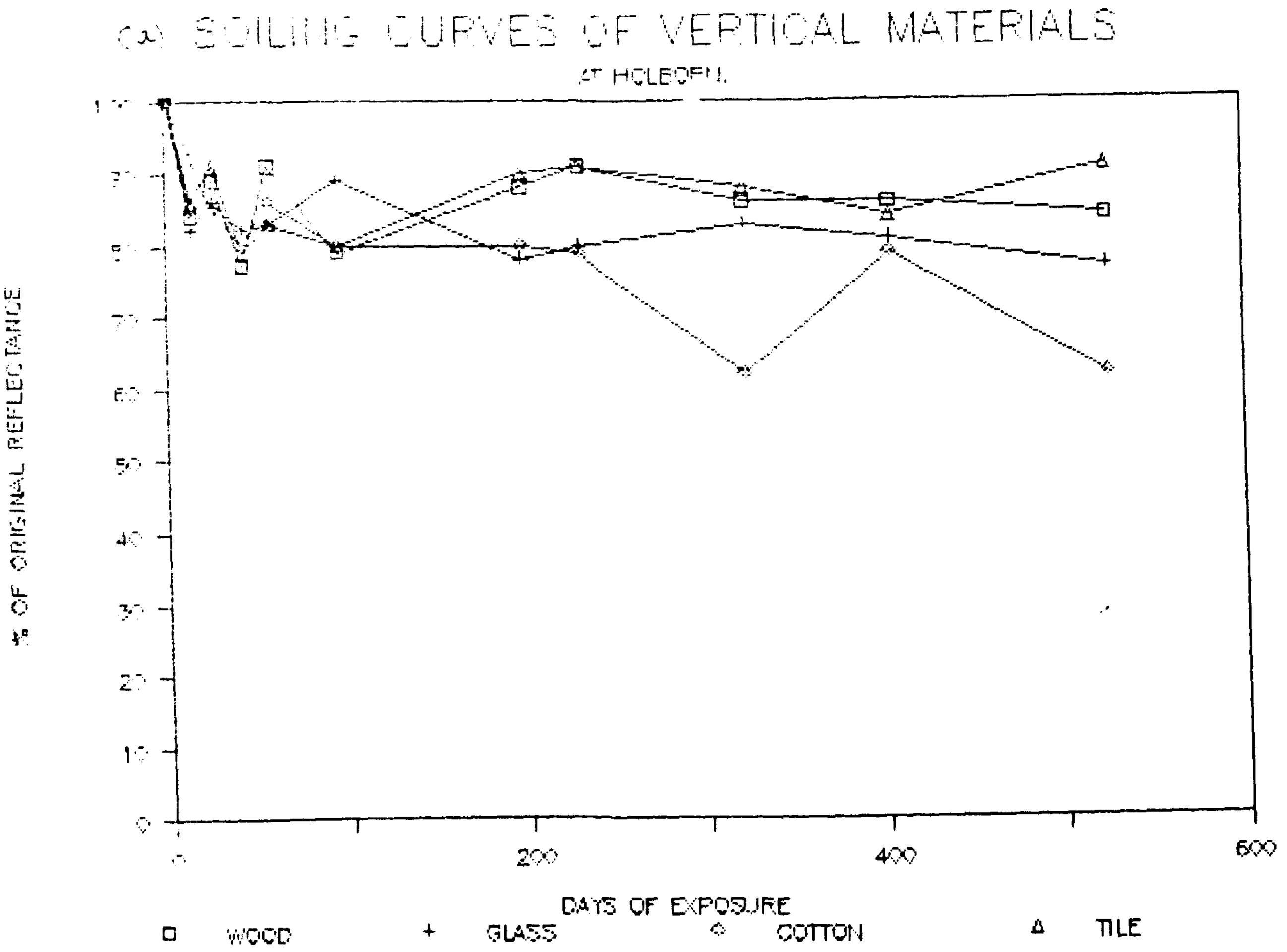
Table C.1 The percentage of the materials' original reflectance, smoke and rainfall measurements recorded at the High Holborn site during the exposure period

TQ reference for site: TQ 3035381452

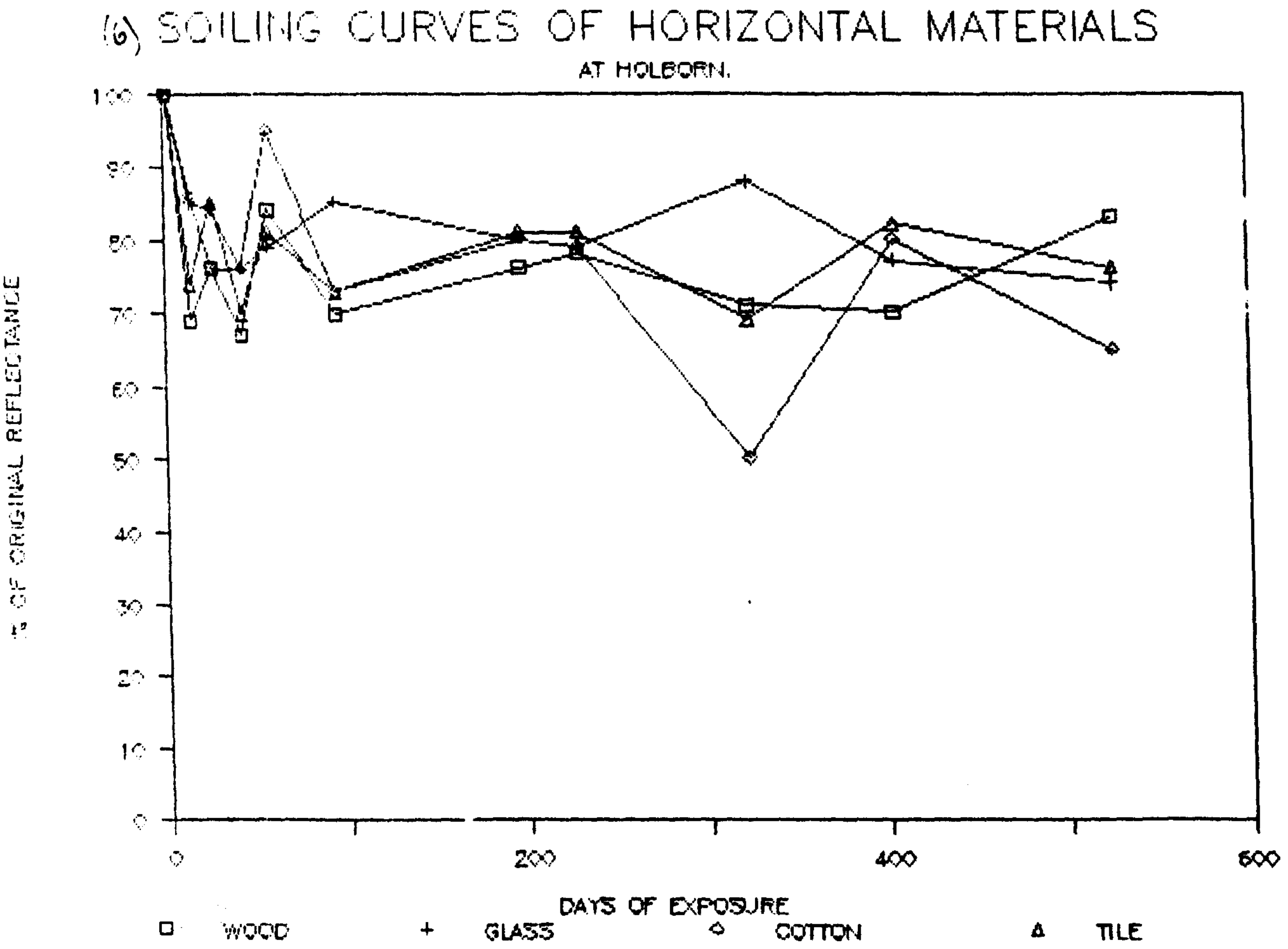
Site 1 on Figure 6.7.

days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
14	21	25	69	84	85	82	86	92	74	86
26	15	12	76	89	84	86	76	85	85	91
42	12	23	67	77	76	82	76	80	70	79
57	15	17	94	91	79	83	95	86	81	83
96	19	52	70	79	85	89	73	80	73	80
198	23	221	76	88	80	78	80	80	81	90
230	20	74	78	91	79	80	79	72	81	91
324	26	121	71	86	88	83	50	52	69	88
405	23	114	70	86	77	81	80	79	82	84
526	19	292	83	84	74	77	65	62	76	91

Figure C.1.1 The view from the High Holborn roof-top site where the samples were exposed



(a) SOILING CURVES OF VERTICAL MATERIALS AT HOLBORN.



(b) SOILING CURVES OF HORIZONTAL MATERIALS AT HOLBORN.

Figure C.1.2 (a)-(b) The soiling curves of the horizontal and vertical materials at High Holborn

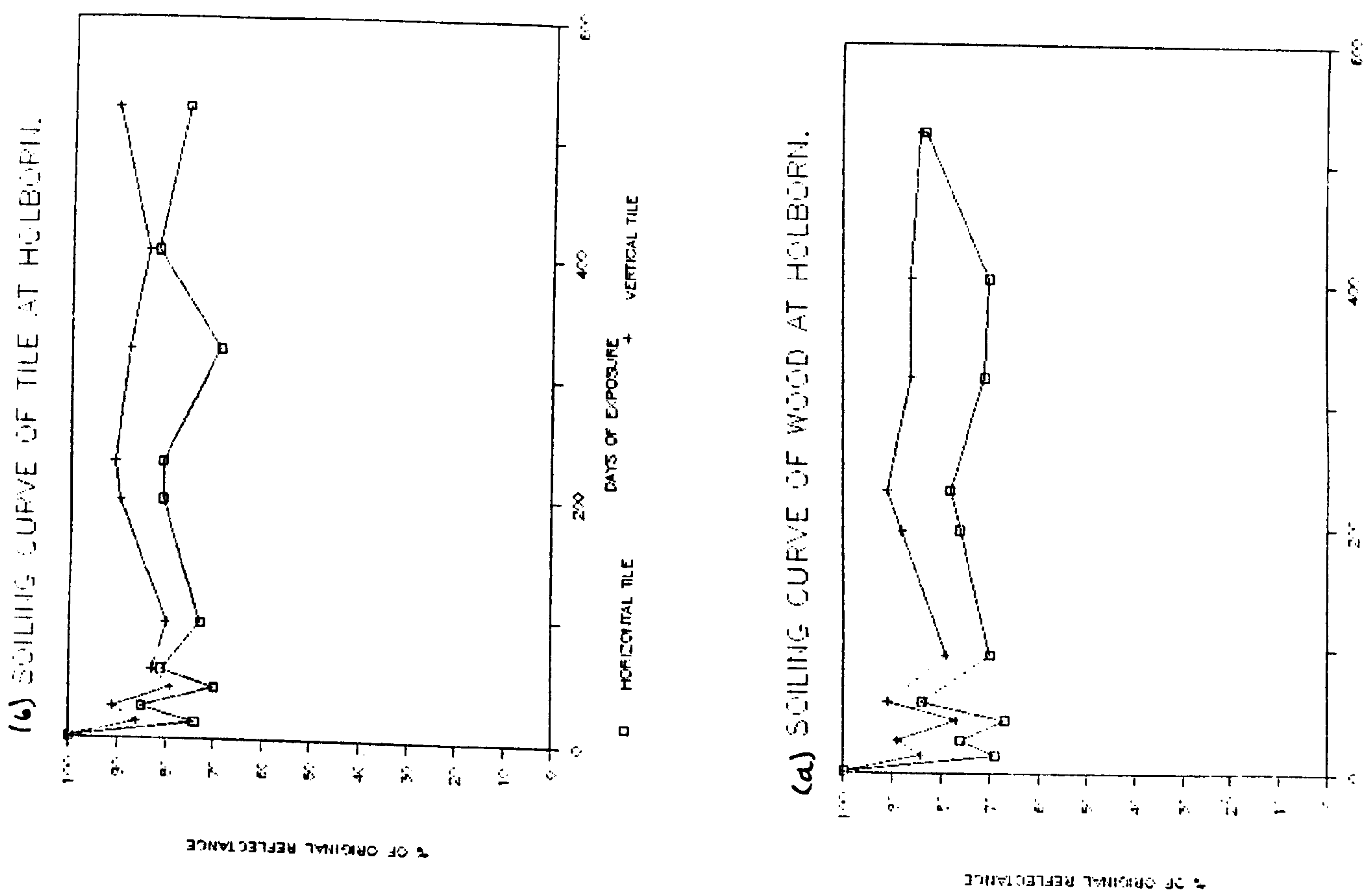


Figure C.1.3 (a)~(d) The soiling curves of the individual materials (horizontal and vertical) at the High Holborn site

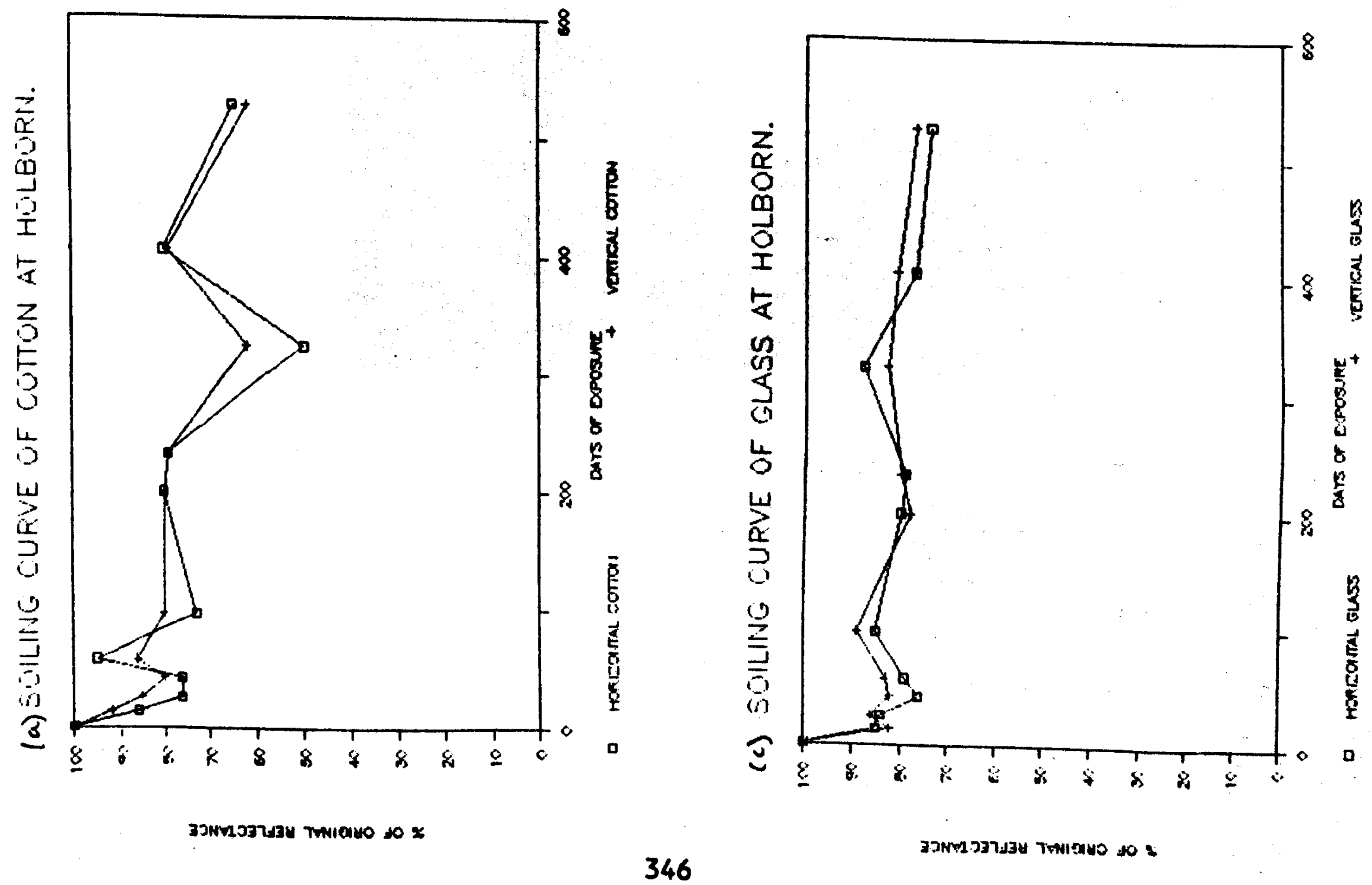


Table C.2 The percentage of the materials' reflectance smoke and rainfall measurements recorded at the Bidborough Street site in Bloomsbury during the exposure period

