THE POTENTIAL OF LICHENS IN SUSTAINABLE CONTEMPORARY FAÇADE DESIGN

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ABSTRACT

In the recent years there has been an increasing focus on contrasting deficiency of green areas in cities. This comes with the urbanization as there is a desire to introduce green areas in the cities to improve the living conditions. The greening of cities involves also the concept of greening the building envelopes. Green façades and green walls exploit the ability of green to occupy the vertical surfaces, integrating green in cities, without the need of ground space.

The existent systems for vertical green present several limits and disadvantages, encouraging researchers to develop new solutions, with a higher level of integration with the building structures. Conversely, undesired biological colonization is common on building materials and many studies have been done regarding the biodeterioration effects that pioneer organisms have on the building structures.

The aim of this thesis is to investigate the possibilities of using lichens as colonizing organisms on contemporary façade design. An experiment was carried out in order to assess the suitability of several natural and artificial common cladding materials as substrate for lichen colonization. Lichens were collected in Iceland and Denmark and inoculated into specimens of several materials. Then the specimens were exposed to environmental conditions, placed on different supporting structures in order to evaluate also the effects of inclination and of other architectural parameters inducing different micro-climate conditions.

Basalt and lava stones specimens appeared to have an higher bioreceptivity compared to the other materials, since an higher quantity of lichens was observed to adhere to the substrates. However, the experiment will be continued for two more years to observe lichens growth.

Also significant differences were observed in the specimens with changing inclination, and whether or not it was sheltered to protect the lichens from hydrodynamic. Higher presence of lichens presence were observed on the specimens placed horizontally and covered with the shelter. However, the results obtained for the specimens oriented vertically were more significant, considering the intended application is on vertical building surfaces.

A second experiment was carried out in a climate room, in order to assess the correlation between pore size and lichen adhesion to the substrate. The presence of other pioneer organisms, such as bacterias and molds, influenced the results of the test. However, from the results obtained it was observed that specimens with larger pores showed a higher degree of bioreceptivity.

To my grandmother.

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INTRODUCTION

1.1 SCOPE OF RESEARCH

The new century has brought a new way of thinking to green: before, the strategies concerning landscape were mainly based on the concept of preservation of the existing green areas. In the urban environment, only quantitative parameters were considered (like standards such as square meters of green per inhabitant).

In the recent years, the diffusion of the concept of sustainability, led to an increased attention towards the environmental emergency, especially in the urban areas. Thanks to this growing awareness, not only architects or city planner, but also the inhabitants understood the importance of a contact with nature (Kellert, 2008). In terms of landscape not only the preservation of the existing areas is now considered, but also the enhancement. In cities it is not enough to fulfil the European parameters of square meters of green per inhabitant. It is necessary to invest on the quality of the spaces reserved to green and on the possibility to use it and to transform it in a system. In the field of building and architecture, this new feeling is translated in a particular attention towards the values of sustainability, the existence of open spaces (such as terraces, gardens, patios..) to live outside, towards the relation between interiors and exteriors of the domestic walls, the quantity and the quality of natural light, the location respect the external contest and towards the construction materials. People look for an house where they can feel good, in harmony with the world and where it is possible to live a new contact with nature and beauty. Today's challenge is to succeed in the transformation of ugly places in inviting places and to invent the green where is missing.

Cities are quickly reaching the maximum level of population density and, even if they are growing in height, it is always more difficult to find areas enough large to contrast the effects of this phenomena. The environmental issues due to the low air quality, the overheating caused by the urban heat island effect, the acoustic pollution and the supremacy of cars as way of transportation is now more evident than never before. Architects, engineers and also common inhabitants try to find new spaces where is possible to place green. It is necessary to re-invent a new way of interpret and live nature in cities, both in private and public sphere: understand the potential value of the qualitative transformation of spaces, nobody's land plots and the urban voids, results of abandonment or design errors, and of the copious unused surfaces at the limit of the cities (Bortolotti, 2011). In the public sphere, governments are, always more often, investing in initiatives and strategies to increase and improve the green present in cities. In Denmark, and especially in Copenhagen, there are many ongoing projects that aim to increase and improve the spaces destined to green. Examples are the 1947 Copenhagen regional plan (or finger plan), the more recent Pocket parks project, or the mandatory green roof policy, beyond many other initiatives. However, creating this "special" type of green, is a real challenge for architects and designers.

Currently, in order to intervene in urban green development, it is not enough to know how to realize parks and gardens. But it is necessary to measure up against all the technical problems related to the extreme conditions where is necessary to intervene: ensuring the type and amount of natural light suitable for plants, choosing them carefully in relation to the expected life condition, defining irrigation methods, providing substrates and type of cultivation appropriate for the different situations, identifying functional design solutions and techniques to operate on a small scale or in a few meters of space, evaluating problems of overloading and need related to waterproofing of building structures, ensuring proper drainage of plants, minimizing the maintenance costs.

The ground spaces available for green, in the always more dense urban centers, are near exhaustion. Therefore, the applications of vegetation on the vertical surfaces characterized by the urban texture, such as façades or surrounding walls, gained an increased interest in the last years.

Regarding green elements integrated in the building envelopes, the solutions proposed since now show several limitations and inconveniences, mostly related to the high installation and maintenance costs, the low integration with the building structures, extra loads to the bearing structures, and many more. Therefore, engineers, architects and designers must have a lot of fantasy and a visionary ability to transform the architectural limits into opportunities, proposing innovative solutions.

An example of innovative solution is the "moss wall" (Figure 1.1) designed by the Icelandic architects of Studio Granda, as part of the Reykjavík city hall. It is a wall placed in front of the building, made with porous black lava stone. Thanks to the use of small pumps, that keep the wall moist, it creates the conditions for the growth of moss directly on the stone material. It is a smart way to integrate vertical green on a wall, at a low installation and maintenance cost.

Figure 1.1: Reykjavík City Hall's "moss wall"

As part of the Nordic Built project, Studio Granda want to try to carry out the same concept. The idea was to investigate the possibilities of growing lichens on building façades materials. The idea of using lichens as vegetation for a green façade is relatively innovative. There is, almost, no literature about this argument, mainly due to the difficulties in growing these organisms. In this Master thesis, the benefits that green façades may offer to the urban environment, the limitation of the existing solutions and the parameters involved in lichens colonization are identified, through a short review of the existing literature. Furthermore, experimental programs were conducted at the Technical University of Denmark, in order to quantify these parameters, and finally to give general indications for the selection of materials in the design of bioreceptive elements that can be used on contemporary façades.

1.2 MOTIVATIONS

The presence of green is not always a positive element both in or outside the urban context. When there is nobody taking care of it, it happen that vegetation can become an emblem of deterioration and of state of abandon, and usually the approach is that it should be managed or eliminated. This theme is rather controversial, the French gardener, garden designer, botanist, entomologist and writer Gilles Clément, in his "Manifeste du tiers paysage", argues that the abandonment of such areas to vegetation and its natural evolution process represents a great opportunity for the preservation of biological diversity (Clément, 2004). Lichens, fungi, algae and mosses have been often considered as invasive species, symbols of deterioration and abandonment of structures. For this reason, there is much more literature about biodeterioration, the research area that tries to define the negative aspect of biological growth on building materials and the solutions to avoid or prevent biofouling, than literature about cultivation of these organisms and the bioprotection that they can offer to structures, in addition to the other positive effects that they may have on the urban environment or may offer to the building.

The motivations behind this research are various, the demand of an integration of green in the urban environment is increasing, and it is necessary to propose innovative solutions. Currently, most of the green façades need several components (a separate structure for soil or for the plants to grow on, an irrigation system, a drainage system, etc.) that contribute to raise both installation and operation costs. Interest in the development of innovative systems is increasing, especially in biological growth on building materials to be used as an added value. This Master thesis wants to investigate the possibilities of integrating even more the green into the façade, developing a building material the can works as substrate for lichens growth. Lichens have been chosen because of their appearance, but also because they are organisms that do not need special soil, and take the nutrients directly from air and rain.

1.3 OBJECTIVES

The general objective of this master thesis is to investigate the possibilities of using structural façade materials as substrates for colonization by lichens. The specific objectives treated in this paper are listed in Table 1.1.

Specific Objectives	
1	Define the chemical and physical properties of materials that have an influence on their bioreceptivity for lichens
2	Compare the suitability of several materials as substrates for lichen colonization
3	Compare the degree of bioreceptivity of cementitious materials and natural stones
4	Evaluate the effects of micro-climate induced by architectural parameters on the lichens' growth and adhesion to the substrate
5	Investigate the effectiveness of applying a culture media, used successfully on in vitro applications, to favourite the adhesion of the lichens to the substrates under environmental conditions
6	Investigate the correlation between substrate's pore size and bioreceptivity for lichens

Table 1.1: Specific objectives

1.4 METHODOLOGY

This thesis combines theoretical and experimental components. The experiments were conducted at the Technical University of Denmark.

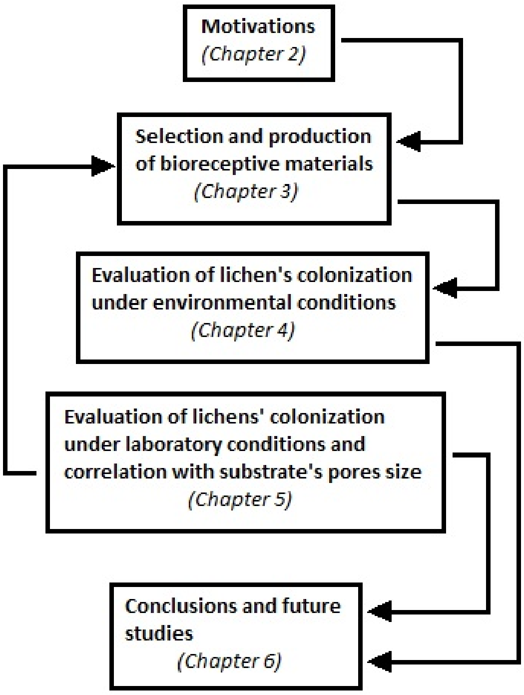


Figure 1.2: Outline of the thesis

The thesis is divided in 6 chapters. Chapter 1, the current one, is a brief introduction of the thesis. The objectives and the reasons behind the research are here presented.

