5. Effect on Material Damage

5.1 Methodology

5.1.1 Background

The quantification of impacts from air pollution on building materials follows the methodology used within the ExternE project (European Commission, 2000), which is based on results from the UN ECE International Co-operative Programme on Effects on Materials (ICP Materials) (Kucera *et al*., 1997). ExternE provides a set of dose-effect models that allow the quantification of the degradation of building materials due to their exposure to SO_2 and wet acid deposition. The dose-effect models used in ExternE are derived from 4-year exposure studies under European climatic conditions that are different from those in Hong Kong. Nevertheless, due to the lack of local and even Far East data such as inventory for materials in hot and humid environment, exposed area of each type of materials, surface area per person, maintenance cost of different material types, etc., the ExternE methodology was applied assuming "Hong Kong as in Europe context" in order to give *a first rough indication of the order of magnitude* of potential material damage from air pollution and acid rain in Hong Kong.

5.1.2 Dose-effect models

The following sections summarize the dose effect models used for the estimation of impacts on building materials in this study. The description is based on chapter 6 of the ExternE reports (European Commission, 1999, 2000) and those written by Tidblad *et al.* (1998). The mechanism of damage is described in the following section 5.1.2.1, and the dose-effect functions are discussed in section 5.1.2.2.

5.1.2.1 Damaging Mechanisms on building materials - review of relevant parameters

Degradation processes of building materials are mainly affected by the climatic situation and the deposition of reactive atmospheric substances onto their surface. An increase in the concentration of atmospheric pollutants can harm building materials, if the pollutants 'depose' on the material surfaces. 'Deposition' in this context is defined as the process by which particles and gases are transferred from the atmosphere to the material surface. Thus, in the following discussion, the effects on building materials are subdivided into the two relevant depositions processes, 'dry deposition' and 'wet deposition'.

Dry effects

'Dry effect' is the deposition of substances in the absence of rainfall. The dry deposition velocity, i.e. "the ratio of surface flux to concentration" depends, beside atmospheric conditions, "on the thickness of the moisture layer and the reactivity of the material and the properties of the corrosion products" (European Commission, 2000). As temperature and relative humidity are the main factors that determine the amount of moisture in periods without rainfall, terms describing the dry deposition processes in dose response functions include temperature and relative humidity as meteorological parameters.

Sulfur dioxide (SO_2) is one of the main contributors to material degradation. It is dissolved in the moisture layer on materials where it forms sulfite and sulfate. This process increases the acidification of the moisture layer and thus accelerates the corrosion process.

The role of NO_X has not yet been fully elucidated, but results from experiments indicate that it is much less detrimental than SO_2. O_3 is an oxidant and like NO_2 shows synergetic effects in combination with SO_2. Additionally, atmospheric particles containing sulfates, sulfites, and nitrates, which have hygroscopic properties and provide ions in aqueous solution increase the atmospheric corrosion process of materials. However, the influences of these pollutants are not considered as separable part in the available exposure response functions.

Wet effects

'Wet effect' is the deposition of substances on material surfaces by rainfall. It is connected with two contrary effects. First, the pure washing effect cleans the facades from previously deposed chemical reactive substances. Second, the transporting effect of harmful substances on the material surfaces enhances the corrosion process. Within the exposure studies, high rain acidity has been identified as an indicator for the domination of the detrimental effect. Thus, the terms describing the wet deposition part in the dose-response functions include the total acid load as one parameter.

5.1.2.2 Effects on building material from air pollution - review of relevant building materials and related damage functions

In the following, the dose-effect functions used for impact assessment are listed for the different building materials. Except the dose-response function for carbonate painting (Haynie, 1986), all of them are based on results from the UN-ECE ICP Materials (Kucera *et al*., 1997).

In a two-step approach, the dose-effect functions link the ambient concentration or deposition of pollutants to the rate of material corrosion, and the rate of corrosion to the time of replacement or maintenance of the material. Performance requirements determine the point at which replacement or maintenance is considered to become necessary. This point is given in terms of critical degradation.

