Air Permeable Concrete

Students' Report

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Synopsis

In this report the theoretical and experimental study on Air Permeable Concrete has been performed. The research focused on establishing the mix designs for APC in order to obtain desired properties, such as high porosity and permeability and satisfactory compressive strength. The addition of Phase Change Materials was considered and their influence on the rheology of cement paste and on the compressive strength of APC was evaluated.

The establishment of the mix designs was based on the tests of the rheology of cement paste and the workability of concrete. The concrete with water/cement ratios of 0.30 and 0.35 together with three different degrees of filling (0.4, 0.5, 0.6) for each water/cement ratio has been tested.

The experimental study focused on developing the methods of mixing, casting and curing which enable obtaining the desired properties of APC. The methods of measurements of the parameters have been determined and the tests of porosity, permeability and compressive strength have been performed. The calculation of theoretical values of porosity has been done and compared with laboratory results.

The comparison of obtained results with results from other studies on APC has been performed.

Preface

The report is written by Marco Contri at the 10th semester of the Master Course of Structural and Civil Engineering at Aalborg University. The project is entitled "Air Permeable Concrete" and is completed within the period of 1st of February to 9th of June 2011 under the supervision of Eigil Verner Sørensen.

The aim of the project is to perform an experimental study on Air Permeable Concrete and establish the right recipe for obtaining satisfactory values of porosity, permeability and compressive strength. The recipe contains Phase Changing Material.

The work embraces two areas, the theoretical study and the experimental work. The report also includes an appendix.

The reference system adopted in the report is written as [no.] and all the details about the references such as title, author, editor and year of publication appear in the bibliography at the end of the report. The sources of all pictures and tables are mentioned unless they are made by the author.

Chapter 1

Introduction

Nowadays, the pursuit for clean energy and ecological solutions are present in every field of life, technology and industry. It is powered both by the growing awareness of societies caring about the "future of the planet" but also by economical reasons, regarding e.g. high costs of energy. Different legislations concerning limitations of the emission of CO_2 were implemented and various solutions were found to achieve the goals of the "environmentally friendly" requirements.

The construction sector is also following the search for new ecological technologies. Passive buildings, green roofs and high-tech insulating materials are well known and already in use. However, the search of new solutions is still being developed and new techniques have been invented. One of this new ideas, concerning the building in its core structure, is the dynamic breathable concrete, also know as air permeable concrete (APC). The idea of the air permeable concrete is based on the concept of a breathing wall, which functions not only as a building facade or interior wall, but also as a heat exchanger, a source ventilation and air filter. The main task of dynamic insulation is to exchange heat and provide ventilation and filtration for incoming air. To satisfy the assumptions for the functions of APC, the concrete needs to have special properties and parameters.

One of the researches on the air permeable concrete was done by Imbabi et al. [8]. The study was focused on the most important parameters of APC: porosity, permeability, thermal conductivity and compressive strength. The entire research and the results induced the interest in the methods of obtaining certain properties of the APC. Despite the fact that the new idea can be developed in many various directions, the areas of study for this report were chosen following the specialization of the Master's Course, which is Structural Engineering. Therefore, the project work has been focused on developing the recipe for air permeable concrete and a method for mixing and casting the specimens. Furthermore, the following parameters has been examined: porosity, permeability and compressive strength strength. Finally, Phase Change Materials and their influence on the structure and the properties of APC has been examined.