In the second chapter, the state of the art is discussed. First some data about the problems due to urbanization are presented with the potential solutions that urban green may offer, then the current strategies to integrating green in cities are briefly presented, focusing on vertical green. Finally, the motivation of this thesis are described, analyzing the advantages and disadvantages of using structural materials directly as substrates for biological growth. There is also a brief section regarding lichens, briefly describing the characteristics of these organisms and presenting studies about their interaction with the substrates and the environment.

In chapter 3, there is a first approach to the experimental program. The properties of the materials used for the bio-receptivity comparison, are here presented. Also the methods and dosages to cast the specimens based on Magnesium phosphate concrete are discussed. Finally, there is an analysis of the results obtained from the porosity, the roughness and the pH tests.

In chapter 4, the suitability of several materials for lichens colonization is analyzed. First, the methods used for the experiment are presented. In this part of the project, several parameters influencing lichen colonization are evaluated through an experiment, where specimens are exposed to environmental condition, with different orientation and with or without a shelter, to protect the lichens from heavy rain and wind.

In chapter 5, the second experimental part of the project is described, where the direct relation between substrate's pore size and lichens' growth and adhesion to the substrate is evaluated. pH neutral clay test plates, with different porosity, have been used to understand the relation between the porosity of the material and its suitability as substrate for lichen's attachment and growth.

Chapter 6 is the conclusive chapter of this thesis, where a synthesis of the results, obtained from the experiments and during the research project, are discussed. Finally, there is a brief section showing the potential future studies concerning the argument and the suggestions in order to carry out the experiment under environmental conditions, introducing the need for further analysis.

2

STATE OF THE ART

2.1 INTRODUCTION

The interest into the use of green in cities, increased substantially since the beginning of the twentieth century. It can be observed that the amount of publications, studies and research, focus on the integration of green in the buildings' envelopes, increased considerably in recent years (Köhler, 2008). Beside the added aesthetical value that urban greenery may give, there are other effects that have been widely studied in the past years, and they affect three different levels: the ecological, the economic and the social level (Heidt and Neef, 2008).

Regarding the ecological level, the main benefits offered by the presence of vegetation in urban areas are the reduction of CO2 and the production of oxygen, due to the photosynthetic process (Jo, 2002), the general positive effects on air and water quality, the regulation of the micro-climate, mitigating the urban heat island effect, and the reduction of noise (Bolund and Hunhammar, 1999) and the preservation of the biodiversity, which guarantees the survival of life on Earth (Attwell, 2000).

The economic benefits, are related to the ecological and the social ones. The benefits of urban green on air quality, water and more generally on life, allow to save many of the costs related to the strategies and initiatives used for solving the problems generated by urbanization. For example, the purifying effect of plants on the air, leads to the reduction of the costs necessary for applying the other strategies used to reduce or prevent pollution.

Finally, the social benefits offered by green areas in cities range from the interaction opportunities to the positive effects on human health. It is evident the biophilic design can have a positive impact on health, by reducing stress, improving emotional well-being, alleviating pain, and fostering improvements in other outcomes (Ulrich, 2008).

The concept of greening cities involves not only the creation of green areas, but also the greening of the building envelope. Vertical green can have an important role in the environmental condition balance of cities. Green has the capacity of taking advantage of the vertical dimension of space. It is possible to imagine what results could have the same approach transferred to the dimensions of the urban texture, where the available ground surfaces for green are running out. Green façades may also aesthetically enhance cities, replacing, with a pleasant view, all the lateral blind walls of many buildings, due to demolitions or disinterest in design and urban planning. In many European cities, in the best cases, this spaces are occupied by advertising billboards or graffiti (Bortolotti, 2011).

Green façades, covered with climbing plants, or green walls, with the growing media supported on the face of the wall, can contribute to deal with the environmental emergency and can contrast the aesthetic depletion in cities. It is possible to take advantage of their ability to filter the particular matter present in the air, to reduce summer temperatures, to increment the biodiversity, sometimes becoming an habitat for birds and insects, to strengthen the acoustic insulation, and also to contribute to important savings for the buildings users. Green façades and green walls can be a solution in building renovation cases, where they can increase the insulation properties of a façade. The same façade can be protected from atmospheric agents and, if separated from the structure with an air gap, can considerably limit the temperature leaps due to solar radiation.

Architecture produced several interrupted scenarios, like the blind walls on the sides or back of entire buildings. Vertical green, can, in many cases, represent an important element for an aesthetic renovation. The architect Frank LLoyd Wright said: "A doctor can bury his mistakes but an architect can only advise his clients to plant vines."

Currently the use of vegetation only as a factor of aesthetic concealing of architectural mistakes, is leaving space to a more thoughtful and organic use of vertical green in new projects. Green, in many different shapes (green roofs, suspended green, green walls and green façades) is now a qualifying element in all the projects that look for an innovative, more ecological, building envelope.

Many studies have been made on the thermal insulating properties of envelopes, doors, windows and in general on strategies for insulating buildings. But it is only few years that studies on thermal properties and effects on heat losses of the vegetation on the building envelope, have started.

The most common criticism for vertical green are related to dirt, moisture and the presence of animals, but they are often unjustified fears.

There is a difference between the two main strategies currently used for vertical green, the green façade is usually covered with climbing plants, where the soil is only at the base of the wall, and the green wall, which is usually more complicate, have the growing media supported on the façade of the wall.

It seems that there is the necessity of innovative systems, with a higher level of integration of the green into the building envolope.

The new approach, proposed by Manso (2014), to grow living organisms on the building envelope, using directly the façade materials has growth media, is investigated in this thesis, with a particular focus on lichens as colonizing organisms.

The choice of using lichens is manly related to their aesthetic appearance, but also related to the fact that lichens are organisms that can grow almost anywhere, in a very wide range of environmental conditions, and on almost any surface. In general, lichens may absorb certain mineral nutrients from the substrates on which they grow, but they are usually self-reliant in feeding themselves through the photosynthetic process that take place in the algal cells and taking the other necessary nutrients from air and rain water.

In this chapter, there is a short review of the current environmental situation in European main cities, in order to motivate the necessity of integrating nature into urban areas and more specifically the direct application of green on structure envelopes. The benefits that common green vertical systems can offer, contrasting the environmental issues derived by urbanization. Furthermore, the main disadvantages of common green walls and façades are identified, thus identifying also the main reasons and motivations behind this project. Finally, a short review of the literature concerning the positive and negative effects of the interaction between lichens and structures' envelopes are discussed.

2.2 ENVIRONMENTAL SITUATION IN EUROPEAN CITIES

In the recent years, many different tools and indicators have been developed to evaluate the multidimensional aspects of the urban environmental quality. However, it seems that a generally accepted framework, or a coherent system to evaluate these aspects in relation to well-being, has not been developed yet, mainly because of the various fields involved. The definition of a multidisciplinary conceptual framework would be useful to implement indicators and tools developed to evaluate all the aspects that influence the urban environmental quality (Van Kamp et al., 2003).

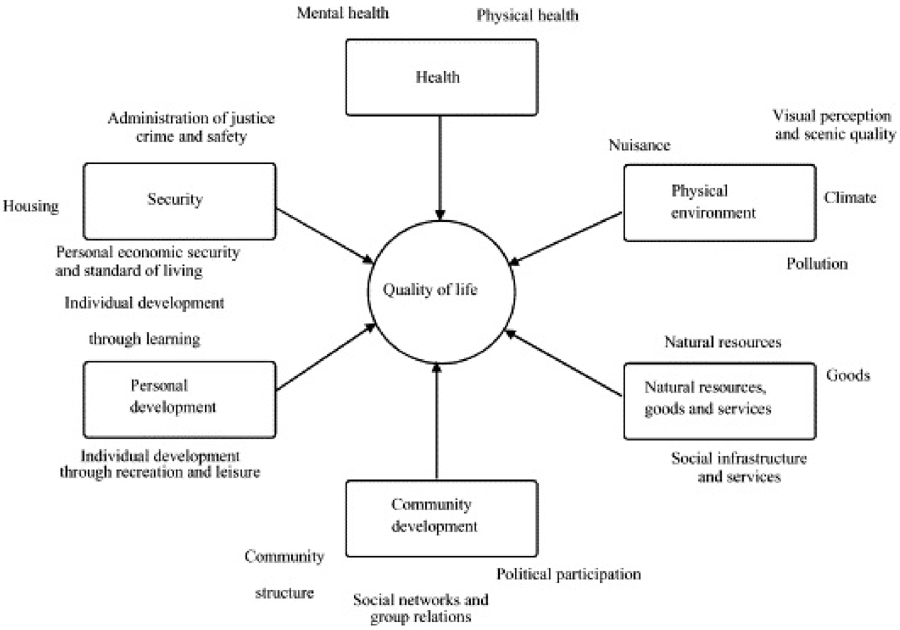


Figure 2.1: Quality-of-life components (Mitchell, 2000)

Figure 2.1, shows a scheme of the components that Mitchell (2000) used to define the quality of life in urban environments. It can be notice that many of these parameters are interconnected and urban green may have a direct or indirect influence on almost all of them.

At an European level, many different instruments are used and several tools have been developed to evaluate the environmental situation in the different countries. The European Commission (EC) set the targets to improve the urban environmental situation, to fight climate changes and to reduce energy consumptions, defining strategies and directives that are then applied at a national level in the European countries. Regarding the urban level, the application of these directives are entrusted to local municipalities that translate them, with local strategies. However, since there are not uniform indicators and tools yet, it is not always easy to assess and compare the environmental performances of cities.

It is assumed that almost the 80% of the European population will be living in urban areas by 2020 (EEA, 010c). In order to ensure the well-being of the inhabitants, and therefore all the related parameters that define the quality of life, the European Commission has started to focus more on the urban issues. An action program entitled *"Sustainable Cities: "Working together for Common Solutions"* has been included in the more general 7th Environmental Action Programme (EC, 2014) under Priority Objective 8. The aim of the action program is to help cities become more sustainable, defining the set of problems that interest most of the cities such as poor air quality, high levels of noise, greenhouse gasses emissions and urban heat island effect, promoting and expanding initiatives to support innovation and sharing of information in cities. In general, the objective is to ensure that European cities will implement the policies to improve the quality of life, trhough a sustainable urban planning and design.

