THE SUPERBS CASE STUDIES

The SUPERBS case studies report on good examples of sustainable urban development practices in eleven model projects in the countries around the Baltic Sea. The case studies give both theoretical background and applications. The basic assumption is that sustainable development requires that all aspects, i.e., environmental, social, economic etc., of sustainability are addressed at the urban and neighborhood level. Each case study is accompanied by a 30 min TV program in the TV series City 2000. The case study reports and TV programs are used for competence development for urban planners, courses for university students, and material for interest groups in the Baltic Sea Region.

The Superbs project aims at developing a comprehensive understanding of sustainable urban planning and community development strategies in the Baltic Sea region.

THE BALTIC UNIVERSITY PROGRAMME

University co-operation in the Baltic Sea region

The Baltic University Programme is a network of 174 universities in 14 countries around the Baltic Sea. The Programme focuses on issues of sustainable development in the Baltic Sea region. It includes education, research, and co-operation with other actors in the societies, e.g., municipalities and authorities. The Programme is co-ordinated by a secretariat at Uppsala University. 13 national centres in the region provide contact and information and take part in the development of the Programme in the participating countries. The Programme offers courses on undergraduate and master university level, and continuing education for teachers and specialists. Courses are arranged at more than 100 universities for a total of 7,000 students.

Urban Environmental Management

Reports from the Superbs project
SUPERBS
Sustainable Urban PattErns aRround the Baltic Sea

The Superbs project aims at developing a comprehensive description of sustainable urban planning and community development strategies in the Baltic Sea region. The basic assumption is that sustainable development requires that all aspects, i.e. environmental, social, economic etc., of sustainability are addressed at the urban and neighbourhood level.

The SUPERBS project is focused on a broad Baltic co-operation. It involves 11 main partners, in three EU-Member States, four Phare countries and one partner in TACIS. The west-east co-operation is built on the existing well established networks, namely Union of the Baltic Cities (UBC) and the Baltic University Programme. The project is focusing on the requirements for sustainability in urban planning and community development.

Each partner has a model project with a project team. The team consists of three actors; municipalities (urban planners), university researchers and TV producers. The task of the municipality is to design, construct, implement and demonstrate good example of best practice of sustainable urban development. The task of the university researcher is to write a report illuminating several aspects of the model. While the TV producer will make a short television film documenting how the best practice have been carried out as well as showing the accomplished results. It is important to point out that the development of the project models are a broad-based participatory process and models have different time perspectives, some models are completed while others are still underway.

The SUPERBS project has two major objectives: first is to highlight good examples of best practice of sustainable urban development acquired within the 11 model projects which can be copied in other cities and towns around the Baltic Sea Region. Secondly, the material produced within the project (case study reports, books and TV programs) will be used for competence development for urban planners, courses for university.

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Table: Sustainable Urban Patterns Around the Baltic Sea

<table>
<thead>
<tr>
<th>COUNTRY</th>
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<th>UNIVERSITY</th>
<th>TV PARTNER</th>
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<td>Multimedia Fabriken</td>
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The purpose of the case studies is first to serve as study material in education on sustainable community development, secondly to be used by others who find the approaches used worth repeating.

In addition to these reports a TV series - City 2000 - is produced with one program from each one of the eleven model sites. The TV series will be the visual companion to the reports and, more than anything else, bring the inhabitants of each place into the picture.

The reports in this volume constitute a considerable amount of work spread out over more than a year. I would like to use this occasion to express my gratitude to all those who after many difficulties have put together their results. I hope and believe that the efforts made were well invested. The reports together provide a highly interesting reading on efforts in many different countries in our region to deal with the outstanding problems of our time: environmental pollution, economic and sometimes social decline. It is about how insightful individuals, cities and universities have found new ways to develop meaningful patterns of living, patterns that we may all be proud of and that will last, be sustainable. Thank you for sharing it with us.

Lars Rydén
Series editor

1. Municipal environmental audit – The UBC manual as a tool to develop local environmental management applied in the Finnish cities of Turku and Pori
Mikko Jokinen and Matti Lankinen
The manual for Municipal Environmental Audit developed by the Union of Baltic Cities (UBC) in 1996-98 to support the environmental work of cities in the Baltic Sea Region, was used by the two neighbors, Turku and Pori to review their environmental management. Expert teams from the two cities visited the other city in the six selected areas: air pollution monitoring, noise abatement, waste management, water protection, nature protection and biodiversity, and environmental administration. Results from the process are summarised in the article. The environmental administration in both cities confirmed the great value of feedback from expert colleagues to improve work and routines in environmental management.
Mikko Jokinen is head of environmental management in the city of Turku, and Matti Lankinen is one of the authors of the UBC-Municipal Environmental Audit handbook. mikko.jokinen@turku.fi
Matti Lankinen is head of the environmental protection office in the city of Pori, mati.lankinen@pori.fi