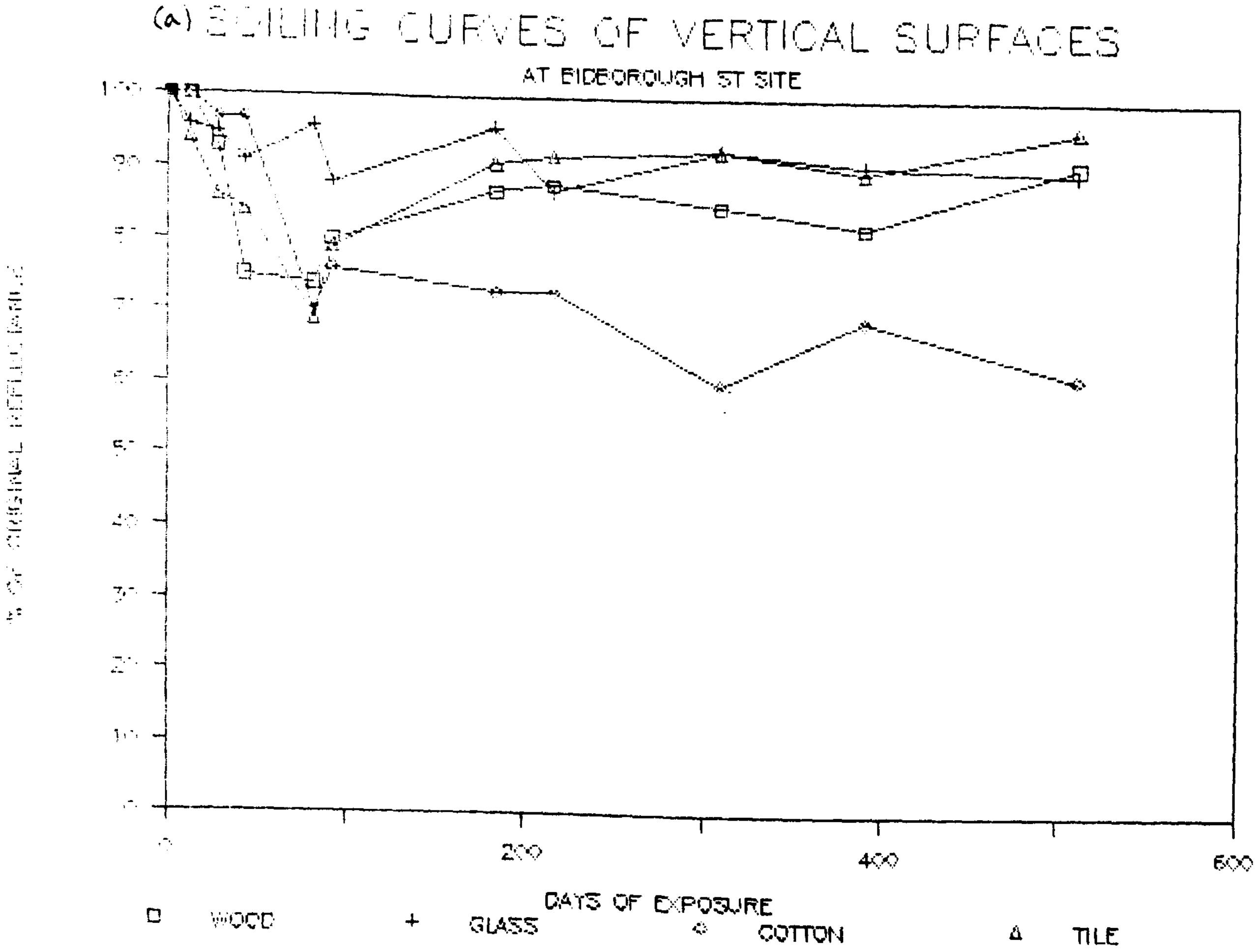
TQ reference for site: TQ 3002682712

Site 2 on Figure 6.7

days of exposure	smoke (µg m^{-3})	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
12	10	12	8	100	*	96	100	100	82	94
28	9	28	84	93	*	95	88	97	79	86
43	14	17	74	75	*	91	97	97	74	84
82	15	52	65	74	*	96	67	70	60	69
92	17	9	69	80	100	88	84	76	71	79
184	21	213	74	87	91	96	70	73	81	91
216	20	75	79	88	81	87	73	73	82	92
310	21	118	66	85	95	93	50	60	72	93
391	22	114	76	82	91	91	61	69	85	90
512	22	292	81	91	95	90	61	61	78	96

* = material not exposed

Figure C.2.1 The view from the Bidborough Street roof-top site where the samples were exposed



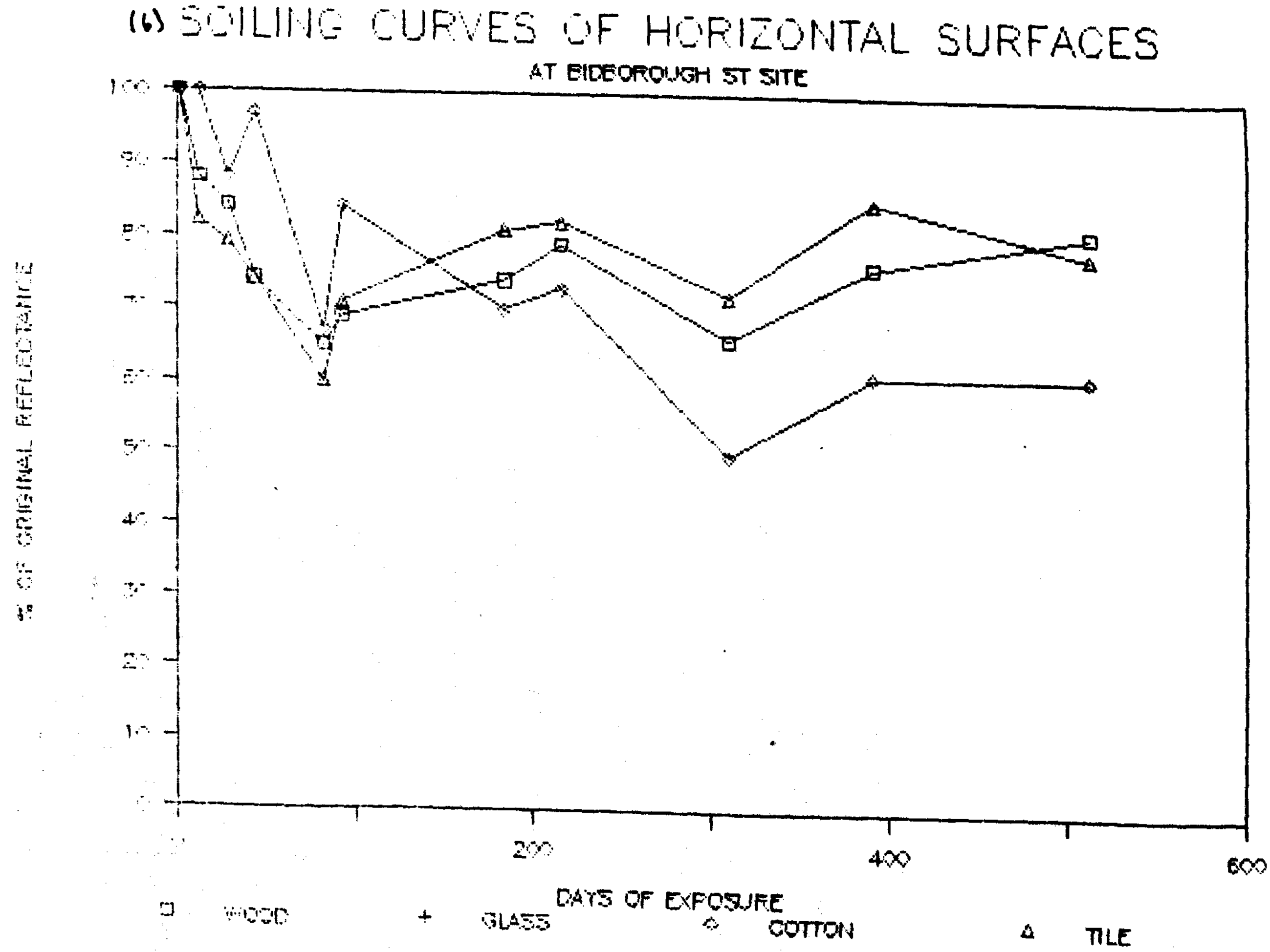
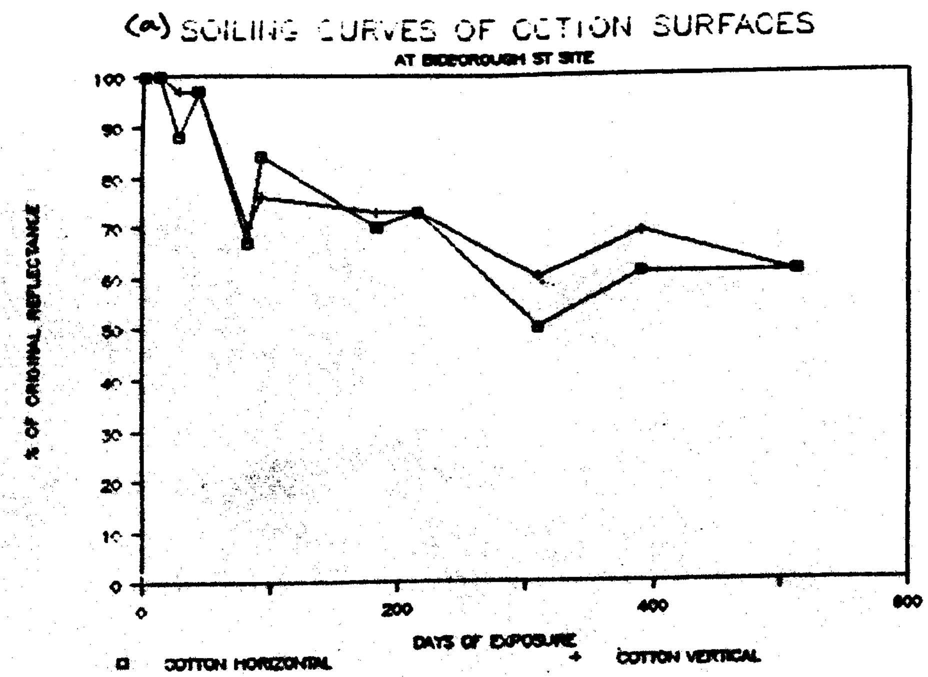


Figure C.2.2 (a)-(b) The soiling curves of the horizontal and vertical materials at Bidborough Street site



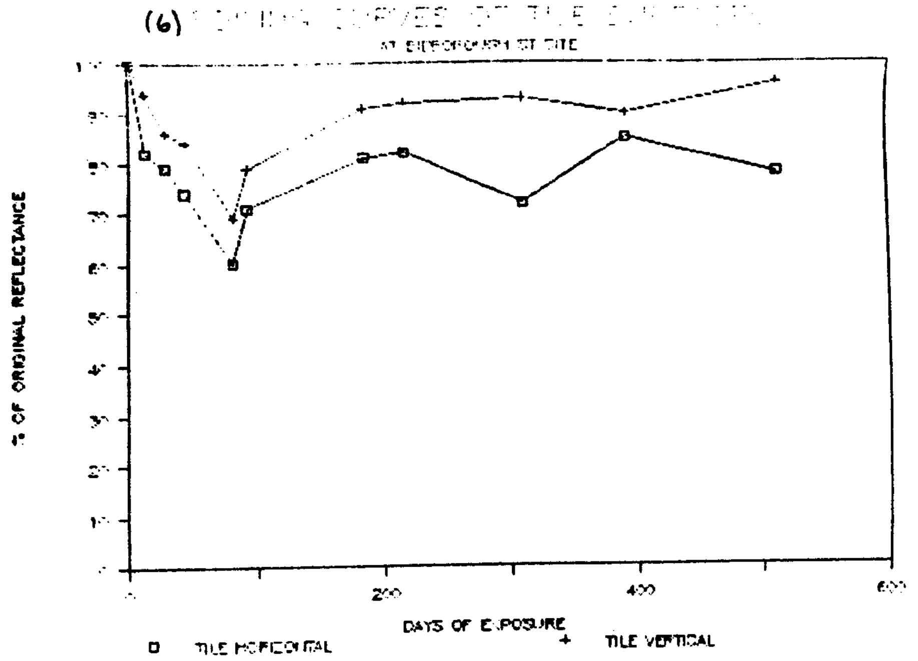
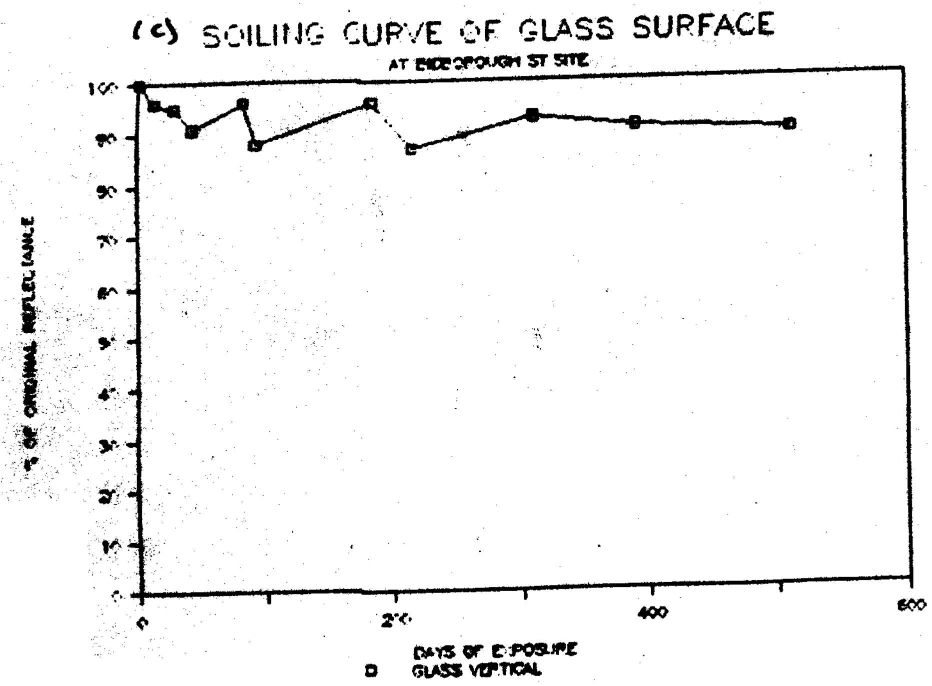


Figure C.2.3 (a) - (d) **The soiling curves of the individual materials horizontal and vertical at the Bidborough Street site**