Other instruments and initiatives that the European Commission proposed to improve the urban environment are (EUp):

- the EU's general environmental legislation
- the European Green Capital and the European Green Leaf initiatives
- the objective of developing a tool to allow cities to benchmark their environmental performance, comparing their progresses with other similar cities, sharing methods and ideas and tracking their improvement.

The European Environmental Agency (EEA), collected and analysed, in several reports, the data retrieved from the monitoring stations across all Europe, assessing air quality, noise pollution, climate conditions and changes and CO_2.

Another instrument used to assess and compare the environmental performances of European cities is the Urban Ecosystem Europe Report (Berrini and Bono, 2007), which takes into consideration different aspects, including air quality, green areas, mobility, waste management and socio-economic structural patterns. The data have been collected between 2006 and 2007, thanks to the active participation of 32 of the main biggest cities in Europe. The data presented in the next sessions to define the environmental situation in European cities, were mainly extrapolated from these reports, in addition to the data retrieved from the applications for the European Green Capital initiative, especially for Copenhagen and Reykjavik.

2.2.1 *Climate, energy saving and* CO_2

The Europe 2020 strategy sets three objectives for climate and energy policy, to be reached by 2020 (EC, 2014)):

- Reducing GHG emissions by at least 20% compared with 1990 levels;
- Increasing the share of renewable energy in final energy consumption to 20%;
- Moving towards a 20% increase in energy efficiency.

These targets are also known as the '20-20-20' targets. Additionally, the strategy points out that the EU is committed to taking a decision to move to a 30% these reduction by 2020 compared to 1990 levels. The Europe 2020 strategy's three climate and energy targets are interrelated and mutually support one another. Figure 2.2 shows the relations between these targets.

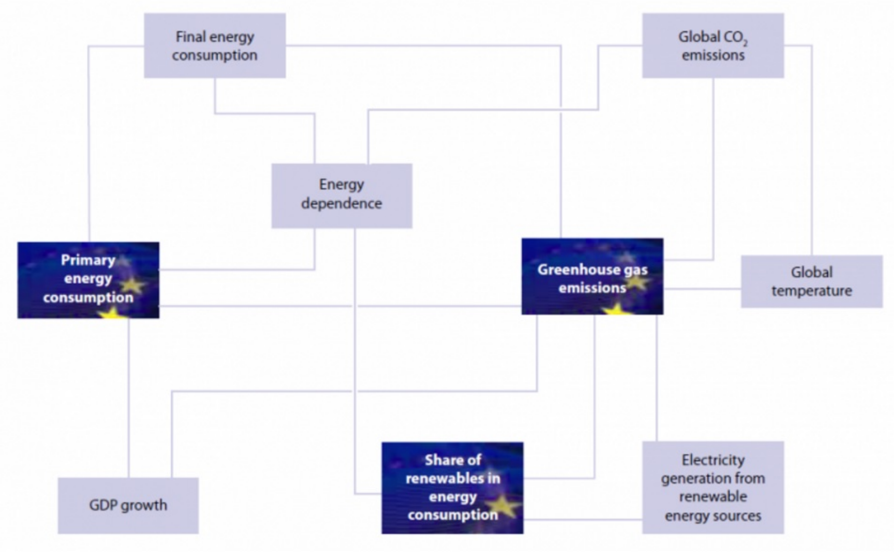


Figure 2.2: Indicators used in European 2020 strategy and their correlation with the headline indicators on the climate change and energy targets (EC, 2014)

According to the Ecosystem Europe report (Berrini and Bono, 2007), administrations use different strategies and highly innovative local regulation in order to respect the Kyoto Protocol, thus proving their concern for CO_2 emissions.

Danish government has an ambitious energy and climate policy. The broad energy agreement, adopted in spring 2012, was a significant step forward to meeting both the energy policy goals and the target to reduce greenhouse gas emissions of 40% by 2020. Furthermore, the Danish government's goal is that already by 2035 Danish electricity and heating supply will be completely based on renewable energy. The goal for 2050 is that all energy consumption, including the transport sector, will be based only on renewable energy sources.

2.2.2 *Air quality*

Humans can be adversely affected by exposure to air pollutants in ambient air. European and national anti-pollution laws and policies have been developed in the last 40 years, to control and reduce the amount of pollutants in the air. Currently the European Union developed an extensive body of legislation which establishes the requirements for the maximum concentration of a number of pollutants in air. These requirements are stated in the Air Quality Directives (EU, 2008). Furthermore, in 2013, the EU proposed a Clean Air Policy Package to further reduce emissions of air pollutants until 2030. The air quality in

Europe - 2015 report by the EEA (2015), reviews the progress towards meeting the requirements of these air quality directives. The limits are summarized in Table 2.1 below.

Pollutant	**Concentration**	**Averaging Period**	**Permitted exceedances each year**
Fine particles ($PM_{2.5}$)	25 μg/m^{3***}	1 year	n/a
Sulphur dioxide (SO_2)	350 μg/m^3 125 μg/m^3	1 hour 24 hours	24 3
Nitrogen dioxide (NO_2)	200 μg/m^3 40 μg/m^3	1 hour 1 year	18 n/a
PM_{10}	50 μg/m^3 40 μg/m^3	24 hours 1 year	35 n/a
Carbon monoxide (CO)	10 μg/m^3	Maximum daily 8 hour mean	n/a
Benzene	5 μg/m^3	1 year	n/a
Ozone	120 μg/m^3	Maximum daily 8 hour mean	25 days averaged over 3 years

Table 2.1: List of Air quality standards and limits, European Commission (2015)

According to the EEA 2015 Report, the EU limit and target values for particulate matter (PM) were exceeded in most parts of Europe in 2013. The EU daily limit value for PM with a diameter of 10 μm or less (PM_{10}) was exceeded in 22 of the 28 EU Member States, and the target value for PM with a diameter of 2.5 μm or less ($PM_{2.5}$) was exceeded in 7 Member States. A total of 17% of the EU-28 urban population was exposed to PM_{10} levels above the daily limit value. The ozone (O_3) requirement for the protection of human health was exceeded in 18 of the 28 EU Member States in 2013. Some 15% of the EU-28 urban population lives in areas where the EU O_3 target value threshold for protecting human health was exceeded in 2013. The annual limit value for nitrogen dioxide (NO_2) was widely exceeded across Europe in 2013, with 93% of all exceedances occurring close to roads. A total of 19 of the 28 EU Member States recorded exceedances of this limit value at one or more monitoring stations. Of the EU-28 urban population, 9% lives in areas in which the annual EU limit value for NO_2 were exceeded in 2013. The EU-28 urban population was exposed to only a few exceedances of the sulphur dioxide (SO_2) EU daily limit value in 2013. Exposure of the European population to carbon monoxide (CO) concentrations above the EU limit value is very limited, localised and sporadic.

Figure 2.3 shows the percentage of urban population resident in areas where pollutant concentrations were higher than the legal limits.

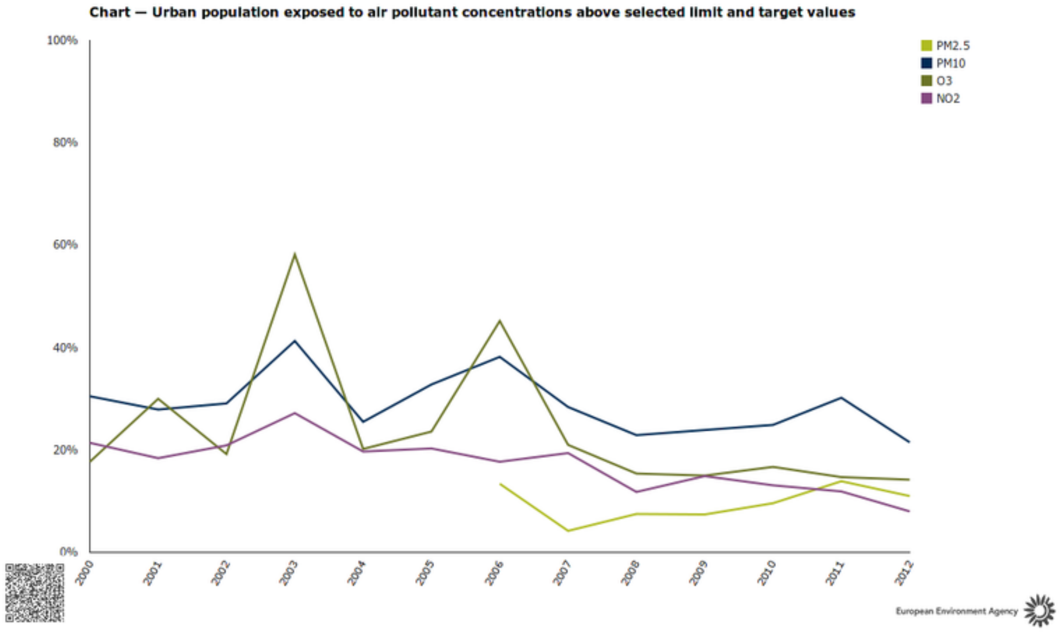


Figure 2.3: Percentage of urban population resident in areas where pollutant concentrations are higher than selected limit/target values, 2000-2012 (EU-28) (Eurostat, 2012)

The data gathered in the Urban Ecosystem Report (Berrini and Bono, 2007) regarding European main cities, show that at least 45% of the cities analysed in the report were exceeding the European limit value for urban areas of 40 μg/m^3 of particulate matter (PM$_{10}$). In big cities, the most critical situation was observed, with 65% of the cities analyzed, exceeding the limit in districts with heavy traffic. The maximum number of days per year, were the limit of 50 μg/m^3 could be exceeded, was 35 days. This period was exceeded in 84% of the cities under study. 90% of the cities, also did not fulfil the requirement of 40 μg/m^3 of NO$_2$ and 60% overstep the 2005 limit of 50 μg/m^3.

2.2.3 *Public green areas availability*

In the Urban Ecosystem Europe report (Berrini and Bono, 2007), a requirement to be considered a sustainable city is that citizens have more than 200m^2 of green areas, of which 40m^2/inhab of urban green spaces. Green urban areas are not always classified in the same way by individual cities. From the data obtained the green areas have been subdivided in two categories:

- Urban green areas: including public parks and protected areas located within the urban center;

- Other green areas: including peripheral parks and woods and agricultural spaces, often located at the limits of an urban area;

The results collected from 20 of the 32 studied cities are presented in Figure 2.4 below.