Chapter 2

State of the Art

Concrete is the most commonly used building material worldwide. The annual global production of concrete being about 10 billion tonnes clearly indicates the significance and the huge role that concrete has in the construction industry and in the global economy. [1]

Despite concrete seems a modern invention, its first applications date back to antiquity. It was know by Romans, who used the mixture of sand, limestone and pozzolana to build arches, vaults and bridges. The most stunning concrete construction is undoubtedly the dome of Pantheon, 43.2 m high and 43.2 m wide which is still the world's largest unreinforced dome (Fig. 2.1). As it was built in 125 a.d., its condition and durability is outstanding. [2]

Figure 2.1: Model of Pantheon
[11]

In the Middle Ages and later, until XIX century, concrete was forgotten and replaced by stone, bricks and wood. However, in 1756 the modern prototype of cement was invented by John Smeaton, English engineer, who discovered that the role that clayey material has in the properties of the mortar is significant. The idea of burning a mixture of lime and clay was developed later in 1824 by Joseph Aspdin, who patented the Portland cement, which is commonly used in concrete. This invention caused the spread of concrete construction and development of concrete technology. [3]

Through the years, the form, the properties and the use of concrete has changed. From temples in antiquity to skyscrapers in present day, from a simple material made without any mix designs to high-tech concrete with specific properties. Concrete was evolving as the necessities of societies for different types of constructions were arising. Many various parameters were developed and manipulated in order to fulfill particular requirements. The characteristics of concrete can be extremely diverse, from lightweight aerated concrete blocks that shorten the construction time of the house to few months, to high strength concrete of 140 MPa used to build bridges. Further, on one hand there are prefabricated concrete panels, prestressed concrete, chemically-resistant concrete for marine structures; on the other hand – colourful, decorative architectural concrete (e.g. Fig.2.2). The range of properties and possible applications is very wide. [4]

Figure 2.2: Museum of Modern Art in Aarhus [26]

2.1 The challenge today

Nowadays, the importance of clean energy and renewable energy resources is mentioned in every field of life and industry. With growing awareness of limited natural sources and harmful effect of the CO_2 and other gases on the environment, the efforts are made to limit the amount of energy production and consumption also within the construction field.

Considerable attempts were made to adjust building design to modern, environmentally friendly constructions. The ideas of e.g. green building were described as solutions which aim to reduce the negative impact that new buildings have on the natural environment and human health. This should be done for example by efficient use of energy (such as heating, electricity) and water, by improvement of the quality of indoor environment (proper ventilation) and waste reduction. Various solutions were found to achieve the goals of environmentally friendly buildings. They emphasize the use of renewable sources of energy (e.g. solar panels, Fig. 2.3), recycled materials (stone, metal), green roofs (roofs covered with vegetation, providing insulation and lowering the interior temperature, Fig. 2.4) or high-tech insulation materials. [5]

Figure 2.3: Solar panels on the roof of a house [19]

Figure 2.4: Green roof on a skyscraper in Chicago [20]

The above mentioned techniques provide "outer" solutions and they do not interfere with the building's core structure i.e with the building material. However, new innovative ideas were found, concerning the properties of concrete and the possibility to use them as a tool for an environmentally friendly building, especially as regards heating and ventilation issues. One of these ideas is dynamic breathing concrete, the properties and parameters of which will be analyzed in this project.

2.2 The idea of breathable concrete

Intuitional knowledge may suggest that if a building is air tight, it is more efficient as regards insulation and heating demands. In other words, a thick insulation layer is expected to reduce the need for energy. However, such an attitude proved to be harmful to the ventilation and the quality of the indoor air. The phenomenon of sick building syndrome is likely to occur caused by accumulation of volatile organic compounds, moisture, polluted outdoor air, gases (radon, carbon dioxide), microbial contaminants such as mould and bacteria. Together with higher indoor temperature caused by e.g large number of office machinery, it results in poor quality of indoor air and lowered level of comfort.

The essential change in traditional approach resulted in the idea of air permeable, breathable concrete. Air permeable concrete (APC) was invented in order to create dynamic insulation systems. The basic concept of dynamic insulation is to draw outdoor air into the building (passively or actively) through the layer of breathable concrete wall. Due to the particular parameters of concrete, the air passing through the wall is cooled or heated and cleaned from the airborne pollutants. In other words, the task of the dynamic insulation is to exchange heat and provide ventilation and filtration of incoming air. This is done by allowing the air and moisture to move through the building envelope. Therefore, the two main goals of dynamic insulation are achieved: the reduction of energy consumption for heating and ventilation and improvement of the indoor air quality. [7]

High permeability of APC ensures lower thermal conductivity, both static and dynamic. The detailed explanation of the terms of static thermal conductivity and methods of its calculation for APC will be given in the following chapters. The dynamic thermal conductivity will not be analysed in this report.