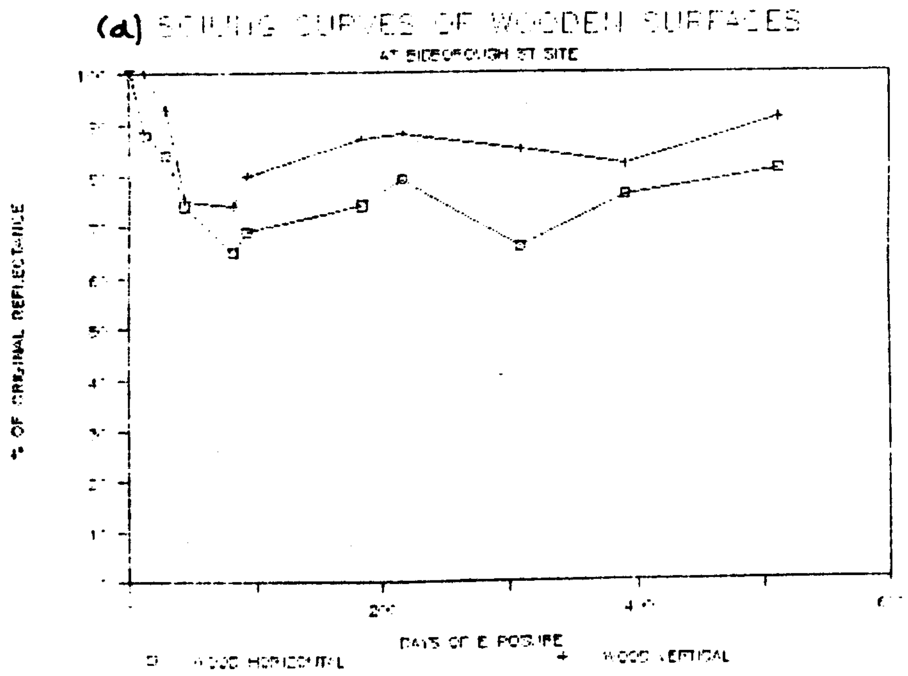


Table C.3 The percentage of the materials' original reflectance, smoke and rainfall measurements recorded at the Euston Road site during the exposure period

TQ reference for site: TQ 29758262

Site 3 on Figure 6.7

days of exposure	smoke (µg m^{-3})	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
7	59	1	68	100	94	94	91	87	76	97
49	47	37	81	96	88	99	81	87	87	96
69	37	50	75	92	94	100	56	59	85	92
83	51	25	55	52	58	94	35	38	40	53
95	35	12	76	91	85	86	49	68	78	89
111	33	28	74	83	87	92	63	69	80	84
126	50	17	52	67	91	100	76	76	52	68
165	44	52	72	79	94	86	54	59	74	82
175	51	9	72	84	75	85	66	65	76	84
267	53	213	73	85	86	80	65	69	75	81
299	48	75	71	85	74	66	62	63	73	87
351	45	75	64	86	67	71	65	66	47	83
393	59	47	62	85	72	68	53	61	40	85
474	47	114	44	55	49	46	50	45	38	63
595	47	292	60	82	72	84	59	54	62	82

Figure C.3.1 The view of the Euston Road site where the samples were exposed (on the flat roof of the stone storeroom)

The soiling curves for the materials from this site are given in Chapter Six, Figures 6.9-6.10

Table C.4 The percentage of the materials' original reflectance, smoke and rainfall measurements recorded at the Islington site during the exposure period

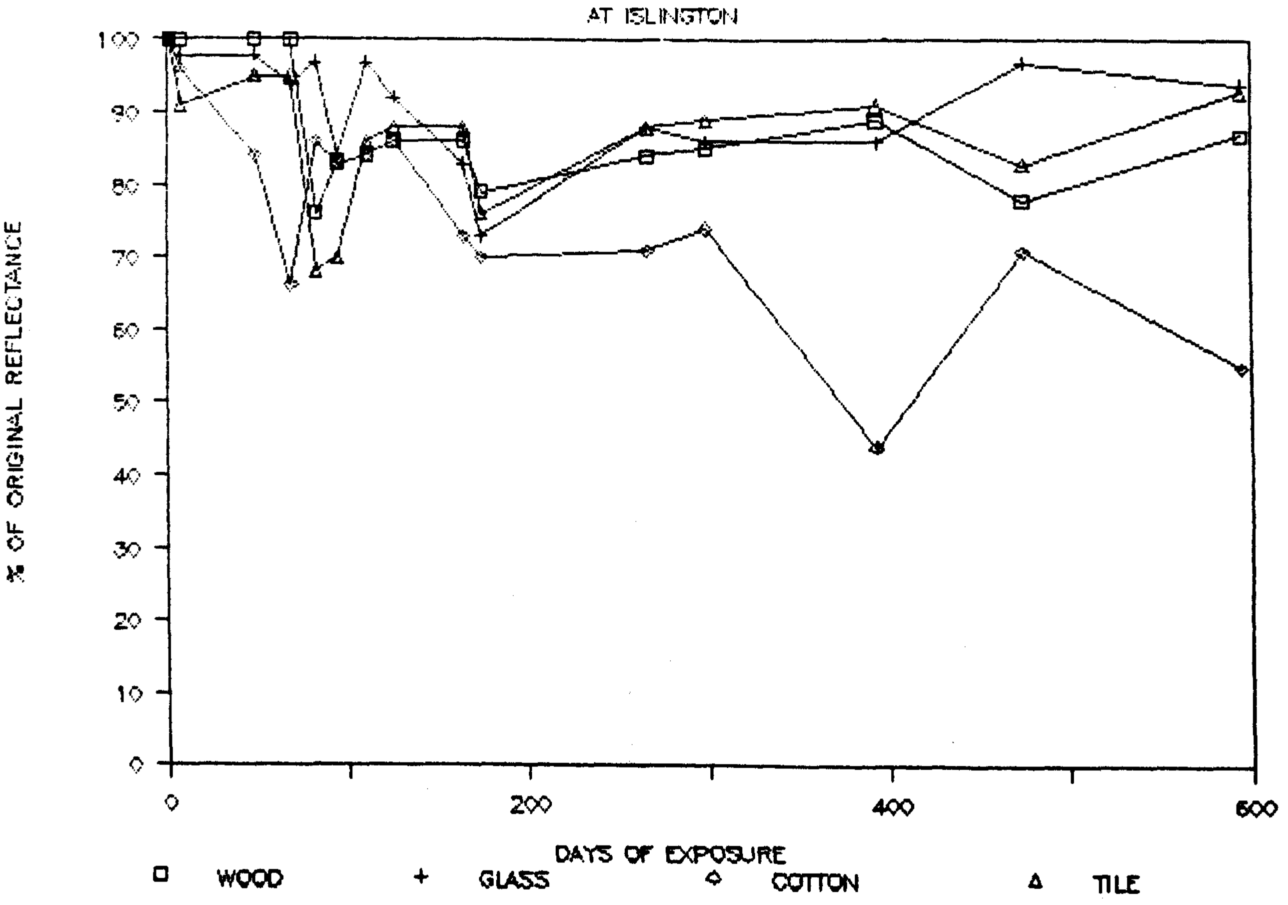
TQ reference for site: TQ 31628413

Site 4 on Figure 6.7

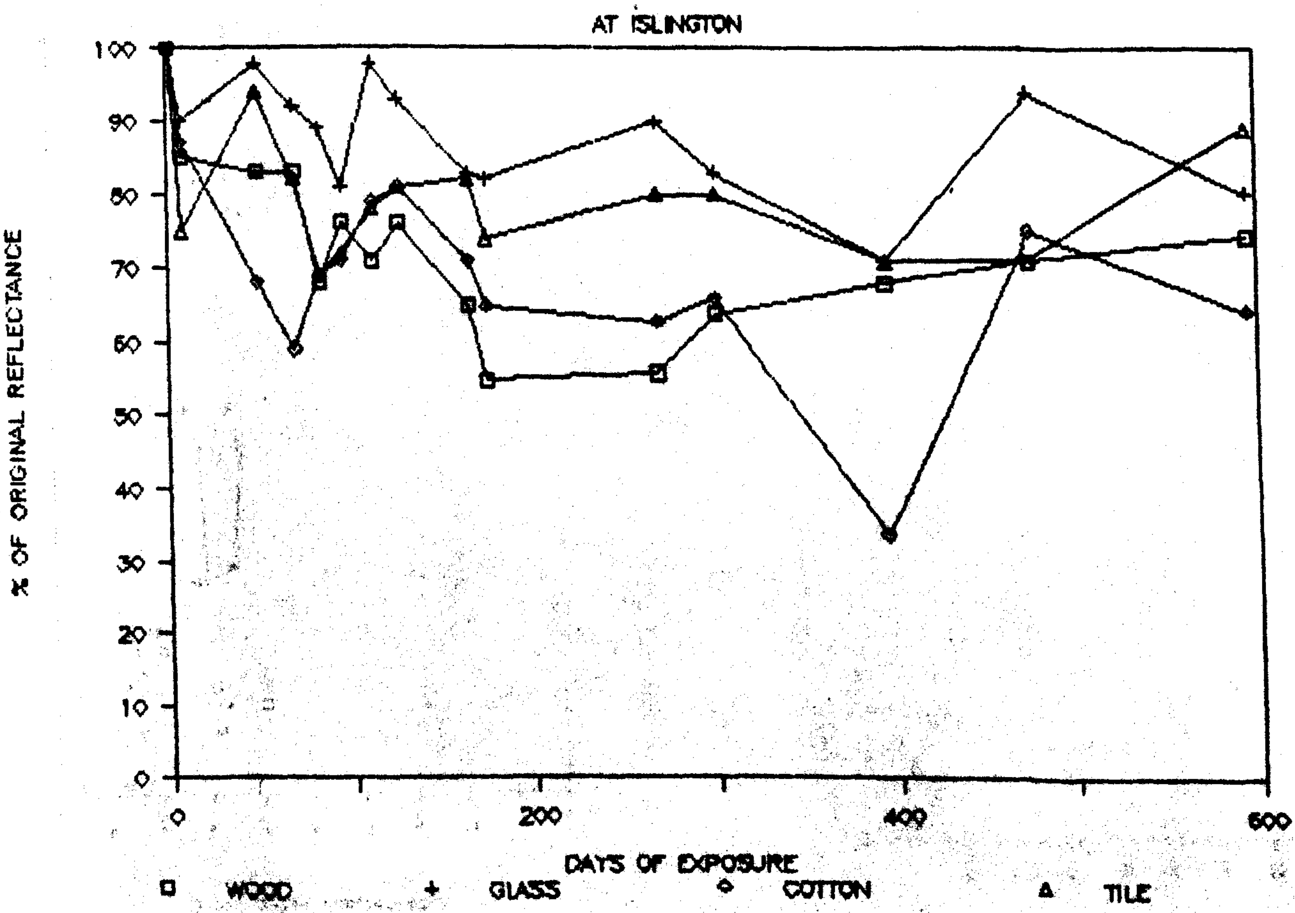
days of exposure	smoke (µg m^{-3})	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
7	34	1.1	95	100	90	98	87	96	75	91
47	12	37.0	93	100	98	93	68	84	74	95
69	11	50.0	83	100	92	94	59	66	72	95
83	14	25.0	69	76	89	97	69	65	69	68
95	19	12.0	76	83	81	84	71	83	72	70
111	8	22.0	71	84	98	97	79	84	73	84
126	17	17.0	76	86	93	92	81	86	81	82
165	14	52.0	65	86	83	83	71	73	82	80
175	12	2.0	55	79	92	73	65	70	74	76
267	27	215.0	56	84	90	89	53	71	80	88
299	27	74.0	64	85	93	86	66	74	80	89
474	17	114.0	71	78	94	97	75	71	71	83
595	11	292.0	74	87	90	94	64	55	89	93

Figure C.4.1 The view from the Islington site where the samples were exposed

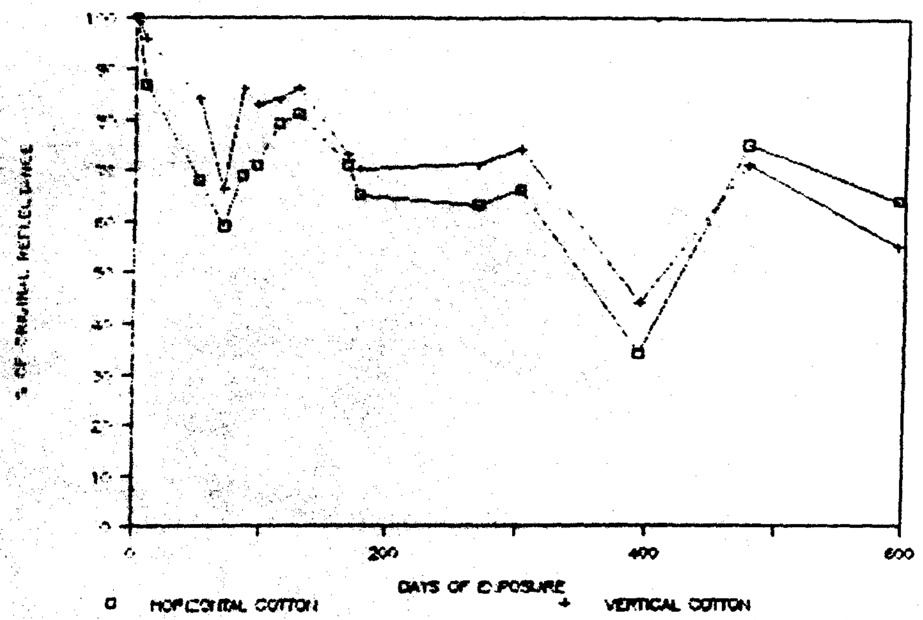
(a) SOILING CURVE OF VERTICAL MATERIALS



(b) SOILING CURVE OF HORIZONTAL MATERIALS



FigureC4.2 (a)-(b) **The soiling curves of the horizontal and vertical materials at the Islington site**


(a) SOILING CURVE OF COTTON AT ISLINGTON.