2. Local sustainability indicators – The development and monitoring of six local indicators in Kaunas
Linas Klucnikinas
In order to monitor local sustainable development processes in Kaunas, Lithuania, six indicators, four with a clear environmental profile, were chosen from the set of ten core indicators recommend by the European Sustainable Cities and Towns Campaign. These were citizens' satisfaction with the local community, local air quality, local mobility, local contribution to climate change, availability of public open areas and services, and noise pollution. Background descriptions including legal requirements especially in EC Directives, monitoring methodologies, limitations, and preliminary results from monitoring work are reported.
Linas Klucnikinas is an Associate Professor of environmental engineering at Kaunas University of Technology. kluku@vandens.sk-uc.klu.fi

3. Waste management and nutrient flows in the city of Turku – A detailed N and P flow study to estimate the capacity of biowaste sorting to contribute to nutrient recycling
Toni Tikkonen
A detailed quantitative study of flows of nitrogen and phosphorus in all organic waste in Turku was made to evaluate the potential of recycling of nutrients. Both inputs and outputs in all municipal and private nutrient-containing fluent and solid waste flows were estimated. These included municipal and private sewerage, municipal solid waste, and municipal as well as private composting. The volume or weight of each of these was measured as well as their content of N and P either measured or estimated using reference values from literature. The total flows for the 171,000 inhabitants and their animals were found to be 3,074 kg of N and 583 kg of P per day. 64 % of the inputs were found in the municipal wastewater. 11 % in pig manure, 10 % in solid organic waste sent to incineration and 7 % in organic waste sent to landfill. The major flows of output nitrogen included 53 % (1,647 kg/day), to surface waters and 23 % (716 kg/day) to sludge, while for phosphorus 15 % (40 kg/day) went to surface waters and 61 % (308 kg/day) to sludge. The remaining nutrients were recycled for new agricultural production. If separate sorting of biowaste is achieved (planned for 2005) this figure will increase to 7 % and with maximum recycling amount to 15-16 %.
Toni Tikkonen is a Project Manager working in the Green Know-How network of Turku (www.greenknowhowturku.com)

4. Air pollution and damage to the cultural heritage in cities – The decay of the cultural heritage of Kraków
Wanda Wilczyska-Michalik
Air pollution is both detrimental for human health and cause corrosion and deterioration of materials. Air pollution also has a significant impact on the effects of air pollution on the stone cultural monuments in Kraków showed that it has caused damages to be far reaching and serious. Biodiversity is a serious threat for the Krakow monuments, especially the historical buildings were made of Libasz dolomite. Upper Jurassic limestone. Pieków limestone and Carpathian flysch sandstone, used in the Wawel Castle and the Church of St. Mary of the Assumption. Excessive weathering was caused by wet and dry deposition of nitrogen and sulphur, the formation of gypsum crystals, and dust, metal impurities and microbial activities. The mechanisms of pollution-causing weatherings were studied by electron microscopy and chemical analysis, and several black and multi-colored sculpures, have either been replaced by copies, or restored. Costs for restoration work have so far exceeded 40 M PLN.
Wanda Wilczyska-Michalik is geologist and an Associate Professor of Geography at Krakow Pedagogical University. armichal@up.krakow.pl

5. Health concerns in environmental management – The city of Kaunas' health profile
Juozas Kame内eckas
A quantitative descriptive description of health (the health profile) of the 400,000 inhabitants of Kaunas, the second largest city in Lithuania was made using available statistics from 1980 up to 2000. Mortality rates, decreasing since the mid 1990s, were comparable to values in Lithuania as a whole and dominated by cardiovascular diseases and other causes. In 1999 close to 80 % of the population experienced themselves as not having full health. Complaints were dominated by respiratory diseases (close to 10%). Separate studies in 9 districts in the city proved the health situation to be worse in areas with more traffic, close to a power plant, and less greenery, but also less good social status. The City has in its health plan included work to improve the environment, especially decreasing air pollution.
Juozas Kame内eckas is a politician and head of the Kaunas healthy city office.