2.3 Current research

The research on air permeable concrete is aiming to provide a mix design for concrete which assures desired properties and parameters. Dynamic insulation should deal with three main issues. Firstly, it acts as a heat exchanger in order to lower the demand for energy and therefore ensures that the building is environmentally friendly. Secondly, it is a source of ventilation and thirdly, it acts as an air filter. The above mentioned features provide good indoor air quality and lower the cost of energy used for heating and ventilation.

Therefore, the main objective of the design of the concrete mixture is to obtain sufficient air flow though the element. The air flow and therefore porosity and permeability depend on the internal structure of concrete. To obtain satisfactory parameters including sufficient compressive strength, the mix design has to be manipulated.

All above mentioned parameters have to result in low values of effective thermal conductivity and thus satisfactory values of dynamic U-value (heat transfer coefficient) of the element.

2.4 The assumption of the APC model

The research made by Imbabi et al. [7], [8] at Aberdeen University is aiming to develop breathable concrete for dynamic insulation. Therefore, attempts were made to achieve required combinations of thermal properties, porosity, permeability and compressive strength. The above mentioned parameters and the terminology used in the report is explained in section 4.

Taking into consideration that the internal structure of APC needs to be highly porous in order to allow permeation through the voids as well as to ensure high air content and thus low thermal conductivity, the following model of APC was assumed (Fig. 2.5):

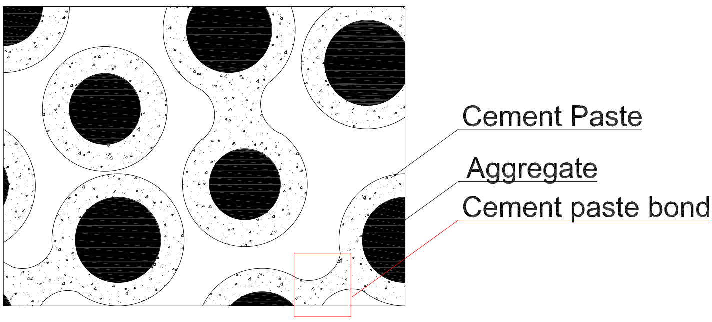

Figure 2.5: Idealized model of physical structure of APC [7]

As can be seen from the idealized model of the structure of APC (Fig. 2.5), it consists of perfectly rounded, mono-size aggregate of 2 mm diameter, cement paste precisely covering each grain, and interconnected channels. With such a model, the desired high permeability is reached thanks to:

1) high porosity (total volume of voids);

2) interconnectivity of voids (the channels are continuous to allow permeation);

3) regular pore size distribution (large amount of small voids increases the turbulent flow, comparing to smaller amount of larger voids, when the flow is laminar).

To present a heat transfer path through the structure of APC, a 1-D model of a single aggregate grain surrounded by cement paste and air was assumed by Imbabi et. al [8]. The simplified ways of the heat flow are presented in Fig. 2.6. There are 3 paths of the heat flux: 1) air - air, 2) air - cement paste - air and 3) air - cement paste - aggregate

- cement paste - air. Path 1) omits solid material and transfers heat only through the air surrounding the particle. Paths 2) and 3) conducts through the solid particles as well.