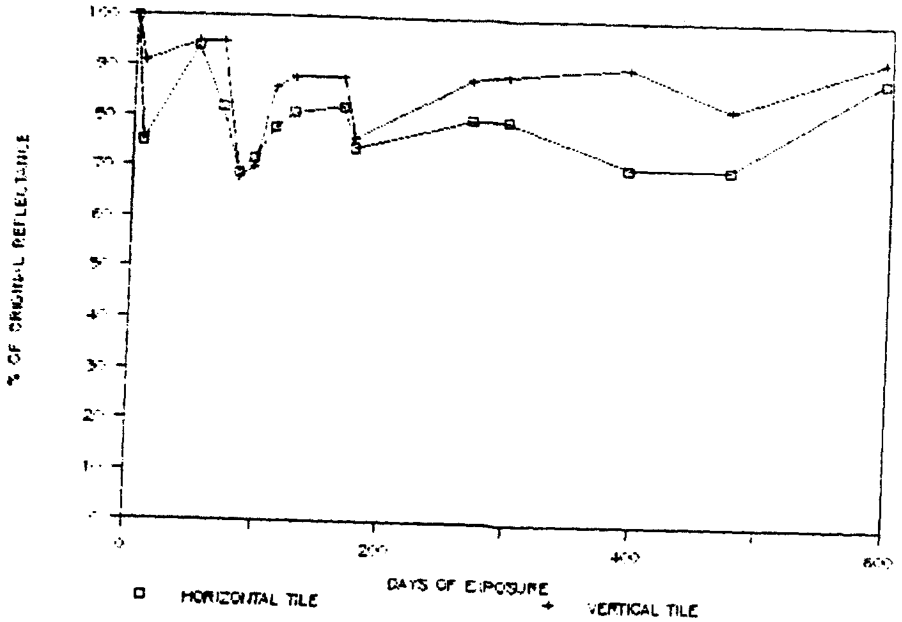
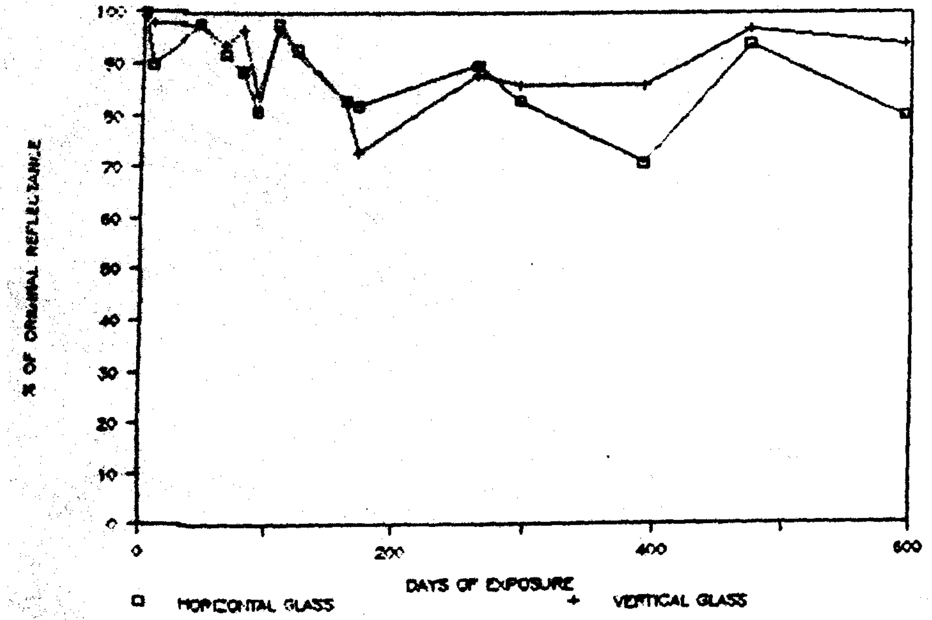

(b) SOILING CURVE OF TILE AT ISLINGTON.

Figure C.4.3 **(a) – (d)** **The soiling curves of the individual materials (horizontal and vertical) at the Islington site**


(c) SOILING CURVE OF GLASS AT ISLINGTON.

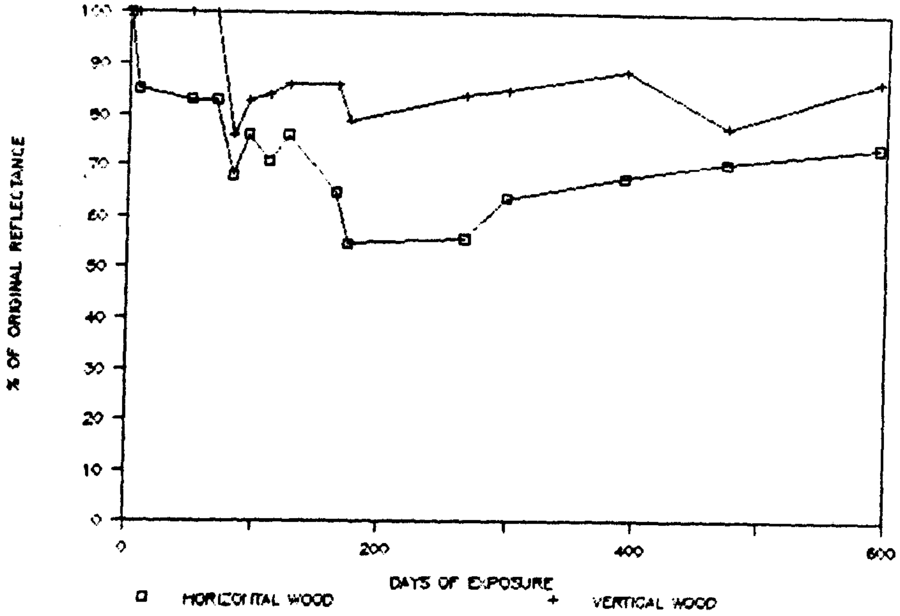

(d) SOILING CURVE OF WOOD AT ISLINGTON.

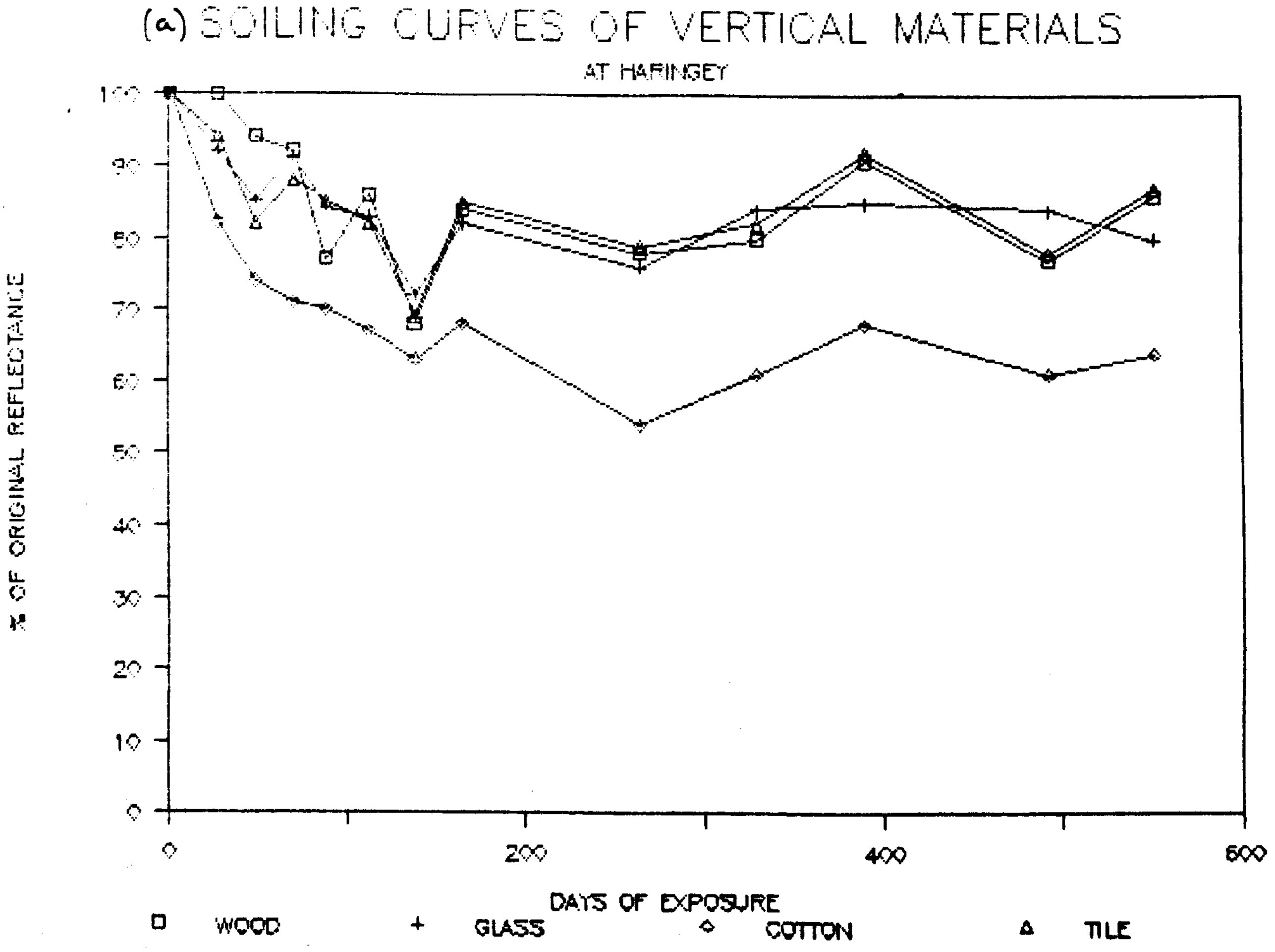
Table C.5 The percentage of the materials' original reflectance, smoke and rainfall measurements recorded at the Haringey site during the exposure period.

TQ reference for site: TQ 33628934

Site 5 on Figure 6.7

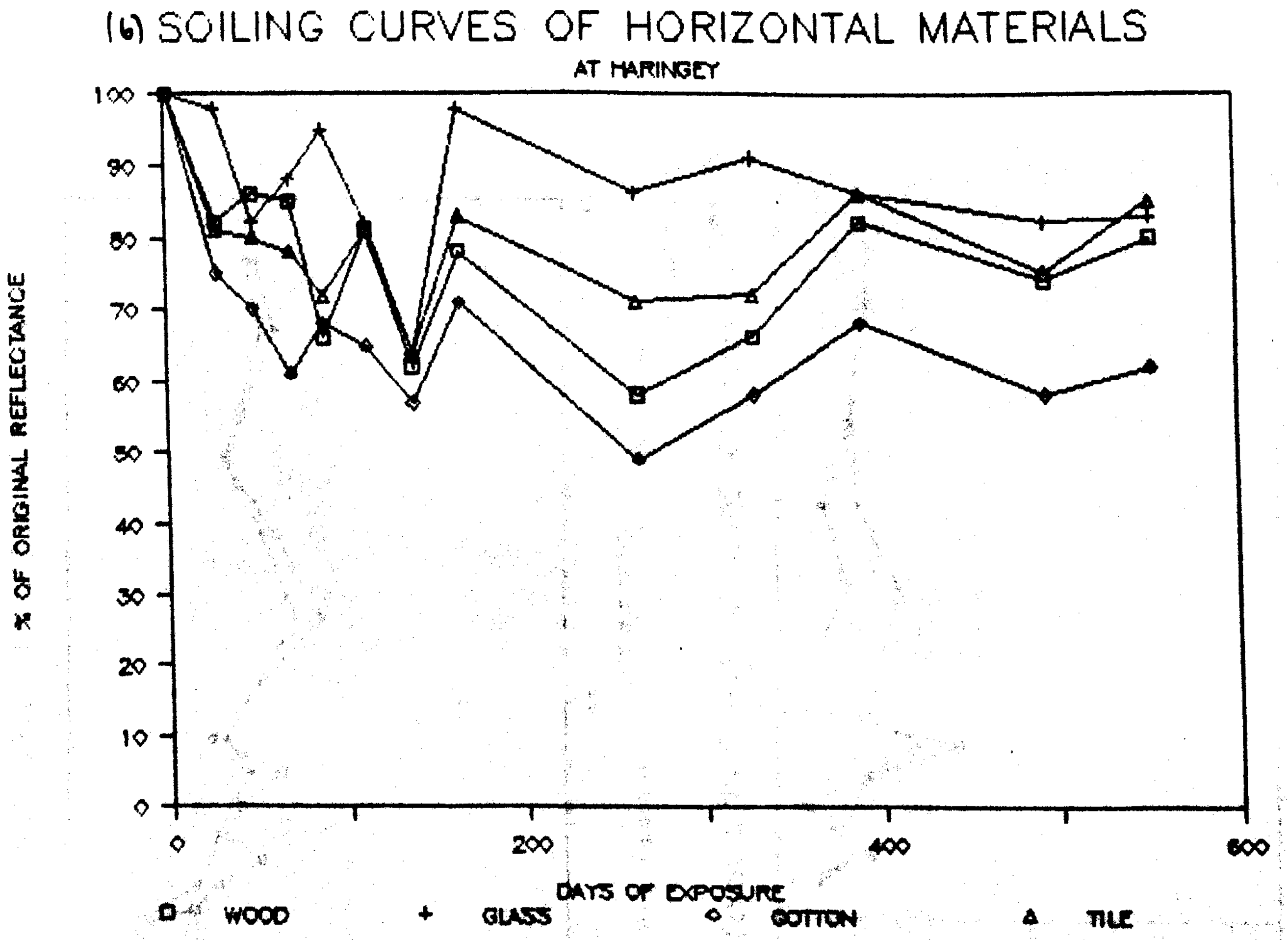
days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
28	23	7	82	100	98	92	75	82	81	94
49	11	49	86	94	82	85	70	74	80	82
70	8	53	85	92	88	91	61	71	78	88
98	7	14	66	77	95	84	68	70	72	85
112	7	39	81	86	82	83	65	67	81	82
138	7	10	62	68	64	72	57	63	64	69
165	4	55	78	84	98	82	71	68	83	85
264	11	220	58	78	86	76	49	54	71	79
330	13	138	66	80	91	84	58	61	72	82
390	21	55	82	91	86	85	68	68	86	92
493	17	76	74	77	82	84	58	61	75	78
552	11	246	80	86	83	80	62	64	85	87

Figure C.5.1 The view from the Haringey roof-top site where the samples were exposed. (chimney not used)



(a) SOILING CURVES OF VERTICAL MATERIALS

AT HARINGEY

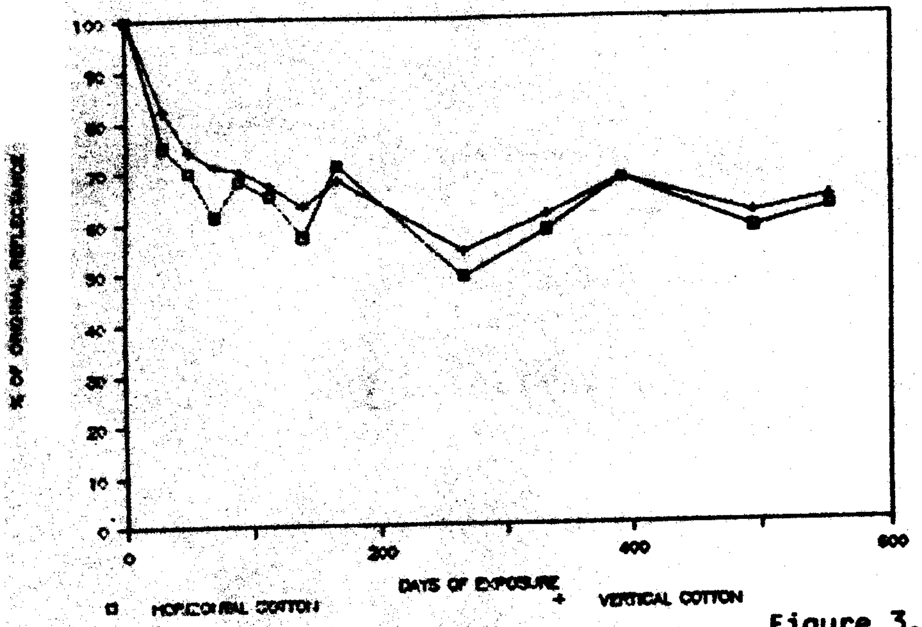


(b) SOILING CURVES OF HORIZONTAL MATERIALS

AT HARINGEY

Figure C.5.2 (a)-(b) <u>The soiling curves of the horizontal and vertical materials at the Haringey site</u>

(a) SOILING CURVE OF COTTON AT HARINGEY.



(b) SOILING CURVE OF TILE AT HARINGEY.