Silvia Schubert
Inhabitants in ecological communities develop integrated strategies for environmentally friendly lifestyles. The eco-community of Braamwisch in the northeastern part of Hamburg, Germany, has developed its own ecological strategies in several ways. Braamwisch includes 40 houses built 1996-2000, all with low energy construction methods, and extremely good insulation. Much of the heating is made using local solar heating, while green electricity was bought from outside, and to an extent came from local photovoltaic cells. All building materials used were environmentally safe. Toilets were mostly dry composting toilets. Water consumption was considerably reduced without water toilets (about 20,000 liters per year and person), and further reduced by the use of rainwater. Wastewater consists only of grey water, which is treated locally in three reed beds. Kitchen waste is mostly composted in the same bin as toilet waste. The inhabitants cause little environmental impact by traffic as they use car-sharing and in addition, the community is located close to the public transport of Hamburg city. The inhabitants buy and sell used things and needed commodities, such as shops, schools and doctors office, are within walking distance. The social dimension of life in an eco-community is also important as described in this report.
Silvia Schubert lives in Braamwisch, with her family. Silvia.Schubert@anu-hamburg.de

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The decay of the cultural heritage of Kraków

Wanda Wilczyńska-Michalik

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4.1 AIR POLLUTION IN KRAKÓW

4.1.1 A history of air pollution

Kraków is a city troubled by air pollution. Smoke and sulphur dioxide from combustion of coal in industries and homes dominated earlier, today the traffic is a major source. Data published by the Central Statistical Office (Ochrona Środowiska, 2000) indicate that Kraków still ranks in the top ten of cities in Poland seriously threatened by air pollution.

Air pollution is aggravated by the situation of the city in a valley, and the prevailing climate of low wind velocity, a high number of foggy days and nights, and temperature inversions. Kraków is a poorly ventilated city with numerous narrow, "canyon" streets with high buildings.

The predominance of western winds brings pollution from Upper Silesia, the largest industrial agglomeration in Poland situated about 30 kilometres from Kraków, and from abroad. An important source of air pollution is the Skawina S.A. Power Plant located 15 kilometres to the southwest of the city. It has been assumed that imported pollution sometimes accounts for 47% of the air pollution in Kraków (Rapport o stanie, 1995).

Although the consumption of electricity in households is still growing, particulate and gaseous emission from the Elektrociepłownia Kraków S.A. (a combined heat and power plant) and the municipal district heating company dropped since the late 1990s. The Elektrociepłownia Kraków S.A. power plant reduced its gas and dust emissions by 22% and 33% respectively, and the municipal district heating company reduced its gas and particulate emission by 2% and 26%. The improvements were due to modernisation of the ash retention tanks and the automation of technological processes (Pająk, 1999).

In the city centre harmful substances in the air have decreased, as the furnaces in the homes have been modernised and coal exchanged for e.g. gas or oil. Simultaneously the consumption of gas is decreasing slowly.

However traffic is increasing. The number of road vehicles in Kraków (Table 4.1) and heavy traffic, exceed 4,000 vehicles per hour on some of the transport routes. The highest concentrations of traffic-related air pollutants recorded in 1994-98 were nitrogen dioxide 61-68 mg/m³, carbon monoxide 2,400-3,500 mg/m³, benzo(a)pyrene 6.7-13.3 mg/m³ and particulates [PM10]: 72-86 mg/m³. The average annual concentration of lead and cadmium in particles exceeded permissible standards (Pająk, 1999).

4.1.2 Origin of air pollutants

Gaseous emission from power plants in the Kraków area and in Upper Silesia accounts for about 20% of the total gaseous pollution in Poland. Sulphur dioxide emissions from heat and power plants in Poland is a major cause of the deterioration of stone. Pollution emitted by the Sendzimir Steelworks still contributes significantly to the amount of industrial pollution in Kraków.

Emission of dust from fuel combustion varied between 49% (in 1990) to 56% (in 1999) of the total dust emission in Kraków for the period 1990-1999 (R. Statystyki Krakowa, 2000). In the mid 1990s dust and gaseous emission from power plants in Kraków increased because of the increased production of energy.

During 1998-99 emissions from Śląskie, Małopolskie and Podkarpackie voivodeships (Table 4.2) had a crucial share in the total emission of pollution: 63.0-68.9% of dust, 93.5-98.5% of sulphur dioxide, and 72.6-92.3% of nitrogen oxides (O. Środowiska, 2000). In the Małopolskie voivodeship carbon dioxide emission reached 12,500 thousand tonnes in 1999. 21% came from the municipal heating enterprise and private coal-fired home boilers/furnaces. The air in Kraków is polluted by emissions from homes furnaces and cars. High emissions of nitrogen dioxide and carbon monoxide from traffic is confirmed by traffic-related pollution monitoring station with automatic equipment (city centre, Krakowskiego avenue), where concentrations exceeded permissible standards were recorded (Czamecka, 1999).

In 1998, for the first time in five years, the share of gaseous pollutants in Kraków increased in comparison with particulate emission. This caused the decrease in pH of wet deposition, observed the last few years (Report on the Environment in Kraków 1994-1998, 1999).

Table 4.1 Registered and newly registered road vehicles in Kraków.