Limestone

surface recession: $R = (2.7[SO_2]^{0.48}e^{-0.018T} + 0.019Rain[H^+]) \cdot t^{0.96}$

maintenance frequency: $1/t = [\,(2.7[SO_2]^{0.48}e^{-0.018T} + 0.019Rain[H^+])/R_{crit}\,]^{1/0.96}$

with		
	R	surface recession in µm
	$1/t$	maintenance frequency in 1/a
	$[SO_2]$	SO_2 concentration in µg/m^3
	T	temperature in ^oC
	Rain	precipitation in mm/a
	$[H^+]$	hydrogen ion concentration in precipitation in mg/l
	R_{crit}	critical surface recession, European average value of 4000 µm

Sandstone, natural stone, mortar*, rendering

surface recession: $R = (2.0[SO_2]^{0.52}e^{f(T)} + 0.028Rain[H^+]) \cdot t^{0.91}$

maintenance frequency: $1/t = [(2.0[SO_2]^{0.52}e^{f(T)} + 0.028Rain[H^+])/R_{crit}]^{1/0.91}$

with

R	surface recession in µm
$1/t$	maintenance frequency in 1/a
$[SO_2]$	SO_2 concentration in µg/m^3
T	temperature in ^oC
$f(T)$	$f(T) = 0$ if $T < 10$ ^oC; $f(T) = -0.013(T-10)$ if $T > 10$ ^oC
t	time in years
Rain	precipitation in mm/a
$[H^+]$	hydrogen ion concentration in precipitation in mg/l
R_{crit}	critical surface recession, European average value of 4000 µm

*Cement is included in the mortar as both are of similar nature

Zinc and galvanized steel

mass loss: $ML = 1.4[SO_2]^{0.22}e^{0.018Rh}e^{f1(T)}t^{0.85} + 0.029Rain[H^+]t$

maintenance frequency: $1/t = 0.14[SO_2]^{0.26}e^{0.021Rh}e^{f2(T)}/R_{crit}^{1.18} + 0.0041Rain[H^+]/R_{crit}$

with

ML	mass loss in g/m^2
$1/t$	maintenance frequency in 1/a
$[SO_2]$	SO_2 concentration in µg/m^3
Rh	relative humidity in %
T	temperature in ^oC
$f1(T)$	$f1(T) = 0.062(T-10)$ if $T < 10$ ^oC; $f(T) = -0.021(T-10)$ if $T > 10$ ^oC
$f2(T)$	$f2(T) = 0.073(T-10)$ if $T < 10$ ^oC; $f(T) = -0.025(T-10)$ if $T > 10$ ^oC
t	time in years
Rain	precipitation in mm/a
$[H^+]$	hydrogen ion concentration in precipitation in mg/l
R_{crit}	critical surface recession, European average value of 680 µm for zinc and 64 µm for galvanized steel

Paint on steel

degradation rating: $A = (0.033[SO_2] + 0.013Rh + f(T) + 0.0013Rain[H^+])t^{0.41}$

maintenance frequency: $1/t = [(0.033[SO_2] + 0.013Rh + f(T)+0.0013Rain[H^+])/A_{crit}]^{1/0.41}$

with

A	degradation rating, originally A=(10-ASTM), with ASTM representing a rating between 1 and 10 (10 = unexposed)
$1/t$	maintenance frequency in 1/a
$[SO_2]$	SO_2 concentration in µg/m^3
Rh	relative humidity in %
T	temperature in ^oC
$f(T)$	$f(T) = 0.015(T-11)$ if $T < 11$ ^oC; $f(T) = -0.15(T-11)$ if $T > 11$ ^oC
Rain	precipitation in mm/a
$[H^+]$	hydrogen ion concentration in precipitation in mg/l
A_{crit}	the rating at which maintenance should occur, European value: 5