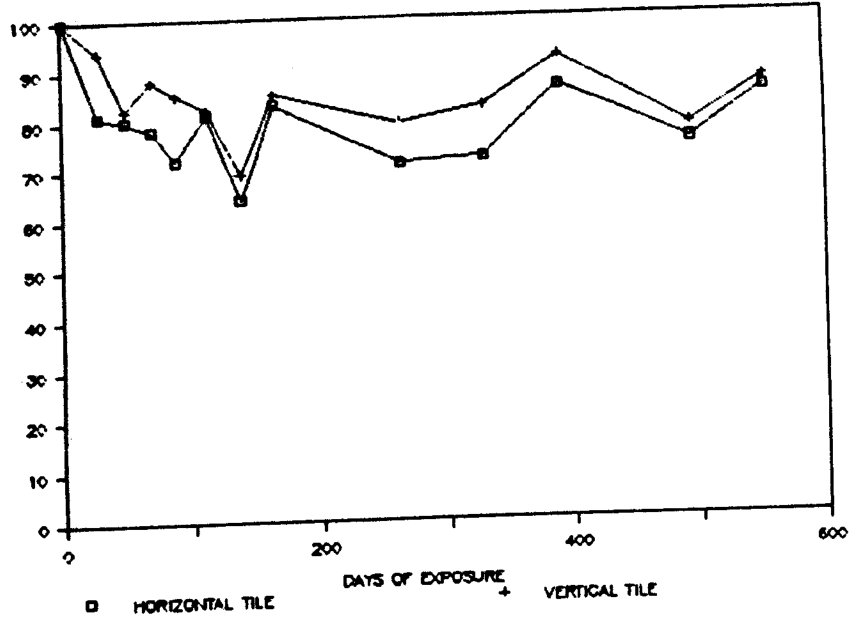
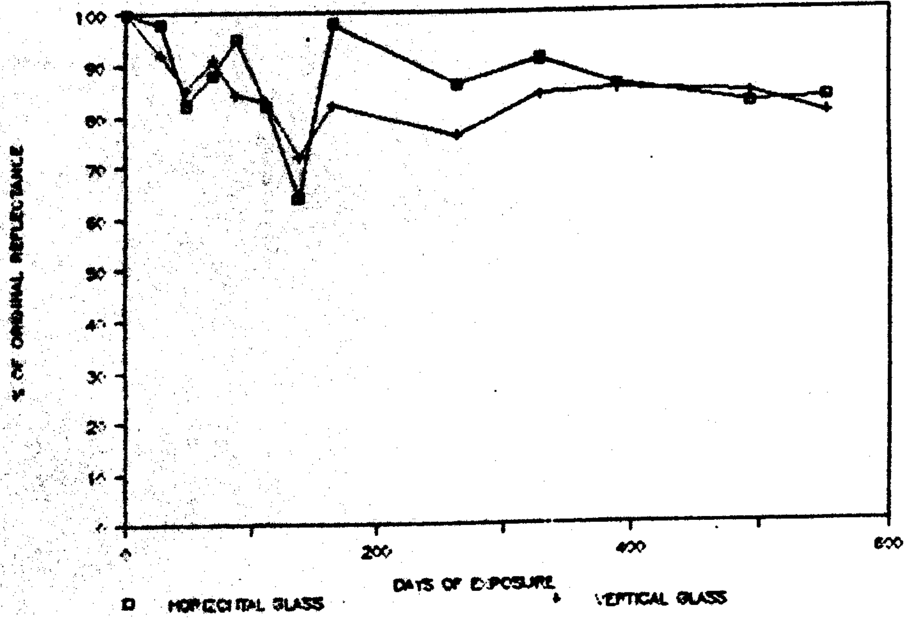


Figure 3.5.3 (a)-(d) The soiling curves of the individual materials (horizontal and vertical) at the Haringey site

(c) SOILING CURVE OF GLASS AT HARINGEY.



(d) SOILING CURVE OF WOOD AT HARINGEY.

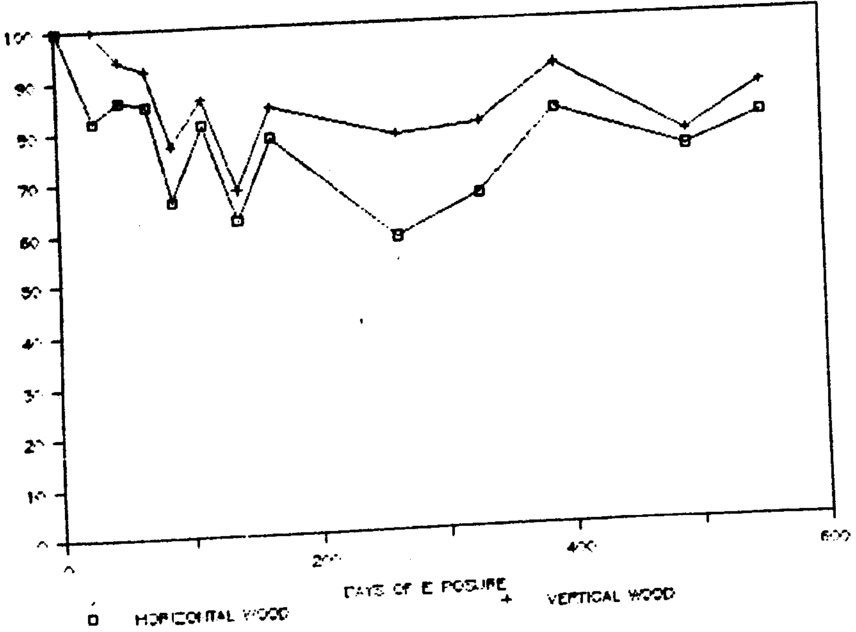


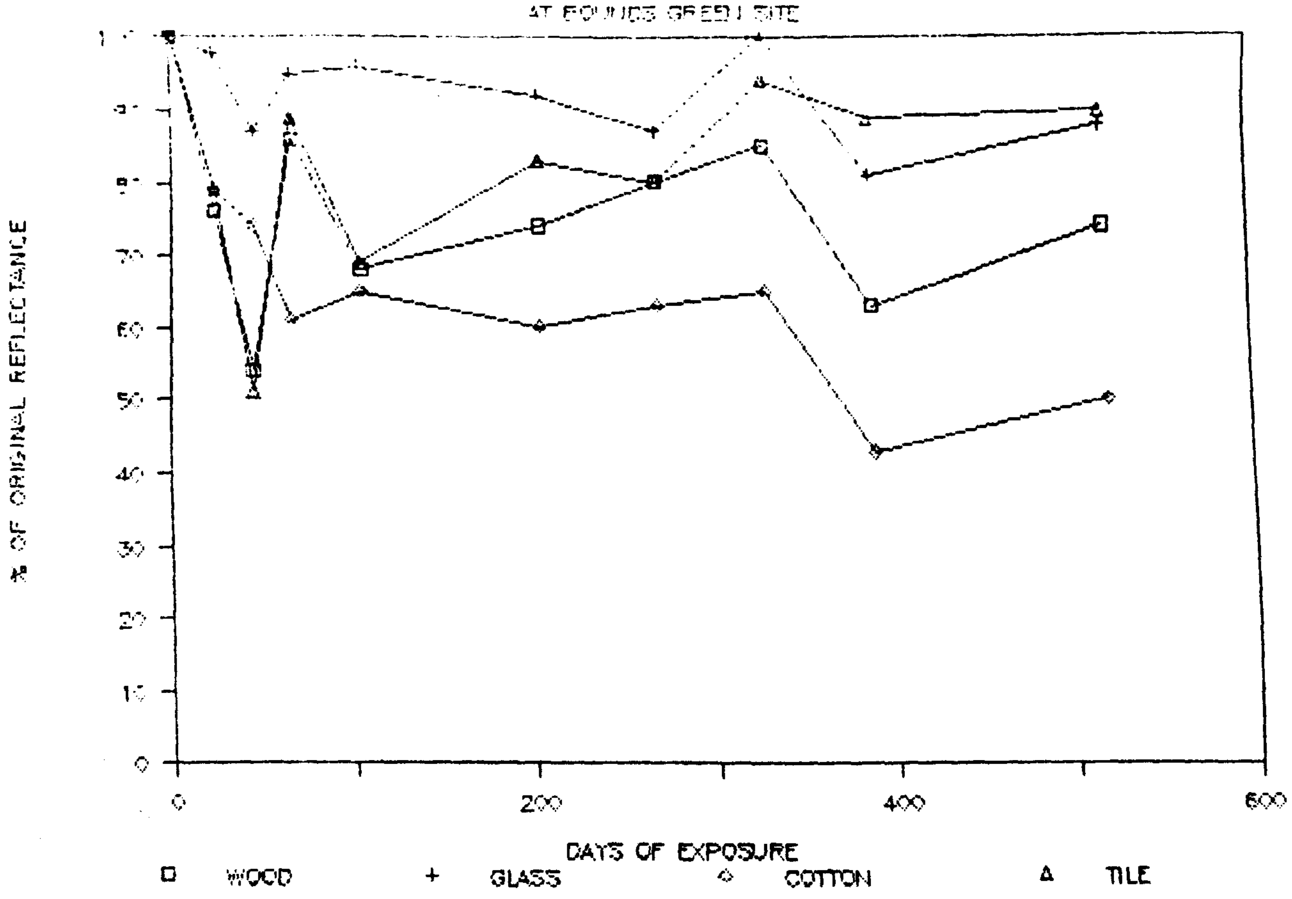
Table C.6 The percentage of the materials' original reflectance, smoke and rainfall measurements recorded at the Bounds Green site during the exposure period

TQ reference for site: TQ 29269184

Site 6 on Figure 6.7.

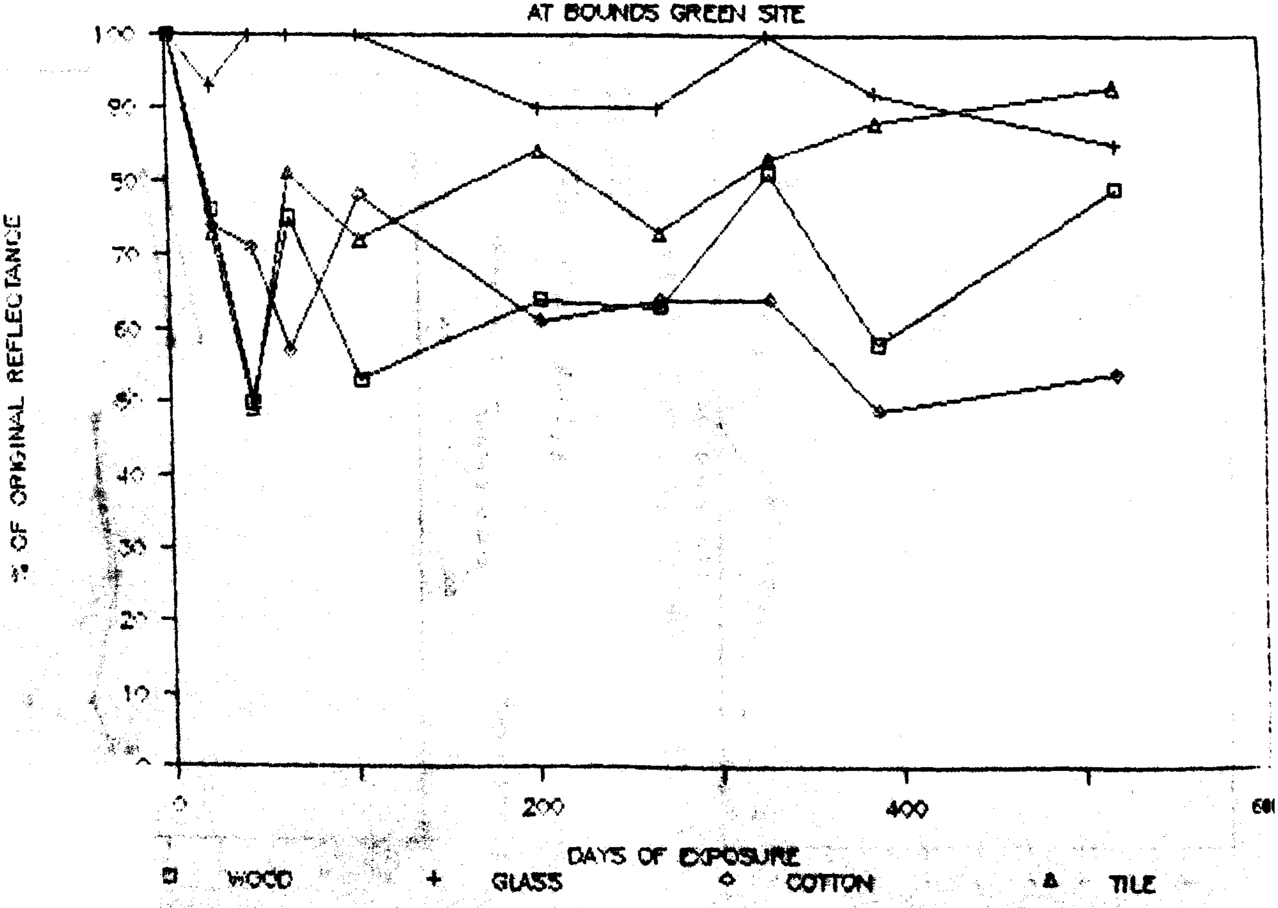
days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
24	13	45	76	76	93	98	74	79	73	79
45	11	35	50	54	100	87	71	74	49	51
66	19	14	75	86	100	95	57	61	81	89
105	20	60	53	68	100	96	78	65	72	69
204	24	220	64	74	90	92	61	60	84	83
270	17	137	63	80	90	87	64	63	73	80
330	17	55	81	85	100	100	64	65	83	94
389	17	76	58	63	92	81	49	43	88	89
519	17	317	79	74	85	88	54	50	93	90

Figure C.6.1 The view from the Bounds Green roof-top site where the samples were exposed



(a) SOILING CURVES OF VERTICAL SURFACES

AT BOUNDS GREEN SITE



(b) SOILING CURVES OF HORIZONTAL SURFACES

AT BOUNDS GREEN SITE

Figure C.6.2 (a) - (b) The soiling curves of the horizontal and vertical materials at the Bounds Green site

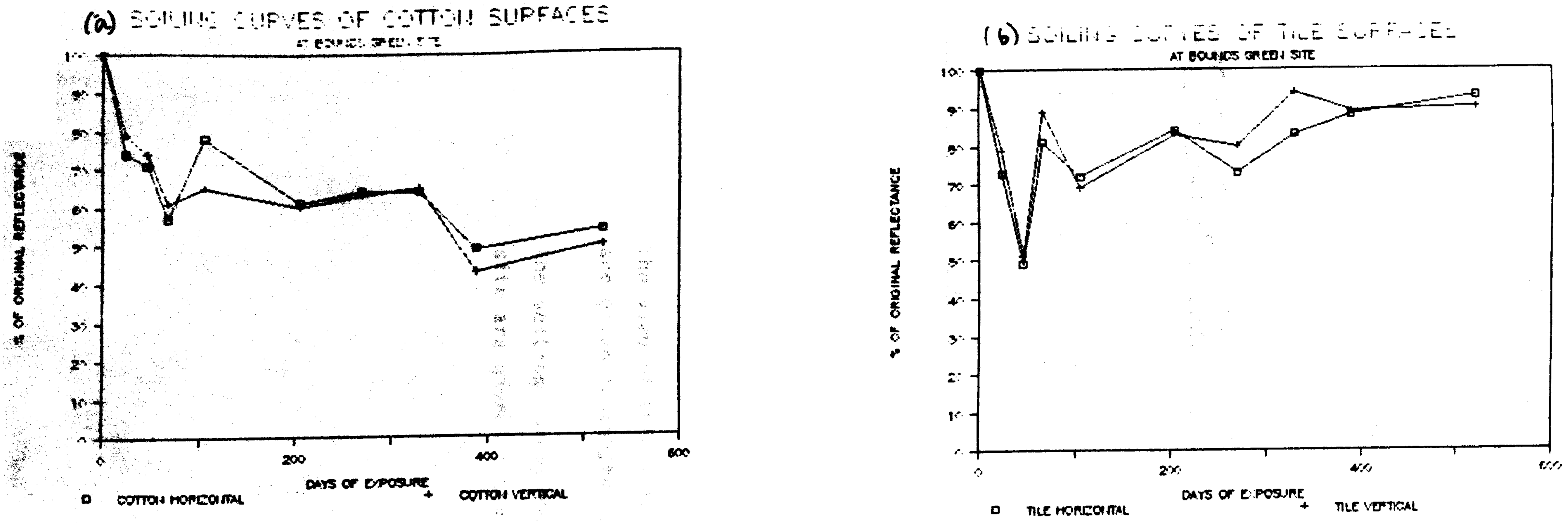


Figure C.6.3 The soiling curves of the individual materials (horizontal and vertical) at the Bounds Green site