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Registered (in thousands)</td>
<td>203.7</td>
<td>215.7</td>
<td>226.3</td>
<td>270.4</td>
</tr>
<tr>
<td>Registered</td>
<td>64</td>
<td>64</td>
<td>70</td>
<td>83</td>
</tr>
<tr>
<td>Registered/100 households (in thousands)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Registered/100 residents (in thousands)</td>
<td>231</td>
<td>243</td>
<td>253</td>
<td>301</td>
</tr>
<tr>
<td>Newly registered (in units)</td>
<td>14,377</td>
<td>17,872</td>
<td>15,598</td>
<td>18,078</td>
</tr>
</tbody>
</table>

4. AIR POLLUTION AND DAMAGES TO THE CULTURAL HERITAGE IN CITIES

Table 4.2 Dust and gaseous emission from major industrial pollutants by voivodeships in 1998-1999 in 1,000 tonnes per year (1,000). $NO_x$ denotes nitrogen oxide (NO) and nitrogen dioxide (NO$_2$) together.

<table>
<thead>
<tr>
<th>Voivodeship</th>
<th>Total Fuel</th>
<th>Total $SO_2$</th>
<th>Total $NO_x$</th>
<th>Total CO</th>
<th>Total CO$_2$</th>
<th>Total hydrocarbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>Fuel</td>
<td>$SO_2$</td>
<td>$NO_x$</td>
<td>CO</td>
<td>CO$_2$</td>
<td>hydrocarbon</td>
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<td>Total</td>
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4.1.3 The formation of air pollutants

Pollution from the emissions from combustion of fossil fuels remains a major environmental issue, with health and material damage effects well documented (Kapuluz & Pakkanen, 1990; Boix et al., 2001; Hewitt, 2001).

Carbon monoxide oxidation is a slow process and the lifetime of CO in the atmosphere is several years. The oxidation rate of CO can be around 2% per hour in urban air and is ten times lower in clean air resulting in an overall lifetime of a few days (Clarke, 1996). Relative humidity (RH) influences sulphur dioxide oxidation rates. Generally, the rate of conversion increases sharply as the relative humidity increases above 70% (Amonaro & Fassa, 1983). The relative humidity of the atmosphere in Kraków is high (Table 4.3), with average monthly RH values in the morning and in the evening often exceeding 80%.

Besides moisture in rain and fog, the relative humidity of the atmosphere in Kraków is a very important source of moisture infiltrating into porous building stones.

Carbon monoxide oxidation is a slow process and the lifetime of CO in the atmosphere is several years. The oxidation rate of CO can be around 2% per hour in urban air and is ten times lower in clean air resulting in an overall lifetime of a few days (Clarke, 1996). Relative humidity (RH) influences sulphur dioxide oxidation rates. Generally, the rate of conversion increases sharply as the relative humidity increases above 70% (Amonaro & Fassa, 1983). The relative humidity of the atmosphere in Kraków is high (Table 4.3), with average monthly RH values in the morning and in the evening often exceeding 80%.

Table 4.3 The average monthly values of relative humidity (RH) in the atmosphere (%)

<table>
<thead>
<tr>
<th>Year</th>
<th>1962-1965</th>
<th>1992*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>7 am hour</td>
<td>12 am</td>
</tr>
<tr>
<td>January</td>
<td>86 78 84</td>
<td>89 78 83</td>
</tr>
<tr>
<td>February</td>
<td>86 74 82</td>
<td>90 70 60</td>
</tr>
<tr>
<td>March</td>
<td>85 65 76</td>
<td>86 54 65</td>
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<tr>
<td>April</td>
<td>85 56 70</td>
<td>76 52 62</td>
</tr>
<tr>
<td>May</td>
<td>79 55 71</td>
<td>79 51 65</td>
</tr>
<tr>
<td>June</td>
<td>79 57 72</td>
<td>76 68 61</td>
</tr>
<tr>
<td>July</td>
<td>80 57 73</td>
<td>75 49 63</td>
</tr>
<tr>
<td>August</td>
<td>84 58 75</td>
<td>76 40 57</td>
</tr>
<tr>
<td>September</td>
<td>88 62 80</td>
<td>89 56 78</td>
</tr>
<tr>
<td>October</td>
<td>89 68 83</td>
<td>91 64 82</td>
</tr>
<tr>
<td>November</td>
<td>68 77 80</td>
<td>69 69 84</td>
</tr>
<tr>
<td>December</td>
<td>86 77 90</td>
<td>90 89 90</td>
</tr>
</tbody>
</table>

* Year with the lowest amount of precipitation in the last 100 years. Source: Institute of Meteorology and Water Management in Kraków.