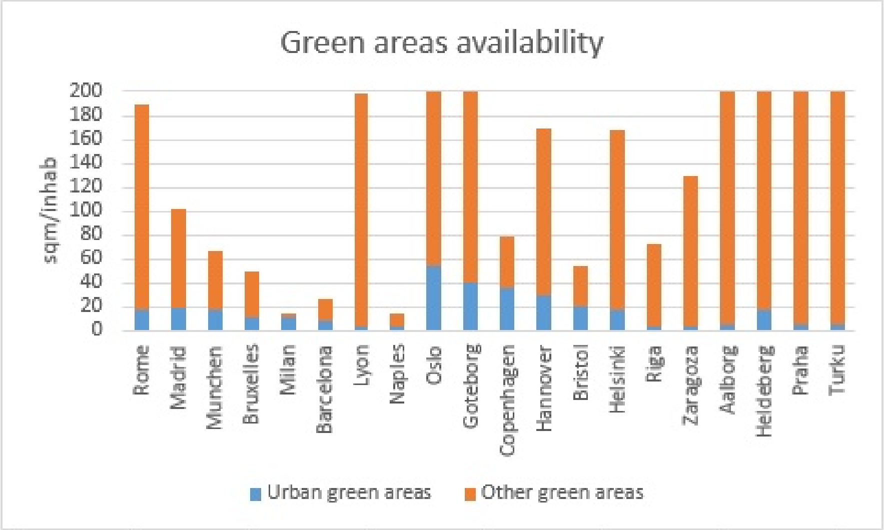


Figure 2.4: Public green areas availability by City

In the city of Reykjavík, in 2009, the 91.7% of the inhabitants lived within 300m, or around 5 minutes walking distance, from recreational areas or other areas of recreational status, such as squares, churchyards or other public open spaces larger than 2000 m^2. The total urban green area for inhabitant amount to 120 m^2, while if peripheral and agricultural green spaces are taken into account, the total is 270 m^2/inhab (European Green Capital application, City of Reykjavík (2012)).

Figure 2.5: Public green areas availability and distances in Reykjavík

According to the Green Account pubblished by the City of Copenhagen (2011), the city's green areas represent about 25% of the city's overall area and there is an average of 42.4 m^2 of green area per inhabitant. Regarding the distances to public green areas, minimum 80% of the citizens lived within a distance of 300 metres to a green area.

2.2.4 *Noise reduction*

The effect of noise on human health vary depending on which individual is considered. Health issues related to noise may include sleep disturbances, negative repercussions on hearing and on other physiological functions. Studies made by the World Health Organization stated that average levels of more than 40 dB(A) may have influence on the quality of life, while levels higher than 60 dB(A) can result in physical and physiological problems on the citizens. Further studies shown that the equivalent level of sound pressure should not exceed the value of 65 dB(A), otherwise there is an high probability of serious health consequences. The European Commission, in 2002, issued a Directive (EU, 2002) on the assessment and management of environmental noise. The aim was to define a general approach to avoid, prevent or reduce the health consequences of exposure to environmental noise. The suggestion was to provide a noise map, so as to characterize the critical areas, and to give an instrument useful to informing citizens and develop noise management strategies. In 2006, half of the cities studied in the Urban Ecosystem report (Berrini and Bono, 2007), have approved a noise map, and 10 more cities were going to approve it in the next two years. Regarding the noise reduction plan, only 8 cities on 32, have approved one in 2006, while other 7 administrations were going to approve it before 2008.

In Reykjavík, the municipality started to comply with noise related issues in 1980. When compared with other European cities, the scale of noise problems in Reykjavík is considerably smaller, mainly due to its population size and also because there are no rail transportation systems. Therefore, the main sources of noise in Reykjavík can be identified in car traffic and activities related to the harbour activity, but that are confined in that areas, and have little impact on residents. There are regulation, approved by the administration, to minimize the noise arising from buisness and industries, in addition to the city authority's monitor compliance.

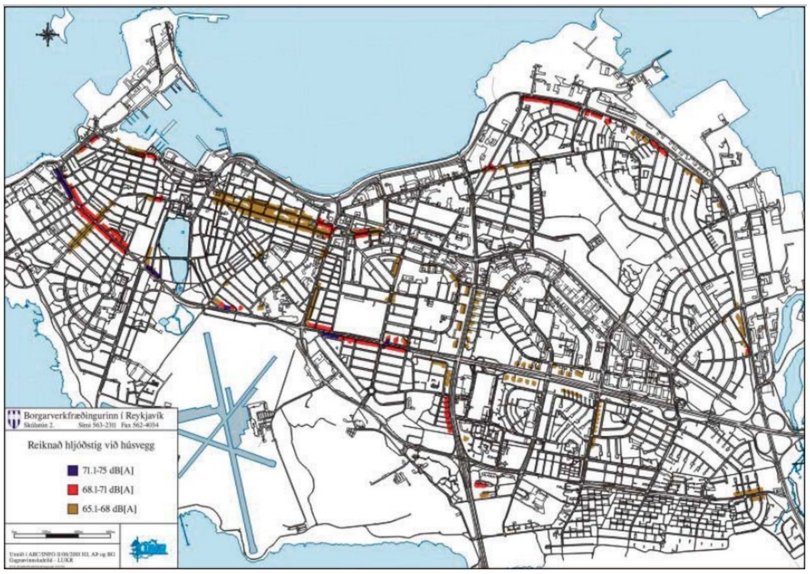


Figure 2.6: Noise map, Reykjavík

A noise map (Figure 2.6) was carried out in 1996 to identify residential buildings adjacent to noise sources over 65dB(A). The L_{eq} was calculated using the Nordic model, Nordic1996, for calculating traffic noise, using SoundPlan software. The results shown that 5,2% experienced noise levels of 65dB(A) outside buildings, which exceeds acceptable levels (of Reykjavík, 2012).

The Danish Government followed the EU Environmental Noise Directive (EU, 2002)) starting in 2002, providing the noise assessment map, while noise action plans were implemented in 2005. From Figure 2.7, which shows the noise map carried out in 2011, it is possible to see that the high noise impacts are in the city center, around the dense urban areas and along the primary road network. 71% of the citizens were exposed to noise levels higher than 55 db(A), and 76% were exposed to level over 45 db(A). The noise action plan focuses on several strategies to reduce exposure to harmful noise levels, including the use of noise-reducing asphalt, renovation of schools and daycare facilities, initiatives for renovation of existing houses, noise consideration in new residential buildings, traffic planning and influencing the transport structure.

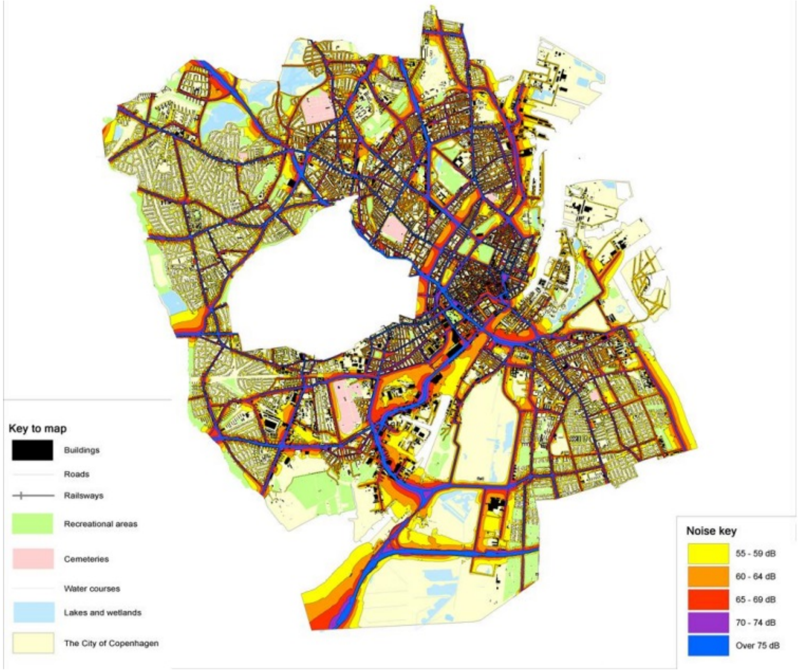


Figure 2.7: Noise map, Copenhagen

2.3 ENVIRONMENTAL IMPACT OF VERTICAL GREEN

The perception of the degradation of the modern built environment and the effects on health and productivity prompted the development of the modern sustainable or green design movement, which already started to have direct consequences on design and construction practices. The prevailing approach to sustainable design has almost exclusively fixated on the low-environmental-impact objectives of avoiding and minimizing harm to the natural systems (Mendler et al., 2006). This way of approaching it, ignores the consequentiality of achieving long-term sustainability of renovating and enhancing the positive interactions between citizens and nature in the built environment, which Kellert defines as *"biophilic design"* (Kellert, 2008).

One of the aspects of biophilic architecture, is the concept of merging the artificial structures with natural structures. This could be achieved bringing nature into a building, utilizing natural materials and surfaces and incorporating plants (or organisms) into the structure (Salingaros and Masden II, 2008). It withal designates the setting of a building within a natural environment in lieu of simply eliminating nature to let space for the building (Kellert, 2005). On an urban scale, cities could be designed and planned to provide an extensive contact between humans and nature. Many green conceptions and techniques can be employed in creating or rebuilding biophilic cities. In Table 2.2, the design elements, listed by Girling and Kellett (2005), that can be utilized for sustainable "green urbanism", across different scales, are presented.

Scale	**Biophilic design elements**
Building	Green rooftops Sky gardens and green atria Rooftop garden Green walls and façades Daylit interior spaces
Block	Green courtyards Clustered housing and around green areas Native species yards and spaces
Street	Green streets Urban trees Low impact development (LID) vegetated swales and skinny streets Edible landscaping High degree of permeability
Neighborhood	Stream daylight and stream restoration Urban forests Ecology parks Community gardens Neighborhood parks/poket parks Greening greyfields and brownfields
[...]	[...]