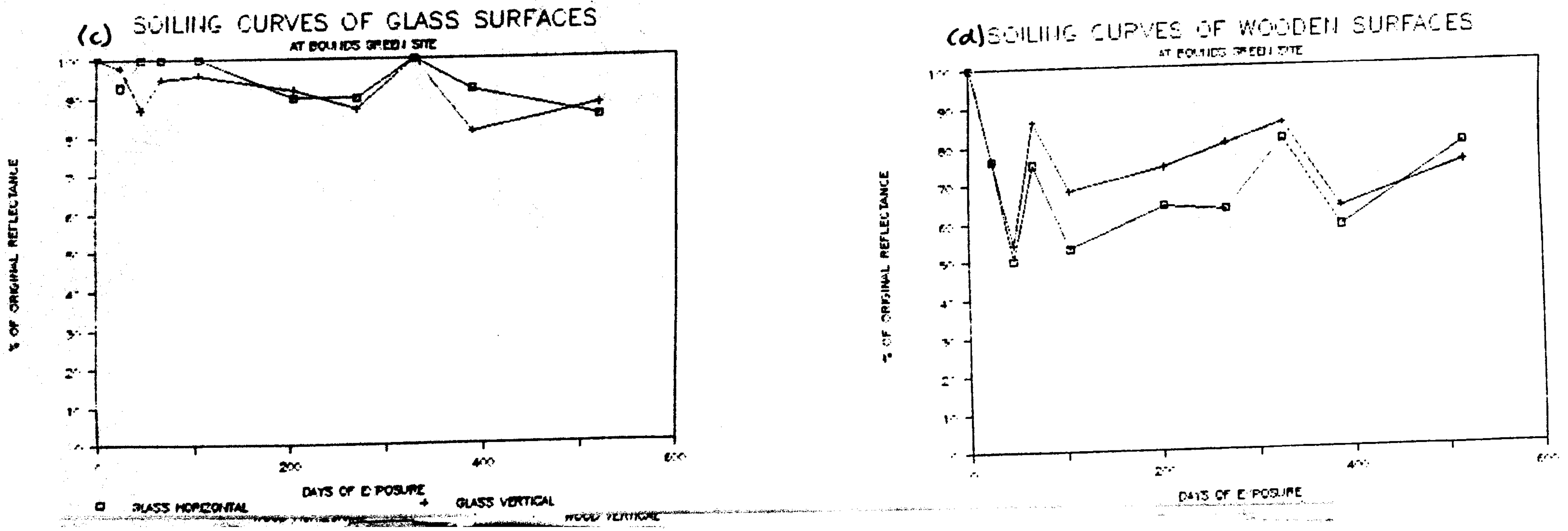


Table C.7 The percentage of the materials' original reflectance, smoke and rainfall measurements at the Enfield site during the exposure period

TQ reference for site: TQ 35089587

Site 7 on Figure 6.7

days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
15	32	26	70	76	100	95	80	82	79	81
43	10	76	85	87	100	99	84	83	91	91
66	16	19	64	68	100	96	81	77	87	83
86	9	34	71	73	94	87	74	76	77	75
100	12	6	52	56	96	86	68	72	63	68
237	18	279	68	76	100	91	68	66	76	78
267	13	70	76	80	100	85	65	75	82	83
321	22	75	52	64	100	89	78	80	54	69
367	27	27	65	81	100	94	80	77	72	81
421	18	76	69	71	72	86	68	85	74	81
527	17	191	79	87	96	85	77	72	96	93
559	17	78	84	89	97	85	67	61	94	94

The view of this site and the exposed materials are given in Chapter Six, Figure 6.8

The soiling curves for the materials from this site are given in Chapter Six, Figures 6.11-6.12.

Table C.8 The percentage of the materials' original reflectance, smoke and rainfall measurements at the Brimsdown site during the exposure period

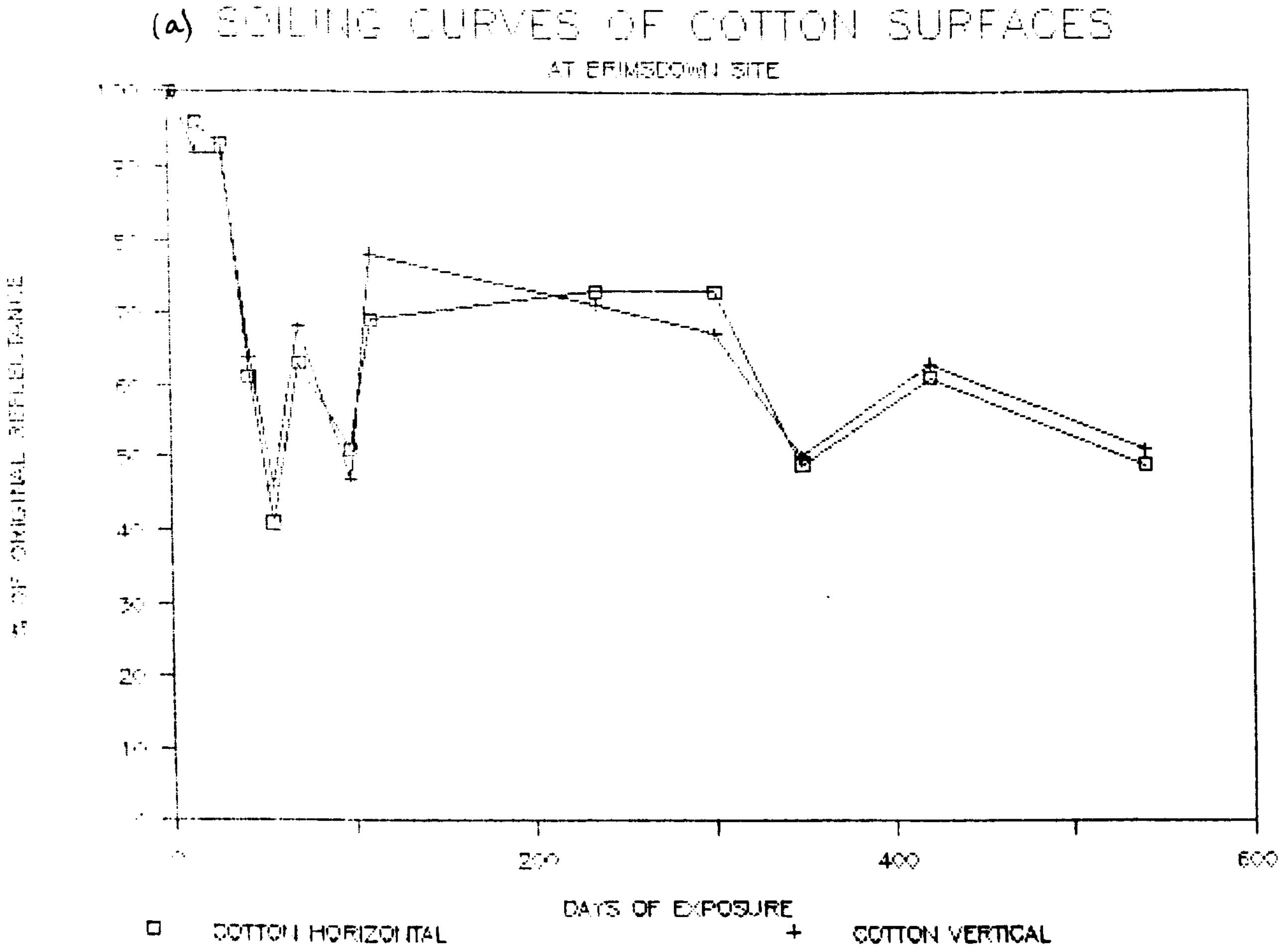
TQ reference for site: TQ 36849811

Site 8 on Figure 6.7

days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
15	20	30	93	95	*	97	96	92	98	97
29	10	31	92	92	*	97	93	92	70	92
43	15	42	81	82	96	95	61	64	89	88
56	19	4	58	66	97	97	41	46	52	76
71	17	30	61	67	94	98	63	68	74	77
99	17	20	20	35	44	41	51	47	26	32
111	19	4	65	80	76	88	69	78	59	77
237	27	28	74	79	92	93	73	71	78	80
303	28	139	66	86	92	95	73	67	70	84
350	32	23	42	54	63	66	49	50	55	55
422	21	148	55	68	87	84	61	63	64	77
541	20	301	75	91	89	93	49	51	84	92

* = material not exposed

Figure C.8.1 The view of the materials at the Brimsdown (industrial estate) site



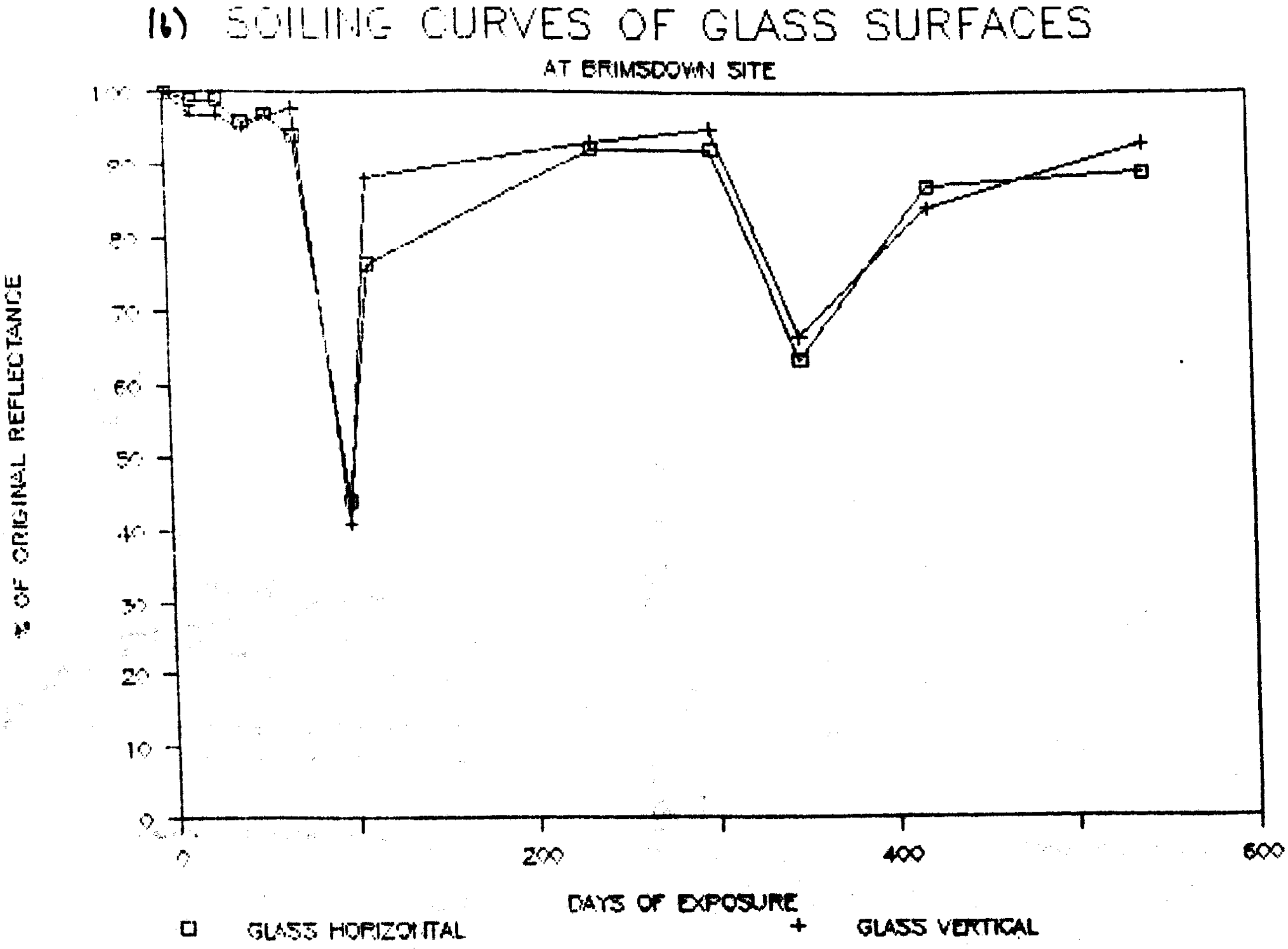


Figure C.8.2 (a) – (b) The soiling curves of the horizontal and vertical materials at the Brimsdown site

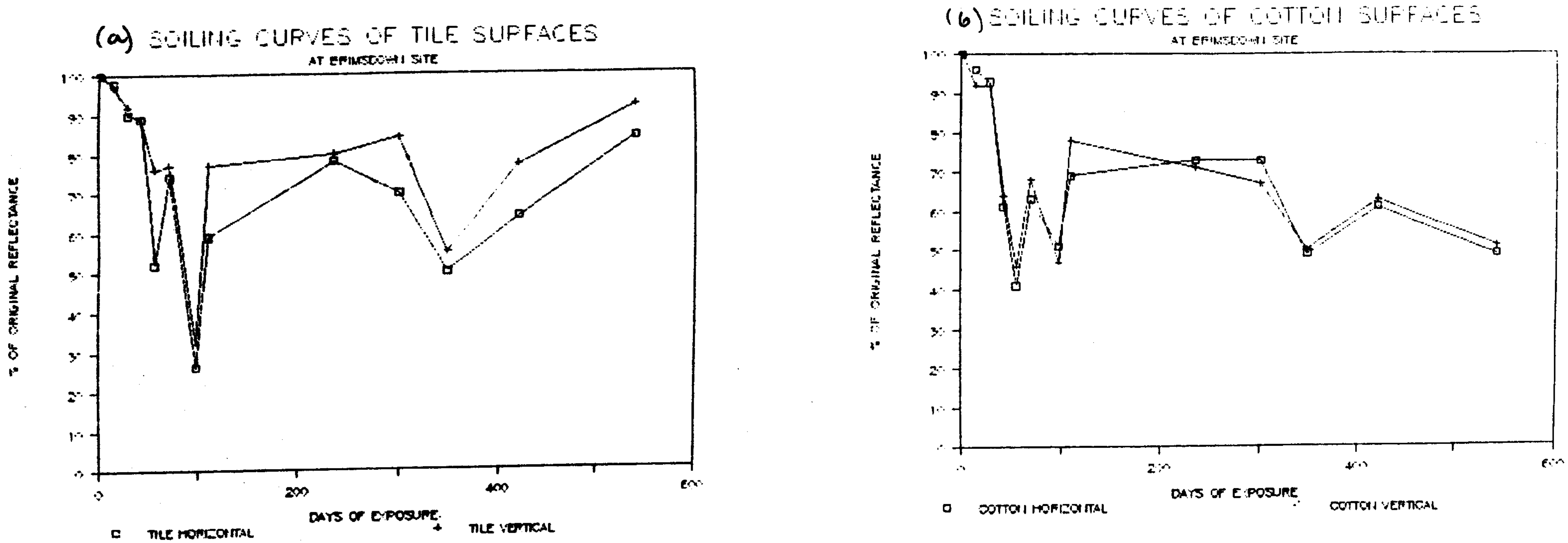


Figure C.8.3 <u>The soiling curves of the individual materials (horizontal and vertical) at the Brimsdown site</u>
(a) - (d)