Paint on galvanized steel

degradation rating: $A = (0.0084[SO_2] + 0.015Rh + f(T) + 0.00082Rain[H^+])t^{0.43}$

maintenance frequency: $1/t = [(0.0084[SO_2]+0.015Rh+f(T)+0.00082Rain[H^+])/A_{crit}]^{1/0.43}$

with

A	degradation rating, originally A=(10-ASTM), with ASTM representing a rating between 1 and 10 (10 = unexposed)
1/t	maintenance frequency in 1/a
$[SO_2]$	SO_2 concentration in $\mu g/m^3$
Rh	relative humidity in %
T	temperature in °C
f(T)	$f(T) = 0.04(T-10)$ if $T < 10$ °C; $f(T) = -0.064(T-10)$ if $T > 10$ °C
Rain	precipitation in mm/a
$[H^+]$	hydrogen ion concentration in precipitation in mg/l
A_{crit}	the rating at which maintenance should occur, European value: 5

Carbonate paint

material loss: $\Delta R = 0.12\ (1 - \exp(-0.121Rh/(100-Rh)))[SO_2] + 0.0174Rain[H^+]$

maintenance frequency: $1/t = (0.12(1-\exp(-0.121Rh/(100-Rh)))[SO_2]+0.0174Rain[H^+])/R_{crit}$

with

ΔR	annual surface recession in µm/a
1/t	maintenance frequency in 1/a
$[SO_2]$	SO_2 concentration in $\mu g/m^3$
Rh	relative humidity in %
Rain	precipitation in mm/a
$[H^+]$	hydrogen ion concentration in precipitation in mg/l
R_{crit}	critical surface recession, European average value of 57 µm

The damage functions were derived at average temperature between 2 and 19 °C and annual rainfall between 327 and 2144 mm/a (European Commission, 2000). A comparison with the respective measured values in Hong Kong given in Table 5-1 below shows that the maximum values of both parameters have been exceeded in Hong Kong during the time period of 1993 to 1999. According to the European Commission (2000), it is emphasized that, in general, an extrapolation of damage functions beyond the range of the environmental parameters used for their derivation needs specific care. Nevertheless, it provides a first rough estimate of potential material damage from acid rain in Hong Kong.

Table 5-1. Data on air pollution/acid rain and meteorology used for the calculations

Parameter	1993	1994	1995	1996	1997	1998	1999
SO_2 (µg/m^3)	31.3	26.3	17.9	19.5	17.2	13.8	20.6
Wet Acid Deposition* (meq/m^2/a)	57.0	40.0	33.8	36.9	33.1	87.7	42.4
Relative Humidity (%)	78	79	77	76	79	79	77
Temperature (°C)	23.1	23.6	22.8	23.3	23.4	24.0	23.0
Precipitation (mm/a)	2343.9	2725.6	2754.4	2249.1	3343.0	2564.6	2194.9

*Wet Acid Deposition = Precipitation x Concentration of H^+ in meq/l (equivalent to mg/l for H^+)

5.1.3 Economic valuation of material impacts

The economic valuation of material impacts is based on maintenance costs from the ExternE studies (European Commission, 1999, 2000). Data on maintenance and replacement costs were derived from studies in the UK, Germany and three different European cities (Ecotech, 1996, Kucera *et al*., 1993 and Lipfert, 1987). The exchange rate of 6.7 HK $ per Euro for conversion into Hong Kong Dollar was used (see Table 5-2).

Table 5-2. Monetary values used for economic valuation of damages on building material (European Commission, 1999, 2000)

Material	Specific Maintenance Cost	
	€$_{2000}$/m^2	HK\$$_{2000}$/m^2
Limestone	299	2003
Sandstone	299	2003
Natural stone	299	2003
Mortar	33	221
Rendering	33	221
Galvanised steel	35	235
Zinc	27	181
Paint	13	87

5.2 Data used for impact assessment

5.2.1 Data on pollutant concentration/deposition and meteorology

Data on air pollution and meteorology were provided by EPD for the years 1993 to 1999 (Table 5-1). They include the annual mean of SO_2 concentration, relative humidity, and temperature as well as the total annual wet acid deposition and precipitation. Except for SO_2 concentration, all data were only available on a less detailed geographical resolution so that they were averaged over the Hong Kong area to derive total values of material degradation in Hong Kong for the years 1993 to 1999.