4.2 POLLUTING GASES, PRECIPITATION AND PARTICLES

4.2.1 Annual variations

Average composition of atmospheric aerosols in Kraków varies during the year. In wintertime, small carbon-containing particles of soot dominate. In summertime, especially in a dry period, natural soil-derived particles are more frequent. In the period of development of vegetation, biological material is also an important component of aerosols (Kozak et al., 1998).

Larger differences in the concentration of air pollution between summertime and wintertime indicate a great influx of pollution from the combustion of fuels (Michalek & Wilczynska-Michalak, 1998).

The average annual total particulate concentration (TPC) and the average annual sulphur dioxide concentration in the city centre from 1994 to 1998 are listed in Table 4.4. Depending on the growing season, the concentration of SO$_2$ ranged between 13.2-22.4 mg/m$^3$. It was the first time for a number of years that the average annual concentration of SO$_2$ in Kraków fell below the standard of 40 mg/m$^3$. By 1998 the permissible concentration of sulphur dioxide was more stringent by as much as 32 mg/m$^3$ (Czarnacka, 1999).

The highest average levels of annual concentration of suspended dust and sulphur dioxide were noted in the city centre in the period 1968 to 1987, when sulphur dioxide concentrations varied from 83 in 1971 to 122 mg/m$^3$ in 1985, and concentration of suspended dust varied from 143 in 1977 to 195 mg/m$^3$ in 1972 (Lach et al., 1996). The average annual concentration of sulphur dioxide in the city centre varied from 122 in 1985 to 75 mg/m$^3$ in 1990 and 1992 (Figure 4.3), and the average annual concentration of suspended dust particles of diameter below 10 $\mu$m varied from 116 in 1986 to 52 mg/m$^3$ in 1992 (Figure 4.4).

4.2.2 Precipitation - composition and effects

Precipitation waters in Kraków have a high concentration of minerals (Wilczynska-Michalak et al., 2000). The mineral composition of the dry residue after evaporation of the pollen is dominated by gypsum, but sulphates, nitrates, carbonates, phosphates, and chlorides are also found. The pH of rainwater in Kraków varies within broad limits (4.8-7.1). Most rainfall has natural to slightly alkaline pH. The average pH value in the close vicinity of Kraków is lower than in the centre of city. The lowest pH occurred in winter, and the highest in spring and summer (Godzik, 1999). From 1994, with a break in 1997 and 1998, the pH of wet deposition has systematically decreased. It is due to a reduction of emissions of dust compared to gases from the industry, as dusts are more alkaline. A gradual acidification of wet deposition may be expected in the future.

Precipitation is an important cause of weathering in Kraków because of the high concentration of pollutants in rain, which causes rock decay by salt crystallisation. The anthropogenic emissions of carbon and sulphur have a much larger acid-generating capacity than natural fluxes. The weathering needed to neutralise these fluxes is far in excess of observed values (Varekap & Thomas, 1998).

The monthly influx of different chemical components from precipitation was calculated as higher than 1 gram per m$^3$. The highest influx of several components does not always coincide with the highest concentration in precipitation (e.g. sulphate ions in June 1998). Recalculation of the influx of calcium and sulphates ions which can hypothetically precipitate, shows that gypsum may during periods be high (e.g. in November 1998 more than 4 g/m$^3$). The amount of hypothetical gypsum exceeds 3 g/m$^3$ per month both in wintertime, when coal-based heating is significant, and in the summertime, when the precipitation is extraordinarily high (Figure 4.5).

Figure 4.1 Major power plants by quantity of particulates and gaseous emission (1999).

Figure 4.2 Sulphur dioxide (SO$_2$) emission in Poland in 1988 due to fuel combustion.

Figure 4.3 Sulphur dioxide (SO$_2$) concentration in Krakow 1994-1998.

Figure 4.4 The monthly influx of gypsum in Kraków.
4. Air Pollution and Damages to the Cultural Heritage in Cities

4.3 Fly ash and soot particles
Dust from the power plants, that is the fly ash (Figure 4.6), consists of usually spherical amorphous aluminosilicate particles of diameter from <1 to 15 μm. Bigger particles (up to 100 μm) occur rarely. Beside silicon and aluminium, they contain calcium, sodium, and potassium. The content of iron, sulphur, titanium, copper, zinc, magnesium varies in individual particles. The average content of carbon is about 0.5%.

Dust from home furnaces, that is the soot, consists of irregular fine-grained particles less than 1 μm (Figure 4.7). The average content of carbon in the soot samples reaches 45%. Formation of soot commonly accompanies carbon monoxide formation and is due to an inadequate air supply.