Table 2.2: Biophilic urban design elements across scales, modified from Girling and Kellett (2005)

From the table it can be observed that green strategies involve different scales of the urban environment. Biophilic individual buildings can not, by themselves, lead the realization of biophilic cities, however these are important steps in this sense, especially when they are situated and configured in a way that permits extensive and deep outside experiencing of nature (Beatley et al., 2008).

Green façades and green walls may contribute in creating biophilic cities, enhancing the quality of life. Several studies have been made to assess the effects of vertical green on the urban environment. These effects may result as a possible solution for the issues presented in the previous section, and can contribute to realize an healthier and sustainable urban environment. The improvement of air quality, is achieved by the capability of plants to interact with air pollutants, through photosynthesis (Smith and Staskawicz, 1977; Fowler et al., 1989; Sternberg et al., 2010), and also thanks to the major absorption surface that is in contact with the atmosphere. During daytime, the plant's leaves provide a surface area able to absorb and filter most of the polluting particles, including PM_x, NO_x, SO_2 and CO_2 (Fowler et al.; Ottelé, 2011). Green façades and green walls can avoid the movement of particulate matter along building envelope and filter them (Minke, 1982). A study carried out in 2009, at the University of Dresden, showed that a green façade, covered with 1000 m^2 of *Hedera helix*, in one year, absorbed 2351 kg of CO_2 and 1019 kg of water, producing 5854 kg of organic mass (of which 4409 kg of water content and 1415 kg of dry mass) and 1712 kg of O_2. According to Ottelé (2011), if this results are compared with the results from an investigation on mature beech tree (Minke, 1982), it can be seen that *Hedera helix* is more efficient in absorbing CO_2 and producing O_2 for the same leaf area.

Regarding energy, in well developed green façades, leaves can absorb up to 50% of the solar radiation directed to the wall, and reflect up to 30%, therefore, reducing up to 80% the radiation that would be received by a bare wall (Rath and Kießl, 1989). This "shielding" effect may protect the building materials and lead to a reduction of maintenance cost, due to UV deterioration.

Another benefit of vertical green, is that it can serve as extra insulation of façades, thanks to a stagnant air layer, present between the façade and the vertical green layer (Minke, 1982). Therefore, lowering the energy demand for heating in winter and for cooling in summer. Vertical vegetation reduce the wind speed along the building sides, preventing the wall to cool down, so increasing the energy saving in winter time. According to a study on the energy saving effect of vertical green system for heating and cooling,with the installation of a green façade it is possible to save 1.2% of energy used for heating ,this value can go up to 6.3% if a green wall (with growing media integrated on the wall) is used, and 43% for cooling (Ottelé, 2011).

Regarding the ecological and social aspect, vertical green can become a suitable habitat for animals, such as birds, bats and insects, thus promoting biodiversity. Furthermore, it can increase the percentage of green covered surfaces in cities, without undermining the available ground space, which is often scarce in densely populated urban areas. The social benefits of integrating nature in building envelopes, is related to the concept of Biophilia. Wilson defines *Biophilia* as *"the urge to affiliate with other forms of life"*. He supports the idea that the contact with green and other living organisms has a psycological influence on humans, making them feeling better (Wilson, 1984).

Plants can also absorb, reflect and diffract noise arising from car traffic or other sources. The ability of reducing the noise pressure level are dependent on the plant type, the planting density, the location and the sound frequency (Rutgers, 2011). In a study made at the National University of Singapore, it was assessed that vertical greening systems can attenuate noise pressure level at low to middle frequencies, especially in the case of green walls, where the substrate acts as an extra absorption layer, while a lower attenuation was observed at high frequencies. Increasing the percentage of green coverage, an increase of the sound absorption coefficient was observed. Vertical green system also have positive effects on the reverberation time, especially at low-middle frequencies. It seems that the substrate absorbs well the noise at low frequencies, while plants have better acoustic performances at high frequencies (Wong et al., 2010).

2.4 VERTICAL GREEN SOLUTIONS

When it comes to vertical green, is important to define which system is used. The project approach, the stability and the duration of the construction, the aesthetic value, the logistical problems and the cost of implementation and maintenance that different systems determinate, lead to very different results. Vertical green technologies are commonly distinguished in green façades and green wall, depending on the rooting location (Figure 2.8).

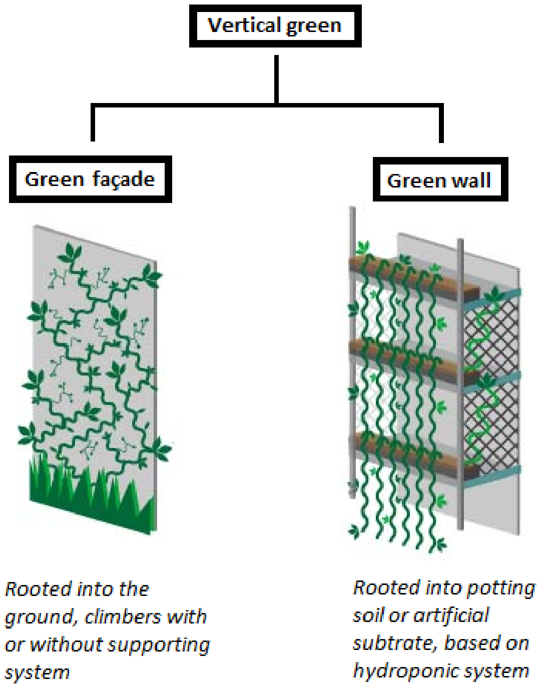


Figure 2.8: Basic classification of vertical greening systems

Green façades exploit the ability of climbing plants of covering hundreds of square meters of vertical surfaces, using few square meters of soil. These systems can be achieved at relatively low cost and since the plant is usually rooted at the ground level, the irrigation, fertilization and substitution operations are easier. Maintenance concerns especially the adhesion of the plants to the wall or supporting structures, during the early stages of growth. Climbers can be divided in plants able to colonize the façades and sustain themselves by their own means (aerial roots and suckers) and in plants that require support structures to develop the vegetation upwards. This last group can be further divided between plant that can grow and adhere autonomously to the support structure, like the vine, and those that have to be linked by man. Within this last category, there are some shrubs or trees that can adapt themselves to grow against a wall as if they are climbing plants. Classic examples are the many fruit trees espalier in central Italy. This can be achieved only if the plants are grown in such a way since they are young, when they still have soft and flexible stems.

Green walls, are made of more complex systems instead, often landless and leveraging the support of vegetative mats, creating façades where dense vegetation is formed by many different small plants juxtaposed to each other. The first maker of these walls was the French botanist Patrick Blanc, who practiced this type of vertical green, based on the hydroponic cultivation. Because of their originality and their spectacular nature are now almost fashionable, but they also have some limits: the most obvious limit is represented by the high construction and maintenance costs, in addition to the relative fragility of these systems, which are based on the principle of "fertigation" (irrigation with dosing of nutrients), therefore subject to the technical installations that compose them, making these vertical gardens realizations more suitable for niche situations and confined surfaces (Bortolotti, 2011)

Currently, on the market there are very sophisticated systems that, instead of the hydroponic cultivation principle, uses different grow media, such as foams, mineral wool or laminar layers of felt sheets. In general, the cost of installation of green walls range from 30 €/m^2, for simple systems, up to 1200 €/m^2 (Ottelé, 2011). This takes into account only the installation costs and not the maintenance costs that can match the ones corresponding to conventional gardens. Possible other issues refer to dampness problems, especially for old structures (Lourenço et al., 2006) or the acceleration of the deterioration process (Johnston and Newton, 2004). However, it seems that damage caused by roots intrusion is not frequent, and usually due to installation errors (Manso, 2014).

When designing a green vertical system, the choice is reduced between a green facade, using climbing plants, and a green wall, using more complicated and expensive systems. It seems that there is still a lack of more integrated solutions, for example, using plants or organisms that can attach and grow directly on building materials. This solution could be classified as something in between the two main categories described in the previous paragraph, where the organisms are "rooted" directly on the superficial layer of the facade material, without any supporting structure or dedicated irrigation and fertilization system. In recent years, a few studies have been made in order to assess the possibilities of designing this kind of vertical green system. The "green concrete" system proposed by Ottelé (2011), is based on an innovative approach that consists in using the surfaces of concrete elements as medium for vegetation. It is composed by two concrete layers, a first layer of self compacting concrete with a structural function and a front layer made with porous concrete casted with coarse lava stone aggregates and filled with a special soil mixture. The results obtained shown that it was possible to grow plants on the "green concrete" elements, but also that the pH of the soil raised from 7.2 to 9.2 within the first three months of the application, because of the contact with concrete, which is a very alkaline material, leading some of the tested plant to death. Furthermore, the necessity of including soil and other issues related to the lack of water, shown that further studies are required in order to develop a more integrated and functional system. In this sense, a research made by Manso (2014), demonstrated the possibility of using stone man-made materials as biological substrate by means of modification of their bioreceptivity. Bioreceptivity is defined as *"the aptitude of a material (or any other inanimate object) to be colonized by one or several groups of living organisms, without necessarily undergoing any biodeterioration"* (Guillitte, 1995).

In her studies, Manso (2014), defined what are the chemical and physical properties that may have an influence on the bioreceptivity of a material. Then, several specimens, made of cementitious materials, were casted, following an objective-oriented design so as to obtain specimens with controlled pH, roughness and porosity. The desired pH range (5 to 9) of the specimens was obtained by using Magnesium Phosphate Cements, while the reduction of the pH in Ordinary Portland cement specimens was achieved by accelerated carbonation. Carbonation is a slow chemical process that interests concrete structures. It is a chemical reaction between the carbon dioxide present in the air and the calcium hydroxide and the hydrated calcium silicate present in the concrete, resulting in a decrease of the concrete pH. Carbonation process starts on the external surface of concrete structures, in contact with air. Fully carbonated cement paste can reach a pH value of 7.

The specimens were compared and their bioreceptivity was assessed, under laboratory conditions, through an accelerated algae fouling test. Results shown that MPC specimens presented a higher bioreceptivity for pioneer colonisers such as *Chlorella vulgaris* than the OPC specimens. However, specimens exposed to environmental conditions did not show any visible colonization (Manso, 2014).