5.2.2 Receptor data

The material inventory for Hong Kong has been estimated on the basis of the material inventory used for Europe within the ExternE studies (European Commission, 1999). From the European inventory, an average factor of material surface area per person for Europe was calculated. This factor was multiplied with the population of Hong Kong to derive an estimate of the surface area of the relevant materials in Hong Kong. With this approach of estimation by population projection, it has an intrinsic potential of overestimation. This is explained by the fact that change in the annual population between years will, by itself, provide difference in the estimation between years even when there is no change in the pollutants level between the years. The increase or decrease in population does not guarantee a proportional increase or decrease in the number of buildings and consumption of various materials in the inventory over the years. In order to reduce such potential overestimation, the average population over the year 1993 to 1999 (6,369,371) is preferred to individual annual population for the present estimation. The resulting values were listed in Table 5-3.

Table 5-3. Material inventory used for the calculations using the average Hong Kong population of 6,369,371 over the year 1993-1999

Material	Surface area (in m^2) per person [a]	Surface (m^2)
Limestone	0.09	573 000
Sandstone	0.13	828 000
Natural stone	0.09	573 000
Mortar	23.6	150 000 000
Rendering	16.0	102 000 000
Galvanised Steel	2.9	18 700 000
Zinc	2.4	15 100 000
Paint		
on galvanised steel	2.7	17 000 000
on steel	6.7	42 500 000
carbonate paint	17.4	110 500 000

[a] derived from the European material inventory

5.3 Effects on building material due to air pollution/acid rain in Hong Kong

The estimated annual effects of air pollution and acid rain on building materials in Hong Kong in the years 1993 to 1999 are given in Table 5-4 (absolute values) and Table 5-5 (in percent of total surface area) in terms of surface area which needs maintenance or replacement. Results indicate that in particular galvanized steel and paintings are affected by air pollution and acid rain, leading to more than one percent of the respective surface area to be maintained per year.

Table 5-4. Surface area of building material[#] which has to be maintained in order to repair impacts from air pollution and acid rain in Hong Kong [m^2/a] as derived from the corresponding dose-response functions listed in 5.1.2.2

	1993	1994	1995	1996	1997	1998	1999
Limestone[@]	1200	1000	860	890	830	860	930
Sandstone	1400	1200	960	1000	930	1000	1100
Natural Stone	940	820	670	700	650	700	730
Mortar	250000	210000	170000	180000	170000	180000	190000
Rendering	170000	140000	120000	120000	110000	120000	130000
Galvanised Steel	250000	220000	190000	190000	190000	250000	210000
Zinc	14000	12000	11000	11000	11000	15000	12000
Other Paints	4500000	3600000	2500000	2700000	2600000	4200000	3000000
Painted Galv. Steel	780000	760000	520000	440000	620000	360000	460000
Painted Steel*	47000	740	0	0	0	0	0

[#]The general equation for calculation is: Area to be maintained = Average population x Area of the material per person x Maintenance Frequency of the material per annum from the dose-response functions in Section 5.1.2.2. An example for limestone in 1993 is illustrated in the footnote.
* Zero values calculated as result of low SO_2 concentration

[@] An example with some numbers is illustrated for limestone in the year 1993:
Damaged limestone area = 6369371 (average population x 0.09 m^2/person x 1/t
with: $1/t = [(2.7[SO_2]^{0.48}e^{-0.018T} + 0.019Rain[H^+])/R_{crit}]^{1/0.96}$
$= ((2.7x31.3^{0.48}e^{(-0.018*23.1)}+0.019*57/4000)^{1/0.96}$
$= 0.00202617$ 1/a
(see Table 5-1 for the parameters for the year 1993: $[SO_2] = 31.3$ μg/m3
Rain[H^+]=Wet Acid Deposition = 57 meq/m^2/a
T = 23.1 °C
Rcrit = 4000 μm)