Several elements are highly concentrated in the dust in comparison with average sedimentary rocks. The concentrations of bismuth, arsenic, cadmium, lead, and antimony in fly ash are 600; 14; 17; 13 and 11 times higher respectively. In soot the concentrations of selenium, lead, zinc, silver, bromine, cadmium, and bismuth are 150; 24; 44; 20; 125; 85 and 10 times higher (Wilczyńska-Michalik & Michalik, 1998b).

The share of carbon and sulphur in soot is higher as compared with the fly ash from power plants (Figure 4.9).

6.3 Decay of Historical Monuments in Kraków

4.3.1 Natural and pollution-caused weathering
Weathering is the process in which stone surfaces are chemically altered or dissolved and washed out as a result of chemical and physical processes. Natural weathering has always occurred. Air pollution may, however, accelerate weathering dramatically. The mechanisms of weathering in a polluted atmosphere differ from the natural ones. Stone decay is caused by the reactions between the components of the rock and the atmospheric pollutants, and crystallisation of new components from precipitation water at the surface and in the pore-spaces of the rock.

Air pollutants in Kraków cause serious damage to historic stone monuments in the city. The decay of building stones is mainly due to sulphuric pollutants, soot, heavy metals, alkalines from petrol combustion, and microorganisms. The stones in the polluted atmosphere show a high degree of surface alteration.

Sulphur dioxide (SO₂) reacts with building materials containing calcium carbonate (CaCO₃) to form gypsum (CaSO₄·2H₂O), which is by far the most common mineral in the black crusts of damaged stones. Carbon particles, especially those containing trace amounts of metal, are believed to act as catalysts for the oxidation of SO₂ (Sabbioni & Zappia, 1992). The deposition of dusts containing soot, iron and manganese facilitates the formation of a black gypsum crust at the surface of the rock. Rodriguez-Navarro & Sebastian (1996) confirmed in experiments the catalytic role of soot and metal-rich particles from vehicle exhaust has on gypsum crust formation on the surface of limestone.

Figure 4.3 The average annual concentration of sulphur dioxide (SO₂) in Kraków voivodeship during the period 1982-1992. According to data of the Voivodeship Inspectorate for Environmental Protection in Kraków, 1994.

Figure 4.4 The average annual concentration of suspended dust (particles below 10 μm in diameter) in Kraków voivodeship during the period 1982-1992. According to data of the Voivodeship Inspectorate for Environmental Protection in Kraków, 1994.

Figure 4.6 Spherical aluminosilicate particles generated by the combustion of fossil fuels (Elektrociepłownia Kraków S.A.). SEM.

Figure 4.7 Carbonaceous particles (soot) generated by the combustion of fossil fuels from home furnaces. SEM.

Figure 4.8 The strongly damaged sculptures of the Apostles from the 18th century. Photo: Wanda Wilczyńska-Michalik.

Figure 4.9 Sulphur and carbon (“graphic” and “organic”) in soot from home furnaces and fly ash from power plants.

Table 4.5 Minerals present in secondary crusts on building stones in Kraków.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
</tr>
<tr>
<td>Barite</td>
<td>CaSO₄·H₂O</td>
</tr>
<tr>
<td>Hexahydrate</td>
<td>MgSO₄·6H₂O</td>
</tr>
<tr>
<td>Epsomite</td>
<td>MgSO₄·7H₂O</td>
</tr>
<tr>
<td>Melanite</td>
<td>FeSO₄·7H₂O</td>
</tr>
<tr>
<td>Langbeite</td>
<td>K₂Mg(SO₄)₂·6H₂O</td>
</tr>
<tr>
<td>Mibrite</td>
<td>Na₂SO₄·5H₂O</td>
</tr>
<tr>
<td>Syngenite</td>
<td>K₂Ca(SO₄)·H₂O</td>
</tr>
<tr>
<td>Burkeite</td>
<td>2Na₂SO₄·4K₂CO₃</td>
</tr>
<tr>
<td>Carbonate</td>
<td>CaCO₃</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMg(CO₃)₂</td>
</tr>
<tr>
<td>Halite</td>
<td>NaCl</td>
</tr>
<tr>
<td>Sylvinite</td>
<td>KCl</td>
</tr>
<tr>
<td>Nitronite</td>
<td>NaNO₃</td>
</tr>
<tr>
<td>Nitramite</td>
<td>NK₂NO₃</td>
</tr>
</tbody>
</table>

Both dry and wet deposition of air pollutants is a cause for the deterioration of stonework. The process may be accelerated by lime etching. Estimations of sulphur dioxide uptake by limestone show a deposition velocity of several millimetres per second (Amoroso & Fassina, 1983). Overall the dry deposition velocities measured experimentally for sulphur dioxide range from below 3 to nearly 20 mm/sec; a typical value of 10 mm/sec is often assumed (Clarke, 1996).