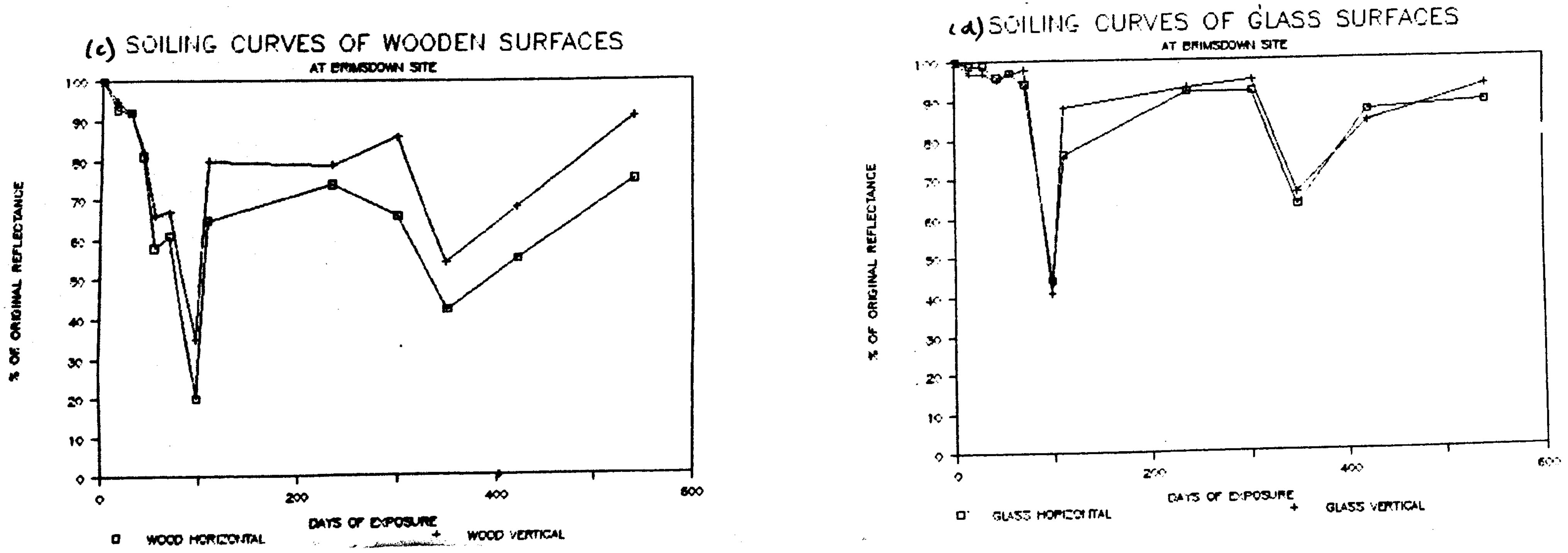


Table C.9 The percentage of the materials' original reflectance, smoke and rainfall measurements at the Trent Park site during the exposure period

TQ reference for site: TQ 29129742

Site 9 on Figure 6.7

days of exposure	smoke ($\mu g\ m^{-3}$)	rainfall (mm)	% of Original Reflectance							
			WOOD		GLASS		COTTON		TILE	
			h	v	h	v	h	v	h	v
13	5	6	92	91	91	93	85	90	88	97
28	5	33	81	84	100	100	100	97	96	97
42	5	29	88	93	100	100	83	77	94	91
56	3	42	89	89	100	97	77	72	86	95
65	2	7	82	85	100	95	64	66	76	76
91	3	35	69	70	98	87	91	75	72	71
120	4	19	63	67	99	88	67	73	69	69
151	4	55	79	84	100	94	91	73	79	97
250	4	220	73	76	100	97	92	83	86	97
281	6	77	75	85	100	95	92	85	93	94
316	6	13	67	74	100	99	79	63	83	93
343	6	23	52	63	100	98	67	59	68	66
475	6	109	66	80	99	91	92	77	80	82
565	6	329	82	92	94	89	92	76	98	94

Figure C.9.1: The view from the Trent Park roof-top site where the samples were exposed

The soiling curves for the materials from this site are given in Chapter Six, Figures 6.13-6.14.

APPENDIX D

Middlesex Polytechnic

Queensway
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Centre for Urban Pollution Research

JB Ellis MSc FGS MIWES
R Hamilton DPhil MInstP
MD Revitt PhD CChem MRSC
RBE Shutes MA MTech MInstBiol

TM/bm

Dear Sir/Madam,

I am currently researching for a doctorate at Middlesex Polytechnic on the topic of "The soiling of building fabric in urban areas". Part of the work involves physical measurement and analyses of soiled material, the other part involves an analysis why people clean buildings and the costs involved.

I am surveying a number of companies such as yours in order to find out some of the characteristics of the market and of the associated costs. I wonder whether you or one of your colleagues would mind completing the enclosed questionnaire? Please feel able to comment freely on any of the issues raised by the questions. If you feel that a face to face or telephone interview would be useful, then do contact me suggesting a time. Please note I am only interested in the cleaning side of your company, rather than restoration work per se.

I should like to emphasise that any data given about your Company's trading position or clients will be treated in the strictest confidence and used for statistical analysis only. Should you have any queries about answering this questionnaire - please do not hesitate to contact me or my supervisor, Dr. Peter Newby at the above address.

I appreciate the time you will spend in completing this survey and will gladly inform you of my results.

Yours sincerely,

Trudie Mansfield

TRUDIE MANSFIELD (MISS)

CUSTOMERS

1. What percentage of the CLEANING work done annually is from

   (a) the private sector?

   (b) the public sector?

2. Could you give some examples of typical clients from

   (a) the private sector?

   (b) the public sector?

3. What reasons are most frequently identified by the client for wanting a building to be cleaned? You may find it useful to confirm your categories with the appropriate percentages.

4. Do the public sector customers differ from the private sector in their motives for wanting a building cleared? Y N

   If yes, please illustrate.

5. What benefits do you consider your customers gain after having their bulding cleaned?

6. Are clients from the private and public sector likely to clean the 'front' of the building only?

   Private Y N Public Y N

   Please add any comments on reasons for full or partial differences on cleaning between sectors.

COSTS

(Your answers to these sections will be treated STRICTLY confidentially.)

7. Can you please indicate your costs excluding scaffolding per m^2 to clean by the following methods:

Water clean only:

Degrease and water clean:

Dry abrasive blasting:

Wet abrasive blasting:

Use of sealant (after cleaning):

8. How much would it cost a customer on average to water clean only the frontage of a building with the following characteristics?

AGE: built in 1850s

STONE: Portland

HEIGHT: 65 feet

AREA: $550m^2$

Assume that the architecture is simple and the building in a good state of repair.

Price (excluding scaffolding) £

9. How frequently would you advise a customer to water clean the above building if it was located in

(a) major city

(b) town

(c) country?

10. What (if any) are the reasons for the differences in the frequencies expressed in question 9?

11. What do you expect to be the mean annual rate and increase in price to the customer for cleaning over the next 5 years? You may find it easier to express your answer as:

- by the rate of inflation
- by less than inflation
- by more than inflation.

STONE CLEANING MARKET

12. What area of the country does your company predominantly serve?

13. In which city or part of city is the majority of your cleaning work done?

14. How much of the stone cleaning market does your company have

    (a) Nationwide (including London)? %

    (b) London? %

15. What was your Company's turnover in stone CLEANING in the financial year 1985/6? If it is easier to send a copy of your company reports please do so.

16. How much do you consider the stone cleaning market to be worth per annum nationwide?

17. Do you forsee any change in the type of market and volume of trade for the stone cleaning industry in general? Please comment freely.

Any Other Comments:

Name:

Company:

Address:

Telephone Number

APPENDIX E

Middlesex Polytechnic Centre for Urban Pollution Research

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01-804 8131
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JB Ellis MSc FGS MIWES
R Hamilton DPhil MInstP
MD Revitt PhD CChem MRSC
RBE Shutes MA MTech MInstBiol

Dear Sir/Madam,

I am currently researching for a doctorate at Middlesex Polytechnic on the topic of "The soiling of building fabric in urban areas". Part of the work involves physical measurement and analyses of soiled material, the other part involves an analysis why people clean buildings and the costs involved.

I have recently surveyed the stone cleaning industry in order to find out some of the characteristics of the market and of the associated costs. Local authorities were identified as their largest customer within the public sector. I wonder whether you or one of your colleagues would mind completing the enclosed questionnaire? Please feel able to comment freely on any of the issues raised by the questions.

I should like to emphasise that any data given will be treated in the strictest confidence and used for statistical analysis only. Should you have any queries about answering this questionnaire please do not hesitate to contact me or my supervisor, Dr Peter Newby at the above address.

I appreciate the time spent in completing this survey and will gladly inform you of my results.

Yours sincerely,

Trudie Mansfield

TRUDIE MANSFIELD (MISS)

1. What are the main reasons for cleaning buildings?
Please list in order of importance.

- Aesthetics - make building look more attractive
- Brighten up the environment
- Improve community morale
- Protect the building from further decay
- To identify suspected faults in fabric beneath soiled exteriors
- To blend in with new extensions and/or restoration work
- Others (please specify)

2. Do you have a cleaning policy which dictates the frequency at which:

(a) exterior paintwork is done? years
(b) exterior window washing occurs? months/year(s)
(c) external stone/brickwork is cleaned? years

3. Does this frequency differ with location and importance/use of the building?

If yes, please exemplify

4. Do you consider the deposited material on buildings harmful to the fabric?

5. What do you think is the chief source of this deposited matter?

6. In the absence of economic constraints etc. how often would you choose to:

(a) paint exterior work?

(b) clean stone/brickwork?

7. When cleaning a building, how often is only the front cleaned? and why?

8. Approximately how much is spent per annum on cleaning exterior stone/brickwork within your organisation?

9. Please rank the following into 3 most important and 3 least important for the benefits accrued as a result of stone cleaning:

	3 most important	3 least important
Prolongs life of fabric		
Promotes civic pride		
Decreases vandalism and graffiti		
Demonstrates council action		
Attracts business activity		
Improved visual environment		
Changing/improving town or city image		
Others		

10. Have you experienced any public reaction as a result of stone cleaning? Please specify.

11. In view of your experience please give examples of buildings:

(a) which you would clean again

(b) buildings which you would not clean again

Name of Organisation :

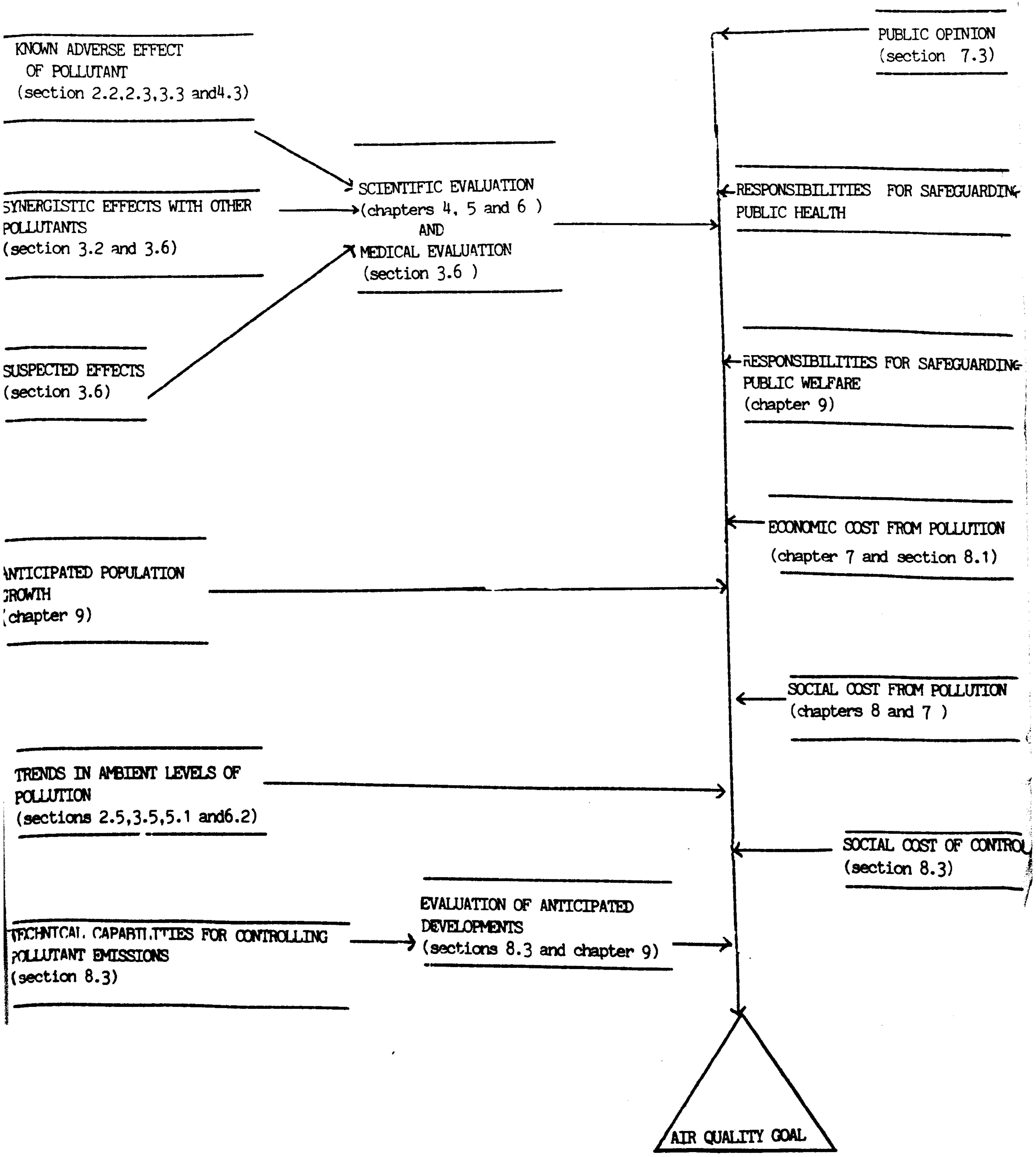
Area :

Person completing form:

This information will be used in the STRICTEST CONFIDENCE and will only be used for aggregate analysis.

AN ADAPTATION OF WILLIAMSON'S MODEL FOR FACTORS WHICH INFLUENCE THE FORMULATION OF AN AIR QUALITY GOAL OR STANDARD FOR A POLLUTANT WITH REFERENCE TO THE SOILING OF MATERIALS.

from " Fundamentals of air pollution. " (1973) published by Addison-Wesley, Reading.



KEY: Figures in parenthesis indicate the section of the thesis in which these areas may be mentioned/examined.

ENVIRONMENTAL CONTAMINATION

2nd International Conference — Amsterdam, September 1986

Co-Sponsor
United Nations Environment Programme (IRPTC)

SOILING OF ENVIRONMENTAL MATERIALS BY SMOKE DEPOSITION

J B ELLIS+ R S HAMILTON+ T A MANSFIELD+ and D J BALL*

ABSTRACT

A set of glass, cotton, wood and ceramic tile samples was mounted at each of 10 sites in London. The soiling of each material at each site was recorded over a period of 100 days. The relative soiling rates are described and discussed in terms of the smoke levels at each site.