Damaged limestone area (Table 5-4) =6369371 x 0.09 m^2/person x 0.00202617 1/a
= 573243 m^2 x 0.00202617 x 1/a
= 1161 m^2/a
= 1200 m^2/a (the rounded values in Table 5-4)

Table 5-5. Percentage# of material building material area affected by air pollution and acid rain per year

	1993	1994	1995	1996	1997	1998	1999
Limestone	0.2	0.18	0.15	0.16	0.15	0.15	0.16
Sandstone	0.16	0.14	0.12	0.12	0.11	0.12	0.13
Natural Stone	0.16	0.14	0.12	0.12	0.11	0.12	0.13
Mortar	0.16	0.14	0.12	0.12	0.11	0.12	0.13
Rendering	0.16	0.14	0.12	0.12	0.11	0.12	0.13
Galvanised Steel	1.31	1.17	1.02	1.04	1.03	1.33	1.11
Zinc	0.09	0.08	0.07	0.07	0.07	0.1	0.08
Other Paints	2.64	2.11	1.49	1.59	1.53	2.44	1.79
Painted Galv. Steel	0.46	0.45	0.3	0.26	0.36	0.21	0.27
Painted Steel	0.03	4.4e-4	0	0	0	0	0

Calculated as: Area affected (table 5-4)/Total surface area (table 5-3) x 100%

5.4. Maintenance costs of building material due to air pollution/acid rain in Hong Kong

For the time period analyzed, the annual costs resulting from maintenance and replacement of material surfaces affected by acid rain and air pollution are between 390 M HK $ in 1995 and 640 M HK $ in 1993 (Table 5-6 and Figure 5-1). There was a decrease in material impacts and resulting damage costs between 1993 and 1997. The increase in acid deposition reported for the year 1998 however caused impacts similar to those at the beginning of the 1990s. Data for 1999 show again a decrease in acid deposition, which is however partly offset by an increase in SO_2 concentration, so that the material damage costs are still higher than in the years 1995 to 1997. As mentioned before, the application of the ExternE methodology to the Hong Kong context is a matter of major uncertainties, in particular due to the lack of appropriate data on material inventory and maintenance costs in Hong Kong. Results should thus be considered as a first rough estimate of the potential damage from acid rain and air pollution on building materials in Hong Kong. The present results suggest that an estimate loss of HK 400-500 million dollars or a 0.030 to 0.055 % of the GDP on material damage is subjected to the acid deposition in Hong Kong.

Table 5-6. Annual maintenance costs* in Million HK $ and percentage of the GDP of the year estimated for material impacts due to air pollution and acid rain in Hong Kong.

	1993	1994	1995	1996	1997	1998	1999
Limestone	2.3	2.1	1.7	1.8	1.7	1.7	1.9
Sandstone	2.7	2.4	1.9	2	1.9	2	2.1
Natural Stone	1.9	1.6	1.3	1.4	1.3	1.4	1.5
Mortar	55	47	38	40	37	41	42
Rendering	37	32	26	27	25	28	29
Galvanised Steel	58	52	45	46	46	59	49
Zinc	2.5	2.2	1.9	1.9	1.9	2.7	2.1
Other Paints	400	320	230	240	230	370	270
Painted Galv. Steel	70	68	47	40	56	32	42
Painted Steel	4.2	0.067	-	-	-	-	-
Total	640	530	390	400	400	540	440
GDP (%)	0.072	0.053	0.036	0.034	0.031	0.044	0.036

* Maintenance cost = Area maintained (Table 5-4) x Specific Maintenance Cost (Table 5-2)