The solubility of calcite in the rock increases very significantly, by a factor of 100 for each pH unit, with increasing acidity of the solution, with temperature. Increasing carbon dioxide concentrations in the air increase the rate of dissolution of carbonates rocks (Winkler, 1970). The weak acid solution formed by dissolved carbon dioxide in rainwater dissolves the calcium and magnesium carbonates in limestone and dolomite, as it forms much more soluble calcium and magnesium bicarbonates (Amoroso & Fassina, 1983).

The production of sulphates in clouds could be the major source of atmospheric sulphates (Easter & Hobbys, 1974). Thus formed airborne sulphates dissolve in precipitation water and could be subsequently deposited on stone surfaces.

Microorganisms attack stone by both mechanical and chemical action. Most commonly, the organisms arrive by air, riding on aerosols, particularly soot and via rainwater (Young, 1996).
The historical monuments

The Wawel Cathedral (Figure 4.10) where the kings of Poland were crowned and buried is strongly associated with the history of Kraków and the whole Polish nation. The Cathedral was erected in the years 1320-1364 to replace the former Romanesque churches. The 17th century walls surrounding Wawel Cathedral were of Libiąż dolomite. Although dating from different periods, all the distinct parts of the Cathedral make a unique and picturesque ensemble. The fortifications surrounding Wawel hill date from different periods. The first fortifications were built in the early medieval period and are known from archaeological excavations. Defence walls, characteristic for the present Wawel Castle landscape, were built in the 14th century (Pianowski, 1991). Fortifications in a neo-gothic style were added in the 19th century. Three bastions are situated at the foothill of Wawel (Pianowski, 1991). The Church of Saints Peter and Paul (built at the beginning of the 17th century) is considered to be one of the most magnificent early baroque churches in Central Europe. The fence topped with sculptures of the Apostles and enclosing the yard in front of the church is a very characteristic feature of this monument (See Figure 4.11).

The precise date of the installation of the sculptures of the Apostles has been a matter of speculation in the past and in reality we may never know the exact truth. However according to Karpowicz (1965), we can be reasonably confident that the sculptures that decorate the fence in front of the Saint Peter and Saint Paul church are most likely from around 1715-1772. The 18th century sculptures were heavily decayed and now are replaced by copies.

4.3 Effects on selected building stones

The mechanism and rate of deterioration of different types of stone used as building materials in some significant monuments in Kraków is described in this paper. Particular attention is given to the most characteristic patterns of weathering observed on surfaces of dolomite, limestones and sandstones. The state of deterioration of selected elements of these monuments and results of applied renovation works are included. Results of studies that identify pollution from fuel combustion and pollution derived salts, as the causes of stone damage are also presented.

The durability of various carbonate rocks in the polluted atmosphere in Kraków differs significantly. Upper Jurassic limestone and Pńczów limestone is much used in Kraków’s architecture. These two types of limestone show a wide range of durability. Weathering of Upper Jurassic limestones is seen in the 19th century fortifications of Wawel Castle, and of Pńczów limestone in the decayed sculptures of the apostles in front of the of Saints Peter and Paul church.

Upper Jurassic limestone is relatively resistant. Since the Roman period Upper Jurassic limestone has been commonly used in Kraków’s architecture. It is light grey or white with some grey veins. The porosity of Upper Jurassic limestone varies from 0% to 15%, but usually it is below 10%.

Pńczów limestone, commonly used for carving since the Renaissance period, is a highly porous (usually above 35% porosity) Miocene sedimentary bioclastic rock. It is light cream with a delicate, greenish tinge. It is formed of crushed reef carbonate fragments deposited together with small amounts of binding material. Calcite skeletons are cemented with the crystalline calcite. Haber et al. (1988) identified two main types of Pńczów limestone, a coarse-grained variety, which is durable and fine-grained, which decays easily. The durability of Pńczów limestone is strongly related to its texture.

4.4 DAMAGES ON THE STONE MATERIAL

4.4.1 Weathering of Libiąż dolomite

The Libiąż dolomite in the historical architecture in Kraków has decayed rapidly during the last fifty years. On the wall surrounding the Wawel Cathedral, the portal of the external gate of the Royal Saccharopolus and the front facade of the Church of Saints Peter and Paul, were 1-30 cm³ alveolar cavities from 1-4 cm deep (Figures 4.12, 4.13). The damaged rock surfaces were carefully examined.

The cavities were crumbly and scaly. Assemblages of gypsum sulphate heptahydrate, epsomite (i.e. magnesium sulphate heptahydrate) and gypsum (calcium sulphate didehydrite) occurred in 100-500 µm thick discontinuous encrustation. Considerable amounts of salts were concentrated at the bottom of the gradually eroded cavities, where they were precipitated from water. The exterior surface of the dolomite stone was covered with a dark crust of minute needle-like gypsum crystals including large amounts of up to 60 µm large dust particles.