INTRODUCTION

A set of experiments conducted in America in the period 1972-74 (ref 1) revealed that the soiling of white painted surfaces by smoke deposition could be described by the relationship:

$$\text{decrease in reflectance} = 0.41\sqrt{\text{dose}} \qquad (1)$$

where dose equals the product of the total suspended particulate level ($\mu g\ m^{-3}$) and the exposure time (months). Poor correlations were obtained for concrete, limestone and window glass. Although soiling rate may be sensitive to a range of geographical factors such as temperature, amount of sunlight and precipitation levels, no attempt has been made to assess the importance of these factors by repeating the experiments under different geographical conditions in other countries. In addition, the implementation of new air quality standards in many countries has altered the composition of airborne particulate matter as well as reducing its level. To investigate the present role of smoke deposition in the soiling of materials, a set of experimental programmes was established in London.

EXPERIMENTAL DETAILS

Breeze blocks measuring 0.44m x 0.11m x 0.20m have been mounted on each corner of a 1.2m x 0.6m wooden base. The vertical and top horizontal surfaces of each block were covered to give exposed surfaces of glass, white ceramic tiles, white cotton and white painted wood. A set of samples was mounted at each of nine sites on a transect from Central to North London, (Fig 1 and Table 1). The reflectance of the different materials at each site was measured at 2-week intervals, using an EEL Reflectometer and the corresponding smoke levels were monitored continuously by the UK National Survey smoke stain method. Meteorological conditions were also recorded.

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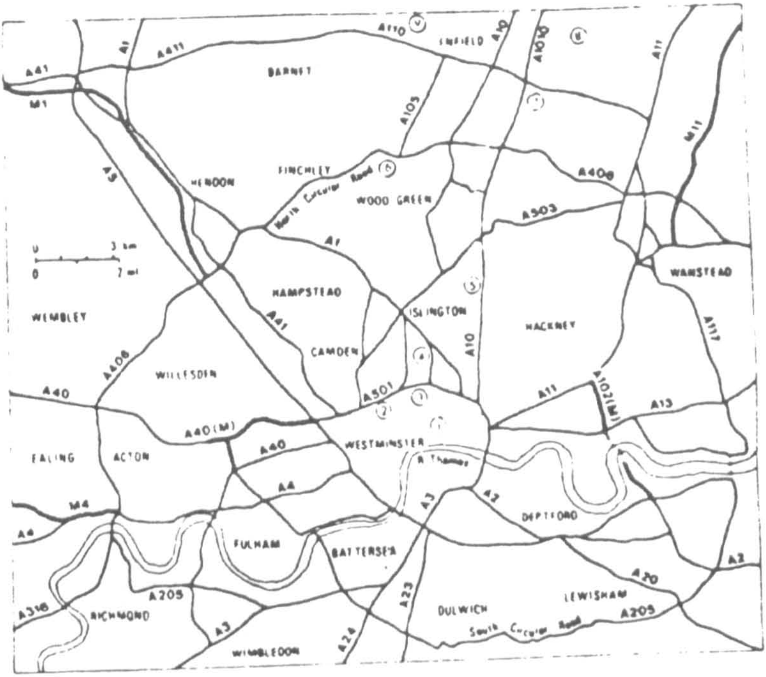

Figure 1 Location of sampling sites

Table 1 Details of sampling sites

site		height above ground level (m)	site description
1	High Holborn	22	business centre circled by major roads
2	Euston Fire station	1	adjacent to major railway and bus station, sited on a major road
3	Bidborough Street	18	business centre, adjacent to two major railway stations, sited on a major road
4	Islington	10	domestic and business centre, sited on a major road
5	Haringey	8	business centre and shopping area, sited on a major road
6	Bounds Green	20	domestic and light industrial centre, sited on a major road
7	Enfield	12	domestic and light industrial centre, sited near a major road
8	Brimsdown	3	heavy industrial centre
9	Trent Park	8	sited in middle of a country park

RESULTS AND DISCUSSION

The reflectance values for cotton, glass and painted wood after exposure times of 50 and 100 days are presented in Table 2. The reflectance values quoted are expressed as a percentage of the initial reflectance to facilitate a comparison of soiling rates for different materials.

Table 2 Soiling of Cotton, Glass and Painted Wood (horizontal surfaces) at Sites in London

	Airborne Smoke Level (μg m^{-3})		Reflectance, expressed as % of initial value					
			Cotton		Glass		Wood	
Site	mean	range	50 days exposure	100 days exposure	50 days exposure	100 days exposure	50 days exposure	100 days exposure
1	15	2-24	76	-	76	-	67	-
2	53	17-100	53	46	91	80	75	74
3	16	2-30	-	-	-	-	-	-
4	14	4-32	56	73	95	80	86	73
5	16	2-44	71	[illegible]	83	75	85	81
6	14	4-29	70	-	100	-	50	-
7	10	2-48	84	51	98	77	88	71
8	16	3-37	59	-	86	-	81	-
9	5	1-19	79	60	98	95	98	69

Sites 1, 2 and 4-9 were established over a four week period in January and February 1986 and because of this time factor, the same exposure periods for the sites cover slightly different dates and consequently the samples were exposed to slightly different meteorological conditions. This could have some effect on the 50 day exposure reflectance values but the effect is likely to be negligible for subsequent exposures. Site 3 was established in April 1986. Equation 1 predicts that the reflectance of white painted wood will fall by 2% and 3% after 50 days exposure and 100 days exposure respectively in an environment where the total suspended particulate level is 15 μg m^{-3}. Our results for sites 1 and 4-8 indicate a much more rapid soiling rate for wood, as well as for cotton and glass. This may be a consequence of the increased contribution of vehicle emissions to airborne particulate matter within urban areas and its greater than average soiling potential (ref 2). This effect might be expected to increase further with diesel engine penetration of the European motor market (ref 3). The correlations for glass were higher in this study than in the American study, suggesting that smoke shade measurements may be more appropriate than gravimetric measurements of total suspended particulate levels for the assessment of soiling potential. The 9 site programme will continue for another 12 months and additional sites will be established in areas of high smoke level.

ACKNOWLEDGEMENTS

We are grateful to Valerie Lee for typing the manuscript, Jim Moore for cartographic assistance and Alan LaGrue for technical assistance. One of us (TAM) is grateful to SERC for financial assistance.

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Soiling of London's Buildings

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Numerous natural stone buildings have been cleaned in the past thirty years, removing the accumulated soiling effects of London's former coal burning days from their facades. However, such buildings are becoming re-blackened by the emergence of a new culprit - the diesel engined vehicle. Londoner's are well accustomed to diesel powered lorries, buses and coaches, and even the general motorist is now becoming interested in the fuel efficiency of diesel cars. In 1972 precisely 94 diesel cars were sold in Britain and in 1984 the number was 45,386. It is estimated that 10% of all new vehicles will be diesel powered by the year 2000, approaching the same levels of dieselisation as now experienced in France and Germany. The increasing use of diesel engines, together with the environmentally adverse physical and chemical characteristics of diesel particulate emissions, could well result in an increase in soiling rates in cities. Such an eventuality has potential aesthetic and economic implications, and is the subject of a current study by the Urban Pollution Research Centre at Middlesex Polytechnic.

Approach and methodology

The Urban Pollution Research Centre has established an experimental sampling design to determine soiling potentials for typical constructional materials at urban sites in Metropolitan London on a transect from central to north London (see Fig 1). Most of the sites are located adjacent to a major road or within an industrial area. However, site 9 is in the middle of a country park. Breeze blocks, measuring 0.4m x 0.1m x 0.2m have been mounted on each corner of a 1.2m x 0.6m wooden base and the vertical and top horizontal surfaces of each block have been covered to give exposed surfaces of glass, white ceramic tiles, white painted wood and white cotton. The reflectance of the different materials at each site is measured at 2-week intervals, using an EEL reflectometer, and the corresponding smoke levels are monitored continuously by the UK National Survey smoke stain method. Meterologicial conditions are also recorded.

Preliminary results

A similar experiment in the United States during 1972-74, suggested that the soiling of white painted surfaces by smoke deposition could be described by the relationship:

$$\text{decrease in reflectance} = 0.41\sqrt{\text{dose}} \qquad \text{(i)}$$

where dose equals the product of the total suspended particulate (TSP) level (μgm^{-3}) and the exposure time (months). Equation (i) predicts that the reflectance of white painted wood would fall by 2%, 3%, 3.5% and 4% after 50, 100, 150 and 200 days exposure respectively in an environment where the total suspended particulate level is 15 μgm^{-3}. The results for all nine sites in the present study, where average smoke levels vary from 7 to 47 μgm^{-3}, all show a decrease in original reflectance of white painted wood from 24 to 42% after 200 days exposure. The results also indicate a much more rapid soiling rate for cotton, tiles and glass than predicted by equation (i), with horizontal surfaces soiling more rapidly than vertical surfaces.

The results of a parallel longer term study are illustrated below (Figure 2). The reflectance values quoted are expressed as a percentage of the initial reflectance to facilitate comparison of soiling rates for the different materials. Equation (i) predicts that after an exposure of 500 days, the decrease in reflectance should fall by 7% where the TSP level is 15 μgm^{-3}. Here again, a far more rapid soiling rate has been observed, particularly in the first 100 days, and tending to level-off after that.

These substantial soiling rates may well be the consequence of vehicle contributions to airborne particulate matter within the urban area, and to their greater than average soiling potential. This effect might be expected to more pronounced if diesel engine penetration of the UK motor market continues. The correlations obtained for glass were higher in this study than in the American study, suggesting, as might be expected, that smoke shade measurements may be more appropriate than the gravimetric measurements of total suspended particulate levels for the assessment of soiling potential.

The nine site programme will continue for another six months with additional sites being established in areas of high smoke levels. The research project is also evaluating the cost implications for the community of the soiling of urban materials.

The author wishes to thank LSS and the London Boroughs of Camden, Enfield, Islington and Haringey for their assistance in this project which is supported by an SERC award.

	Site	Height above ground level (m)
1	High Holborn	22
2	Euston fire station	1
3	Bidborough Street	18
4	Islington	10
5	Haringey	6
6	Bounds Green	20
7	Enfield	12
8	Brimsdown	3
9	Trent Park	8

Figure 1 Details of Sampling sites

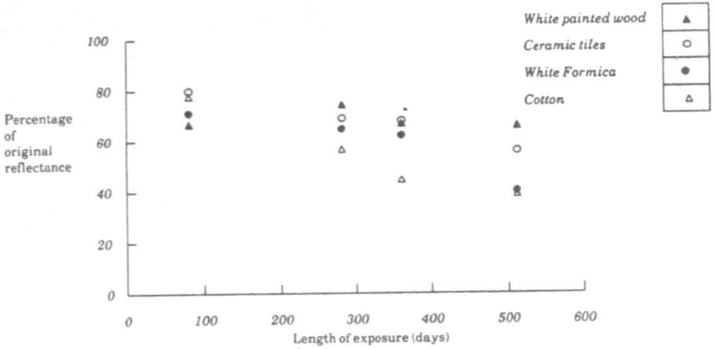

Figure 2 Changes in reflectance for horizontal surfaces with exposure time

Diesels under the spotlight

David Ball

Two years ago the issue of diesel smoke emissions was reported in the LEB (Vol.1, No.4). It was noted that existing European legislation sought only to limit the visual appearance of the emissions at the exhaust pipe. During the intervening period, there has been a flurry of activity. This is partly because this legislation is now under review, but also because of new information on the role of these emissions in the environment.

Diesel exhaust is a rich source of very fine carbon particles known as elemental carbon or EC. It is now believed that EC emissions are the main cause of soiling in European towns, potentially with huge economic implications. Also in question is their role in a wide range of other phenomena, including effects on health, visibility, and, further afield, their contribution to Arctic haze and snowmelt rates on tundra and sea ice.

In the United States, legislation has been introduced to cut smoke emissions from lorries by a factor of seven by 1994, and even earlier in the case of urban buses. Whether or not such stringent standards will be introduced in Europe at this stage, remains to be seen, but clearly these emissions will never again be seen in the same light.

Fuel	EC emissions (tonnes per annum)
Natural gas	470
Petrol	2,000
Diesel fuel	110,000
Gas oil	17,000
Fuel oil	14,300
Jet fuel	2,000
Solid fuel	430

EC emission in Europe (from Ogren and Charlson, Tellus, 36B, 262-271, 1984)


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SOILING OF MATERIALS BY SMOKE

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INTRODUCTION

The deposition of smoke on urban surfaces has long been recognised as a major source of soiling in cities. The introduction of improved control technology for industrial and domestic emissions has produced a steady reduction of smoke levels in most cities. Vehicle emissions may constitute a major source of dark smoke in cities (ref.1) and consequently they have become a major cause of materials and fabric soiling in the urban environment. The increasing use of diesel engines together with the environmentally adverse physical and chemical characteristics of diesel particulate emissions could result in a substantial increase in soiling rates in cities (ref. 2).

Surface soiling has been operationally defined as the difference in reflectance of a substrate containing particles to the reflectance of the bare substrate. The accumulation of particulate matter on the substrate can be modelled in terms of the concentration of airborne particulate matter, its size composition, the deposition mechanism appropriate to each size range and the surface characteristics of the substrate. These processes have been considered by Haynie (ref. 3) and they have produced the following predictions:

1. Reflectance will be reduced by 10-40% over a 12-month period.
2. Horizontal surfaces will soil more rapidly than vertical surfaces.
3. Increased windspeed will result in increased soiling rates.
4. Painted surfaces soil more rapidly than glass.

There are few field measurements available for testing these model predictions. The only extensive study of soiling by particle deposition has been conducted in America, in the period 1972-74 (ref. 4). To assess the magnitude of the effect under current air quality conditions, a set of experimental programmes has been established in the London region.

EXPERIMENTAL

Breeze blocks measuring 0.44m x 0.11m x 0.20m have been mounted on each corner of a 1.2m x 0.6m wooden base. The vertical and top horizontal surfaces of each block were covered to give exposed surfaces of glass, white ceramic tiles, white cotton and white painted wood. A set of samples was mounted at each of ten sites on a transect from Central to North London. Samples of additional materials such as white formica and marble, were exposed at one of the sites. The reflectance of the different materials at each site was measured at 2-week intervals, using an EEL Reflectometer and the corresponding smoke levels were monitored continuously by the UK National Survey smoke stain method. Meteorological conditions were also recorded.

PRELIMINARY RESULTS AND DISCUSSION

Table 1: Increase in Soiling of Horizontal Surfaces With Exposure Time

	WHITE FORMICA	WHITE PAINTED WOOD	WHITE CERAMIC TILES	UNPAINTED WOOD	WHITE COTTON
initial reflectance value	87	86	86	48	79
reflectance after 3 months	62 (71%)	58 (67%)	68 (80%)	37 (77%)	62 (78%)
reflectance after 8 months	57 (65%)	64 (74%)	59 (69%)	25 (52%)	45 (57%)

The values in brackets show the percentage of the initial reflectance which was recorded after 3 and 8 month exposures.

Table 2: Variation in Soiling of White Ceramic Tiles with Site and Orientation

Site	Airborne Smoke Level (ug m^{-3})		% of initial Reflectance recorded after 2 months	
	Mean	Range	Horizontal Surface	Vertical Surface
Trent Park (rural)	11	3 - 19	83	95
Enfield (outer London)	18	1 - 48	86	91
Haringey: Inner	19	1 - 57	78	88
Islington: London	18	4 - 57	79	88

Table 1 shows that the materials studied have soiling rates in the sequence:
unpainted wood > cotton > formica > tiles > painted wood.
Table 2 shows that horizontal surfaces soil more rapidly than vertical surfaces, as predicted by theory. Samples soil more rapidly at sites with higher airborne smoke levels, as expected, with a tendency to demonstrate linear reductions in reflection with mean smoke levels.

Further studies will investigate:
(i) soiling rates at sites with high total suspended particulate concentrations
(ii) the influence of aerosol size composition and elemental carbon composition on soiling rate.
(iii) the cost-benefit implications for the cleaning of soiled urban materials.

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