Another example of growing vegetation directly on building materials is the aforementioned "Moss wall" in front of Reykjavík city hall, designed by Studio Granda.

2.5 LICHENS-SUBSTRATES INTERACTIONS

Lichens are particular organisms, they are a symbiosis between different organisms: a fungi and an algae or a cyanobacteria. The properties of a lichen, differ from the properties of the single organisms that compose it. Algae and cyanobacteria, contain chlorophyll and are called photobionts, while the fungal partner is called mycobiont. The two symbionts live together, drawing mutual benefit: the fungus takes advantage of the organic compounds produced by the photosynthetic process in the cyanobacterium or alga, while the latter receives protection, minerals and water.

Lichens have been found growing almost everywhere on the planet, in a very expanded range of environmental conditions, from the polar climate to the tropics, in humid climates as the rain forest to very dry environments, such as desert. It has been estimated that 6% of the total Earth's land surface, is covered by lichens (Gadd, 2010).

The surfaces (or substrates) on which lichens grow vary from natural substrates (such as soil, rock, wood) to artificial materials (concrete, asphalt, glass, metal, ceramic, etc).

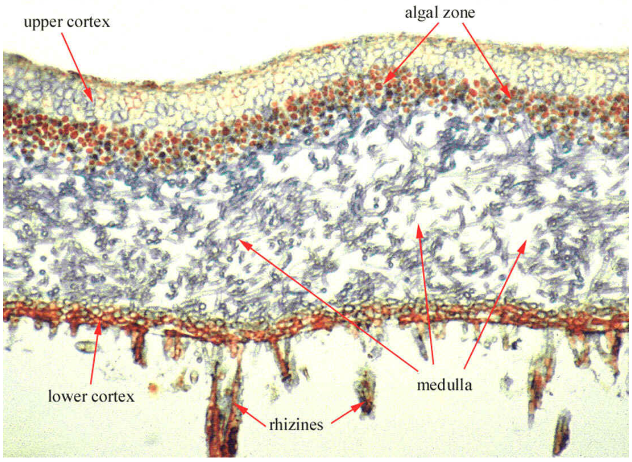


Figure 2.9: Cross section of a lichen, (Hale, 2007)

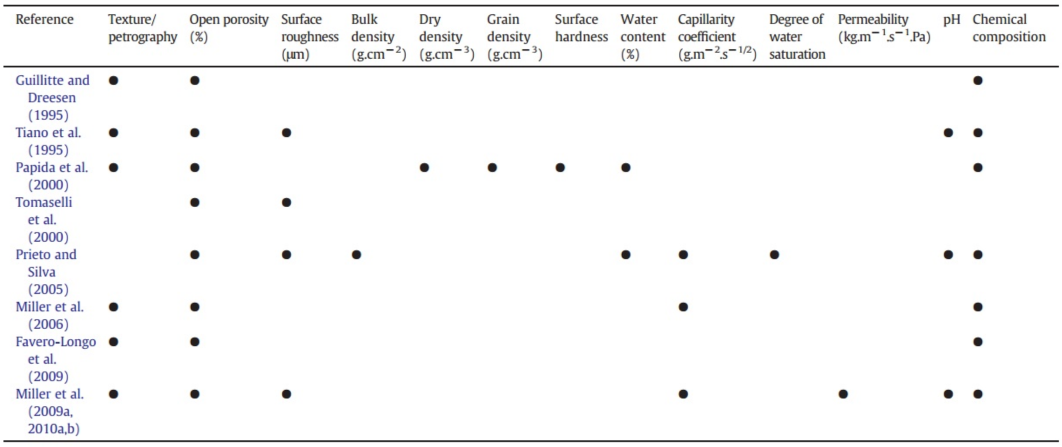
The cross section of a foliose lichen is shown in Figure 2.9 above. The thallus is the bulk of the lichen, and it is composed by an upper surface of compacted hyphae called upper cortex, a layer of photobiont cells, an area of loosely arranged hyphae, where nutrients produced by the photobiont are stored by the fungus, called medulla and a lower surface, composed again of compacted hyphae from where root-like bundles of hyphae, called rhizines, come out, and they have the function of anchoring the thallus to the substrate. Other species of lichen, lack of the lower cortex, and also the rhizines are not always present.

While the environmental conditions have a great impact, also the substrate properties have an important influence on the presence of lichens. Stone materials, both natural or artificial, are often colonized by lichens. The presence of the lichens and their effect on the substrate have been studied by several authors both for natural stones (Hoppert et al., 2004; Vingiani et al., 2013) and for building materials (Barberousse et al., 2006; de los Ríos et al., 2009). Most of the studies concerning this topic, are related to the deterioration and the degradation effects of these organisms on building materials.

Studies demonstrated that lichens growing on rocks determine physico-chemical deterioration processes on the substrate. It can be seen as a problem, when colonization occurs on historical or cultural landmarks. In the last 20 years, the lichen-rock interaction have been studied, developing new protocol for the analysis and showing its complexity and variability depending on lithotypes. Several methods to remove the organisms from the substrates and to prevent biofouling have been studied, but it is important to evaluate each case singularly, so as to have a balance between the conservation of building materials and the preservation of lichens as part of natural and urban ecosystems (Piervittori et al., 1994).

A research made on the bioweathering and biocovering effects of lichen on hazardous building materials such as asbestos, shown that, differing from the current public opinion and the assumptions of some official regulations on the treatment of hazardous materials, fibre loss is significantly lower (30%) where lichens developed and that they may offer a physical barrier to the fibre detachment (Favero-Longo et al., 2009). Even though many studies have been made on the biodeterioration effects, the most important damages caused by biocolonization is mainly aesthetical (Dukes, 1972; Tiano, 1987).

The properties of a material that most influence its bioreceptivity that have been studied by several authors, are presented in Figure 2.10.



Reference	Texture/ petrography	Open porosity (%)	Surface roughness (μm)	Bulk density ($g.cm^{-2}$)	Dry density ($g.cm^{-3}$)	Grain density ($g.cm^{-3}$)	Surface hardness	Water content (%)	Capillarity coefficient ($g.m^{-2}.s^{-1/2}$)	Degree of water saturation	Permeability ($kg.m^{-1}.s^{-1}.Pa$)	pH	Chemical composition
Guillitte and Dreesen (1995)	●	●											●
Tiano et al. (1995)	●	●	●									●	●
Papida et al. (2000)	●	●			●	●	●	●					●
Tomaselli et al. (2000)		●	●										
Prieto and Silva (2005)		●	●	●				●	●	●		●	●
Miller et al. (2006)	●	●							●				●
Favero-Longo et al. (2009)	●	●											●
Miller et al. (2009a, 2010a,b)	●	●	●						●		●	●	●

Figure 2.10: Material's properties studied by several authors in laboratory-based primary bioreceptivity experiments (Miller et al., 2012a)

2.6 INTERACTION BETWEEN LICHENS AND THE ENVIRONMENT

Starting from the last decades of the 19th century, numerous attempt of lichen resynthesis (Culberson and Ahmadjian, 1980; Ahmadjian, 1993), starting from the two separated lichen components, have been made. Successful results were obtained, especially when the fungal part and the photobiont were placed under stress conditions (e.g. by reducing water and nutrient levels), showing that both photobiont and fungus derived benefit from the lichenized association, and suggesting that originally lichen partnerships was formed to overcome adversity.

Lichens are pioneer organisms indeed, able to colonize areas and substrates often inhospitable for plants or other organisms. They can tolerate periods of severe desiccation, suspending their metabolic processes (cryptobiosis). During this state, the growth stop and the upper cortex hardens and gets more opaque, protecting the photobiont. When water is again available, the cortex become more transparent, allowing the photosynthesis to begin. Lichens draw their nutrients mostly from air, this makes them quite susceptible to the presence of contaminants and pollutants in the surrounding environment. Since lichens do not have roots, most of the nutrients are absorbed over the entire thallus surface, and they are unable to avoid pollutant's accumulation. Therefore, lichens are often used by researchers as biomonitors for air quality. The effects of urbanization on lichens' growth was extensively studied. It has been observed that:

- 1. Fruticose lichens are the first to disappear, followed by foliose, then smooth-crustose, and finally leprose-crustose lichens. Leprose lichens are apparently most tolerant of cities
- 2. There are defined geographic gradients along which lichens disappear, some are steeper than others, depending on the size extent of industrialization in the cities or towns involved
- 3. The closer to a city, the poorer the condition of the lichen is and the less surface area they cover.
- 4. The so-called "nitrophilous" lichens (on neutral or alkaline and often highly nitrogenous substrate) are by far the most city tolerant.
- 5. As one approaches a city, there is a restriction of lichens radial to tree bases, parks, and bodies of water
- 6. The disappearance of lichens and the appearance of industrialization are highly correlated, the effects being greatest where fuel consumption and population size are greatest
- 7. A decrease in atmospheric humidity and an increase in atmospheric pollution can be detected towards the center of a town or industrial center. (Brodo, 1966)

The other main environmental factors that influence the presence and the growth of determined species of lichen are the climate and the thermal amplitude, the availability of water, therefore precipitations frequency, hygrometry and distance from the sea and the presence or absence of vegetation (Barberousse et al., 2006; Vingiani et al., 2013).

Consequently, the presence of lichens, and other microorganisms, in cities, should be considered a privilege and a source of pride for municipalities. Growing lichens on building facade can work only in areas were the air quality is already high indeed, and in general where the urban environment does not differ too much from the surrounding areas.

2.7 CONCLUDING REMARKS

The benefits of including vegetation in urban areas have been widely discussed. Because of these positive effects on the environment and on people, the interest in green integration in cities increased in recent time.

Due to the lack of horizontal available surfaces, in always more dense cities, the alternative of covering buildings and other vertical surfaces with green, gained more attention.

The present technologies and solutions for vertical green have often a low level of integration with the structure that supports them. Therefore, it is necessary to come up with new innovative solutions.

The use of building materials directly as growing media, has not been studied intensively yet, and artificial facades created with the specific purpose of being covered with lichens or mosses are rare. Further studies on the parameters that influence biocolonization, not only related to the material itself, but also to the surrounding environmental conditions are necessary to succeed in designing these kind of integrated vertical green system.

In the following chapters, the experiments carried out in order to evaluate the bioreceptivity of several building materials, are described. The objective was to give a first approach to compare different materials and evaluate their bioreceptivity for colonization by lichens.