Cavernous and honeycomb weathering (alveolar pattern) was characteristic of the surfaces exposed to rain and wind action. The porosity (7% to 12%) and imbition (2.3% to 5.6%) of the dolomite permits moderate to good moisture penetration. The movement of ions from the rock dissolved by rainwater towards the stone surface and ions from rainwater into the rock, and cementation of pores by precipitated and crystalized soluble salts, fundamentally alter the properties of the surface layer of the stone compared with those at depth. This is probably the main reason of alveolar pattern development. As wind speeds up the evaporation of water the soluble salts crystallises.

4.4.2 Weathering of Upper Jurassic limestone

The Jurassic limestone in Wawel’s fortification walls from the 19th century, have contrasting black and white zones (Figure 4.16). The white zones develop on surfaces exposed to rains, which washes out airborne pollutants and initiates formation of a crust of gypsum on the surface. The gypsum crust is not stable; solutions migrate freely into the limestone. Here the gypsum repeatedly dissolves and recrystallises in the alternating episodes of wetness and dryness of the stone, and causes mechanical stresses in pores and cracks.

The intensive blacking was typical of humid surfaces exposed to the north. Also here gypsum crust forms. The surface of a black gypsum crust is uneven, from 0.5 to 10 mm thick, with subparallel folds or mushroom-shaped forms. Polarisering microscopes and scanning electron microscope pictures show that the darkening is caused by black fly ash particles (Figure 4.17), but it probably also comes from microorganisms, such as cyanobactena. Their role in weathering of limestone surfaces, often re-
Firstly, the black gypsum crust absorbs more solar radiation than the white surface. The linear coefficient of the thermal expansion of gypsum is about five times that of calcite (Goudie & Viles, 1997). Disruptive thermal gradients between the subsurface and surface can lead to exfoliation development during repeated heating-cooling cycles (Figure 4.18).

Secondly, salt weathering of the limestone is recognised as one of the primary factors of deterioration. Blistering and exfoliation of a few millimetres thick gypsum crusts is the main reason for the decay.

Thirdly, the moisture facilitates microorganism growth. Microorganisms, bacteria, algae and fungi, located on rocks in the city are less frequent than in rural areas, probably limited by rapid salt precipitation, but still found. In winter sulphur oxidising bacteria (Thiobacillus thiooxidans, Th. thiobacillus, and Th. denitrificans), producing sulphuric acid, dominate, and in summer nitifying bacteria (Nocardia, Nostoc, Nitrormonas), oxidising nitrate, are more common. Also cyanobacteria (blue-green algae) chemically attacks calcite crystals and dissolve calcite, producing micro-scale boreholes and pitting. (Figure 4.13b).

4.4.3 Weathering of Pinczów limestone
The sculptures in the Churches of the Apostles from the 18th century, made in Pinczów limestone, were badly blackened and in an advanced stage of decay (Figure 4.8). Some of the badly disintegrated carved elements could not be recognised, and material and stone fragments from surface and subsurface layers of the Pinzów limestone had crumbled. Gypsum crystals had formed under the surfaces layers of the limestone, as rainwater penetrates through the pores deeply into the stone.

Newly formed gypsum is easy to remove from pores of bigger size. Fine-crystalline gypsum has filled the small pores of the rock. The crystallisation of gypsum causes mechanical stresses in small and medium-sized pores and cracks. The deterioration mechanisms are typical for medium porous to high porous carbonate rock (Figure 4.15c).

4.4.4 Weathering of Carpathian flysch sandstone
The statues of the Apostles were placed on bases carved in Carpathian flysch sandstone. Because of its sensitivity to pollution these old sandstone bases experienced severe decay. In sandstones containing carbonate cement, which was the material of the original bases, destruction occurs because the volume of primary cements is reduced and dissolved by precipitation water. Then the carbonate is replaced by gypsum (Figure 4.19). Gypsum fills all empty voids in the rock. All these processes result in the weakening and accelerated decay of the structure of the rock.

The final stage of the process is the formation of gypsum cemented sandstone. This has a "float texture", in which detrital quartz grains are dispersed in gypsum cement. The structure of the rock is weakened not only by exchange of cement but also by mechanical displacement forces induced by the growing gypsum, especially distinctive in highly porous sandstones (containing or devoid of carbonates).

The later stages of weathering of the bases described here, has been manifested as disintegration, exfoliation, crumbling, and rounding of edges (Figure 4.20). Together with the detached gypsum crust some components of sandstone are removed from the rock surface.
References