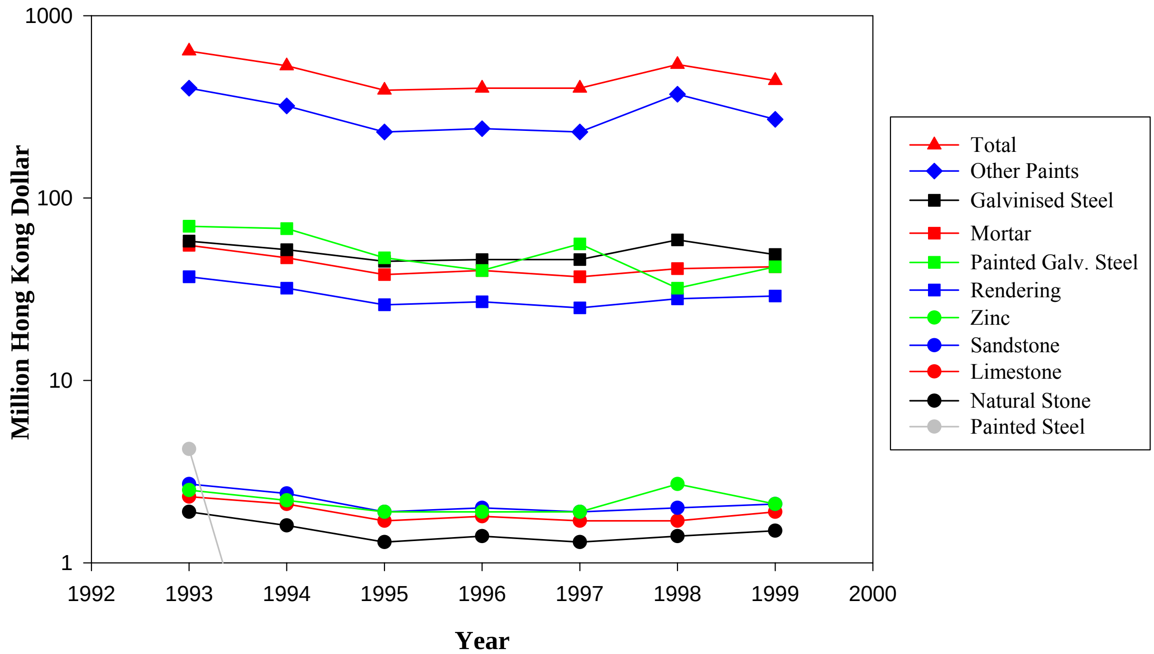

Figure 5-1. Annual maintenance costs on building materials in 1993 to 1999 due to corrosion from air pollution and acid rain

Reference

Ecotech, 1996, An evaluation of the benefits of reduced sulphure dioxide emissions from reduced building damage. Ecotech Research and Consulting Ltd., Birmingham

European Commission, 1995, ExternE, Externalities of Energy, ExternE Report Vol. 2, Methodology. European Commission, DGXII, Science, Research, and Development, EUR 16521

European Commission, 1999, Externalities of Energy., Vol. 7 Methodology 1998 update. European Commission, DG XII, Brussels

European Commission, 2000, ExternE Core/Transport, final report, No. JOS3CT-97-0015, Brussels

Haynie F. H., 1986, Atmospheric Acid Deposition Damage due to Paints, US-EPA Report, EPA/600/M-85/019

Kucera V., Henriksen J., Knotkova D. and Sjöström C., 1993, Model for Calculations of Corrosion Cost Caused by Air Pollution and Its Application in Three Cities. Swedish Corrosion Institute, Report, No. 084, Roslagsvägen

Kucera V., Pearce D. and Brodin Y.W., 1997, Economic Evaluation of Air Pollution Damage to Materials. Swedish Environmental Protection Agency, No. 4761, Stockholm

Lipfert F. W., 1987, Effects of Acid Deposition on the Atmospheric Deterioration of Materials. Materials Performance, National Association of Corrosion Engineers. 12

Tidblad J., Kucera V. and Mikhailov A. A., 1998, Statistical analysis of 8 year materials exposure and acceptable deterioration and pollution levels. Swedish Corrosion Institute, Report, No. 30, Stockholm