The possibility of applications are various, but the experiments were conducted taking in consideration that the final use was mainly addressed for Nordic countries, especially for Denmark and Iceland, where air quality standards are high and where the lichens for the experiments were taken from.

Besides the added aesthetic value that a lichens covered façade can offer, it may also have the same benefits of other green façades, even though further studies are required to quantify these effects. In addition, since lichens are effective biomonitors for the air quality and the presence of pollutant, it may be possible to observe a shifting of the species colonizing the façade, giving a sort of dynamism to the building and offering the possibility to assess the air quality improvements.

Such a façade may be used as feedback for the citizens, offering a "sustainable" way to prove the efforts that the municipality puts into the strategies to improve the air quality and, more in general, the quality of life in urban areas.

3

DESIGN AND SELECTION OF BIORECEPTIVE FAÇADE MATERIALS

3.1 INTRODUCTION

In this chapter the material selection process and the consideration made for the objective-oriented design of the Magnesium Phosphate cement based samples are described. Afterwards, the steps followed to define a suitable formulation depending on physical, chemical and mechanical properties are reported. Finally, the results obtained from the analysis of pH and porosity are delineated and presented.

3.2 MATERIALS AND METHODS

Different materials were selected to be tested in the natural environment. The selection was mainly based on the properties that influence the bioreceptivity, defined by concerning literature and studies, described in the previous chapter. The main material properties that were considered during the selection were pH and porosity. Besides, another factor that influenced the selection was the availability of materials in the main areas chosen for the application, Reykjavík and Copenhagen. The reasons behind the choice of including some local materials in the experiment, were based on the concept of sustainability and of Vernacular architecture, defined as designing buildings that are related to their environmental contexts, utilizing available resources and traditional technologies (Brunskill, 2000).

3.2.1 *Material list*

The list of materials and specimens used for the bioreceptivity test under environmental conditions is presented in Table 3.1 below.

Code	**Material**	**Aggregate**	**Agg. Size**	**Size**	**Thickness**
-	*Material name*	*Type*	*[mm]*	*[cm]*	*[cm]*
OPC	carbonated opc	-	-	14X14	5
MR	marble	-	-	14X14	1
CL	caucasus lava stone	-	-	14X14	2.5
BC	basalt (cut surface)	-	-	14X14	1
BB	basalt (brushed surface)	-	-	14X14	1
BR	basalt (rough surface)	-	-	14X14	1
IL	icelandic lava stone	-	-	14X14	1
M1	mpc	-	-	14X14	2.5
M2	mpc	-	-	14X14	2.5
MC	mpc	cellulose	0/1mm	14X14	2.5
ML	mpc	lava	2/4mm	14X14	2.5
ML1	mpc	lava	0/8mm	14X14	2.5
ML2	mpc	lava	0/8mm	14X14	2.5
MA1	mpc	sand/gravel	2/4mm	14X14	2.5
MA2	mpc	sand/gravel	2/4mm	14X14	2.5

Table 3.1: List of materials selected for the experiment under environmental conditions

3.2.2 *Carbonated Portland Concrete*

Portland cement based materials are very alkaline materials at the beginning of their service life. The pH value of fresh Portland cement paste, due to its content of 20-50 wt% of calcium hydroxide ($Ca(OH)_2$) is usually greater than 12.5.

Carbonation of Portland concrete elements is a process that occur naturally during its service life, when it is in contact with air and water. The process requires the presence of water indeed, because CO_2 dissolves in water forming H_2CO_3. The results of carbonation is a progressive reduction of the pH, starting from the external layer towards the core, reaching values close to neutrality. This process is a very slow long-term reaction. In order to speed up the reaction, and the consequent pH reduction, a solution could be the accelerated carbonation, exposing the concrete specimens to an environment where several parameters such as temperature, CO_2 concentration, relative humidity and pressure, are controlled. Despite the name of the process is accelerated carbonation, this process takes always some time to reach the desired range of pH in the concrete specimens. Therefore, in order to save time, it was decided to utilize an already carbonated specimen of concrete, which was about 50 years old. The external surface of two big concrete tiles, gathered in the area of Copenhagen, was cleaned from dirt and organisms using a solvent, water and a brush. Then 6 specimens were cut out from the 2 main tiles using a rock cutting saw, at the Building Materials Laboratory of the Technical University of Denmark, obtaining specimens with dimension 14x14x5 cm^3. The picture of one of these specimen is shown in Figure 3.1.

Figure 3.1: Picture of an old, already carbonated, Portland concrete specimen

3.2.3 *Marble*

The reason behind the choice of including marble in the group of materials for the test, was based on the observation that old marble and granite stones in graveyards are often colonized by lichens. A picture showing orange lichens colonies on marble gravestone can be seen in Figure 3.2.

Figure 3.2: Lichens on white marble gravestone, in Hólavallagarður cemetery, Reykjavík

Marble is characterized by a very highly crystalline structure and a low, but definite porosity (Yardley, 1989).

Another reason of the selection was that marble has been widely used, since ancient times, as cladding material. The marble was provided by Kurt Kielsgaard Hansen, and collected from Carrara, Italy. A picture of one of the specimens is shown in Figure 3.3.

Figure 3.3: Picture of a white marble specimen

3.2.4 *Basalts*

The inclusion of basalt stones in the experiment was suggested by Steve Christer from Studio Granda. Basalts are dark-coloured stones, widely available in Iceland. As can be seen in the map in Figure 3.4, showing the location of oceanic divergent boundaries and hotspots. These are locations were large volumes of basalt have been formed.

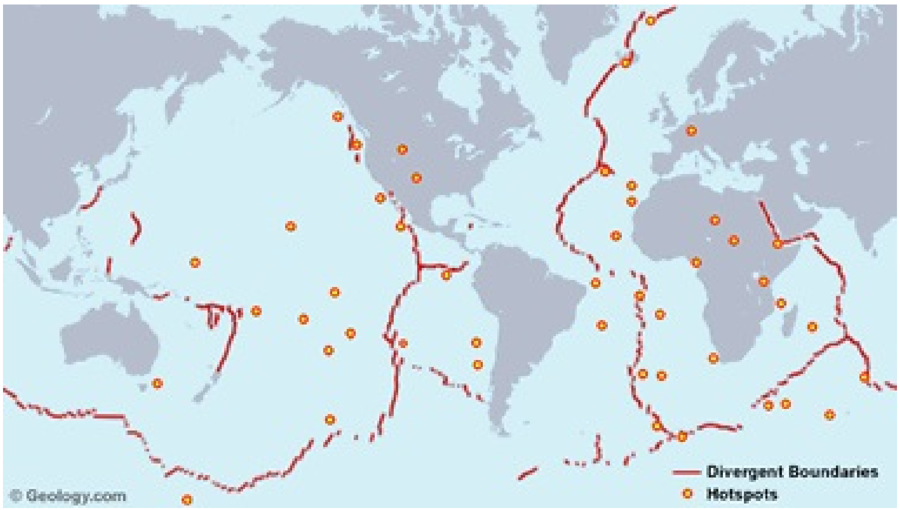


Figure 3.4: Basalt-Forming Environments (Bas).

The choice of basalt was due to the observation that, like marble, also many basalt gravestones are often covered by lichens. A picture of a basalt gravestone is presented in Figure 3.5.

Figure 3.5: Basalt gravestone covered by green lichens

Samples with three different surface's finishing were used as specimens. They were respectively produced with rough, cutting and brushed surfaces, by Steinkompaníið ehf. in Reykjavík. The pictures of the basalt samples are shown in Figure 3.6.


(a) Rough surface (b) Cut surface (c) Brushed surface

Figure 3.6: Basalt stone specimens

3.2.5 *Lava Stones*

Lava stones were chosen because of their physical properties and especially their high porosity. Two different lava stones were selected, a red lava from Caucasus and a dark one from Iceland. The red lava stones were collected by Kurt Kielsgaard Hansen, and cut into 14x14x2.5 cm^3 with a rock cutting saw, at the Building Materials Laboratory of the Technical University of Denmark. The Icelandic lava stone was collected in Iceland and produced by Steinkompaníið ehf. in Reykjavík. The Icelandic lava stones have large pores that allow sun light to pass through, giving them an added architectural value. Two of the samples used for the experiment are shown in Figure 3.7.

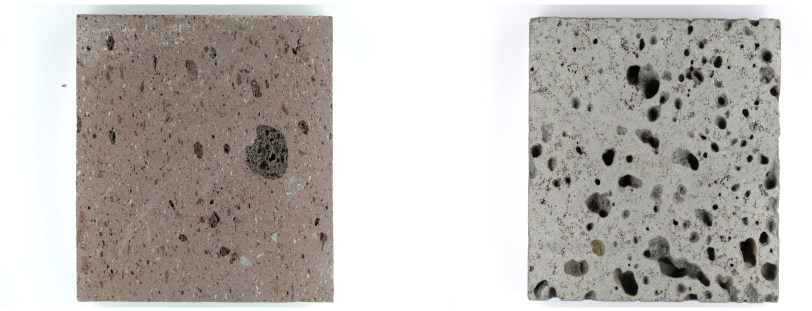

(a) Caucasoid red lava stone (b) Icelandic black lava stone

Figure 3.7: Lava stone specimens

3.2.6 *Magnesium Phosphate Cement*

The selection of Magnesium Phosphate cement (MPC) was based on existing literature and the positive results obtained for its use as substrate for biological colonization. In a series of experiments carried out between the Polytechnical University of Catalonia and the University of Ghent, it was observed that with the correct dosage, it was possible to obtain specimens with a pH in the range of 5.8 and 7, and a chemical composition that makes this hydraulic binder suitable to allow growth of microorganisms. It was also noticed that between the specimens, the one that appeared to be the most receptive for colonization of *Chlorella vulgaris* in laboratory conditions, was the one with the lowest porosity and a lower surface roughness compared to the other specimens included in the experiment. Another conclusion from the experiment was that chemical properties of the specimens seem to have more influence on colonization than physical properties (Manso, 2014).

Due to lack of time and difficulties in finding the components to produce customized MPC specimens, it was chosen to use an already prepared mix, provided by Sika UK, called Sikaset 45. This product is a one component magnesia phosphate based rapid hardening bedding mortar for use in temperatures as low as 0°C. The main uses for this kind of mortar are rapid reparations of horizontal concrete surfaces, industrial floors, roads, bridge decks, etc. It is often used in cold environments because of its very rapid setting time and its good un-primed adhesion.

It was known that both chemical and physical properties of the final product could largely differ from the properties of the specimens produced in Manso's experiment.

3.2.7 *Dosage and Specimens Production*

Several different formulations have been tried in order to produce specimens with different physical properties, mainly focusing on porosity and surface roughness. The water to mix ratio was increased until segregation was observed, during the filling of the moulds and after demoulding. Therefore, a limit of water to mix ratio of 0.2 was defined as the limit to avoid segregation of the specimens, and two different water/mix ratio of 0.1 and 0.2 were adopted, in order to obtain specimens with different physical characteristics and especially different porosity. Also, several kind of aggregates have been used in the specimens production process: lava stone aggregates collected in Iceland, sand and gravel and cellulose aggregates provided by the National Food Institute, Technical University of Denmark.

The mortar mix was thoroughly soaked with clean water until uniformly saturated leaving no standing water and was mechanically mixed using a forced action mixer for three minutes, achieving uniform consistency. Afterwards, the fresh mortar was poured into 14cm x 14cm pre-oiled wooden moulds. The exterior layer was levelled using a steel trowel.

The mortar specimens were immediately left to curing, covered by a polythene sheeting taped down at the edges. This was done in order to retain the original moisture, to avoid arresting or retarding the hydration process through which concrete gains strength. Specimens set very quickly, starting to harden in less than 5 minutes after the application for both the water/mix ratio used.

After 4 to 5 hours, the specimens were removed from the moulds and left for additional curing, in polyethylene bags.

The list of the specimens produced, with the water/mix ratios, the aggregate type and dimension can be seen in Table 3.2.

Code	**Quantity**	**Cement**	**Aggregate**	**Agg. Size**	**w/mix ratio**	**agg/mix ratio**
-	*n°*	*Material*	*Type*	*[mm]*	*[-]*	*[-]*
M1	6	mpc	-	-	0.1	-
M2	6	mpc	-	-	0.2	-
MC	5	mpc	cellulose	0.02/0.05	0.1	0.025
ML	6	mpc	red lava	2/4	0.1	only on surface
ML1	6	mpc	black lava	0/8	0.1	0.2
ML2	6	mpc	black lava	0/8	0.2	0.2
MA1	6	mpc	sand/gravel	2/4	0.1	0.2
MA2	6	mpc	sand/gravel	2/4	0.2	0.2

Table 3.2: List of MPC specimens produced for the experiment

3.3 POROSITY

As mentioned before, porosity is one of the physical properties that most influence the bio-receptivity of a material. LBM-Prøvemetode-2-rev method was used to measure the porosity of the samples. The specimens were dried over night at a temperature of (105± 5)$°C$. For the MPC specimens, due to the possibility of changing the pore structure, it was decided to dry them at a temperature of (70± 5)$°C$. Furthermore, some of the MPC specimens used for this test were broken in pieces when they were demoulded.

After more than 24 hours in the ventilated oven, it was assumed that a constant mass was reached. Then, the specimens were kept in a desiccator for 5 hours, until their temperature reached the room temperature (23.5± 0.5)$°C$. The specimens were then weighed, obtaining measurements of m_{105}. The dried specimen were placed in an evacuation vessel and the pressure was gradually reduced to (2.0± 0.7) kPa. The specimens were kept in the evacuation vessel for at least 3 hours, so as to eliminate the air contained in the open pores. Demineralized water at room temperature was introduced into the vessel, and the specimens were completely covered in water in less then 15 minutes.

The vessel, filled with water and the specimens was left with a maintained pressure of (2.0± 0.7) kPa, for at least an hour without pumping. Afterwards, air was introduced into the vessel, returning to atmospheric pressure. The specimens were left under water throughout the night at atmospheric pressure. The water saturated specimens were weighted in water and the mass in water ($\mathrm{m_{sw}}$) was recorded. After wiping the specimens' surface with a dampened cloth, the specimens were weighed again in air, determining the mass of water saturated specimens ($\mathrm{m_{sst}}$). From the values recorded and after measuring the density of water (ρ_w) and the room and water temperatures (respectively T_r and T_w, presented in Table 3.3), it was possible to calculate:

the volume of the specimens (V) throughout the formula:

$$V = (m_\mathrm{ssd} - m_\mathrm{sw})/\rho_\mathrm{w} \tag{1}$$

the volume of the open pores ($\mathrm{V_{op}}$) with the formula:

$$V_\mathrm{op} = (m_\mathrm{ssd} - m_{105})/\rho_\mathrm{w} \tag{2}$$

the open porosity of the specimens ($\mathrm{p_o}$) throughout the formula:

$$p_\mathrm{o} = V_\mathrm{op}/V \tag{3}$$

the apparent density of the specimens (ρ_f), can be calculated as:

$$\rho_\mathrm{f} = m_{105}/(V - V_\mathrm{op}) \tag{4}$$

the dry density of the specimens (ρ_d), with the formula:

$$\rho_\mathrm{d} = m_{105}/V \tag{5}$$

the density of the water saturated specimens, with dry surface in vacuum conditions (ρ_ssd), can be calculated as:

$$\rho_\mathrm{ssd} = m_\mathrm{ssd}/V \tag{6}$$

Room Temperature	**Water Temperature**	**Water Density**
T_r [°C]	T_w [°C]	$\rho_w [kg/m^3]$
23.5	21.2	997.9

Table 3.3: Temperature conditions and density of water for porosity test

The measured and calculated values are presented in Table 3.4.

Between the MPC specimens, it can be observed that specimens produced with aggregates of higher sizes, showed a slightly higher open porosity value. It can also be noticed that the w/c ratio influences the open porosity as well, showing a general trend where higher w/c ratios

Code	**Material**	**V**	**V_{op}**	**p_o**
-	*Material name*	*[m^3]*	*[m^3]*	*[m^3/m^3]*
OPC	carbonated opc	0.98	0.19	0.19
MR	marble	0.16	0.00	0.00
CL	caucasus lava stone	0.38	0.19	0.48
BC	basalt (cut surface)	0.23	0.02	0.09
BB	basalt (brushed surface)	0.21	0.02	0.10
BR	basalt (rough surface)	0.29	0.01	0.03
IL	icelandic lava stone	0.24	0.03	0.11
M1	mpc	0.47	0.10	0.21
M2a	mpc	0.23	0.07	0.28
M2b	mpc	0.07	0.02	0.28
M2c	mpc	0.07	0.02	0.28
MC	mpc	-	-	-
ML a	mpc	0.28	0.07	0.27
ML b	mpc	0.10	0.03	0.31
ML c	mpc	0.08	0.02	0.30
ML1	mpc	0.46	0.12	0.25
ML2a	mpc	0.14	0.04	0.27
ML2b	mpc	0.14	0.04	0.30
ML2c	mpc	0.07	0.03	0.35
ML2d	mpc	0.13	0.04	0.29
MA1	mpc	0.45	0.08	0.19
MA2a	mpc	0.29	0.08	0.26
MA2b	mpc	0.18	0.05	0.26
MA2c	mpc	0.03	0.01	0.30

Table 3.4: Volume and porosity measurements

lead to specimens with higher values of open porosity. Regarding the other materials, the highest porosity was found for the red lava stone from Caucasus, while marble is the material with the lowest percentage of open voids. It is interesting to observe that the Icelandic lava stone has a low open porosity when compared to other materials. This is due to the very large superficial pores present in the materials that are not considered in the analysis. The method used to assess the porosity is indeed based on the Archimedes' principle, thus the volumes of the specimens are calculated as the volume of the displaced water, when the specimen was immersed.

3.4 PH

Due to the difficulties in assessing pH of solids without breaking the specimens, and without special instrumentation, two first measurements were taken pouring some drops of distilled water on the specimens' surface, waiting for 3 minutes and then using a pH-indicator.

The first measurement was taken just after casting the MPC samples for the MPC and the other materials that were available at that moment. The second one was taken for all the materials, before the porosity test. Finally, after that also the porosity measurements were taken, it was possible to obtain pH measurements according to procedures already used by other authors (Räsänen and Penttala, 2004; Ottelé, 2011; Manso, 2014).

The samples were crushed into powder. The obtained powdered samples were weighed and then suspended in distilled water with a solid:water ratio of 1:2. The pH of the suspension was measured after stirring for 15 minutes, using pH indicators.

The obtained results are listed in Table 3.5.

pH Measurements				
Code	**Material**	**1st**	**2nd**	**3rd**
-	*Material name*	*[-]*	*[-]*	*[-]*
OPC	Carbonated OPC	8.50	8.00	10.50
MR	Marble	8.00	8.50	7.75
CL	Caucasoid Lava	-	7.25	8.25
BC	Basalt Cut	-	8.25	7.25
BB	Basalt Brushed	-	8.25	7.25
BR	Basalt Rough	-	8.50	7.25
IL	Icelandic Lava	-	8.25	7.5
M1	MPC	8.50	8.75	8.75
M2	MPC	9.00	8.67	8.75
MC	MPC/Cellulose	8.50	8.50	-
ML	MPC/Lava	8.50	8.50	9.00
ML1	MPC/Lava	8.50	8.00	9.00
ML2	MPC/Lava	9.00	7.94	9.00
MA1	MPC/Lava	8.50	8.25	8.75
MA2	MPC/Sand	9.00	8.25	9.00

Table 3.5: pH measurements of the samples

First observation is that MPC samples have higher pH values than expected from previous studies (Manso, 2014). This was likely due to the use an already mixed mortar. Also, all the materials have pH values in the range of 7.5 to 9, which are considered good for determined lichen species that prefer alkaline surfaces. Despite the method of test was more accurate for the third measurement, since the whole specimens were crushed into powder, the measures should be considered related to the whole specimens and not only to their surfaces. It can be observed from the table that the last value obtained for the Carbonated OPC was rather higher than the values obtained in the first two measurements. The carbonation process is a very slow reaction and it starts from the external surface of the element. From this difference between first, the second and the last measurements, it seems that the OPC was not completely carbonated.