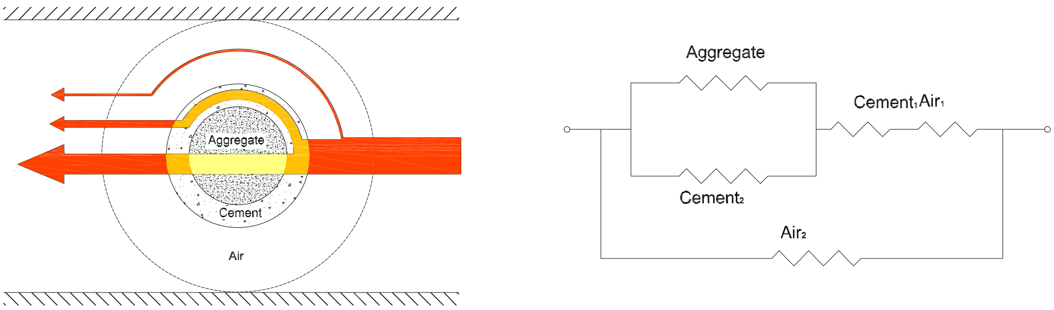

Figure 2.6: Model of heat transfer of APC

The thermal conductivity of APC (λ) depends on its constituents, i.e. aggregate, cement paste and air. Since the thermal conductivity of air is very low ($0.025 W/m \cdot K$), most of the heat will flow through the solid particles (aggregate and cement matrix). However, as can be seen from the model (Fig. 2.6), the structure of breathable concrete cannot be unequivocally defined as parallel or serial. The path of the heat flow is a combination of both parallel and serial models.

The volume fraction of each component has to be adjusted to assure low value of λ.

2.5 Turning the model into reality

The challenge regarding air permeable concrete is how to turn the ideal model of APC into reality, in order to obtain satisfactory parameters that will fulfill the requirements of porosity, permeability and thermal conductivity together with sufficient compressive strength. Therefore, the main problem is the manipulation of the concrete mix design and the properties of the components. The research by Imbabi et al. [8] indicates the main factors influencing the properties of APC.

Firstly, the manipulation of aggregate sizing is mentioned. Regular aggregate of narrow size fraction is recommended. Size, shape and angularity of particles determine the space for cement paste filling as well as the remaining space for air voids. Shape and angularity influence the natural packing density of aggregate. Packing density PD indicates how well the particles of the aggregate fill the mould.

Secondly, porosity and permeability depend mostly on the degree of filling DF, which is defined as the ratio between the volume of fresh cement paste and the volume of voids between the aggregate particles. The volume of those interconnected channels filled with air depends on the packing properties of the aggregate, which result from its shape, angularity and natural porosity. The degree of filling depends on the amount of cement paste and admixtures that fills the void space of the aggregate.

The following table (Tab. 2.1) presents the results obtained by Imbabi et al. [8] on the samples of APC.

Water to cement weight ratio	**Degree of filling**	**Strength [MPa]**	**Averaged permeability** $[m^2/Pah]$	**Averaged concrete porosity**
0.25	0.5	10.8	0.60	0.32
0.25	0.6	18.2	0.32	0.28
0.25	0.7	25.0	0.18	0.22
0.30	0.5	10.7	0.60	0.32
0.30	0.6	15.3	0.32	0.28
0.30	0.7	21.0	0.18	0.22
0.35	0.5	8.5	0.60	0.32
0.35	0.6	12.7	0.32	0.28
0.35	0.7	15.1	0.18	0.22

Table 2.1: Measured properties of APC with different mix designs [8]

According to the table, the compressive strength of APC is very sensitive to the changes of the degree of filling. At constant w/c, e.g $w/c = 0.25$, with degree of filling from 0.5 to 0.7, the strength varies from 10.8 to 25 MPa, which is a wide range. Moreover, the compressive strength slightly decreases with the increase of w/c.

Furthermore, porosity and permeability are significantly influenced by the degree of filling DF. Average porosity and permeability of APC increase with the decrease of degree of filling. This is consistent with what was expected from the theory: the smaller DF, the larger the volume of voids in the concrete and therefore the larger the values of porosity and permeability. Porosity and permeability of APC are not sensitive to changes of w/c, as it affects the porosity of cement paste alone. The achieved results are consistent with the theory.

Further research was done to measure the thermal conductivity of APC. The results were plotted together with the predicted values of the thermal conductivity obtained from the mathematical model (Fig. 2.7).

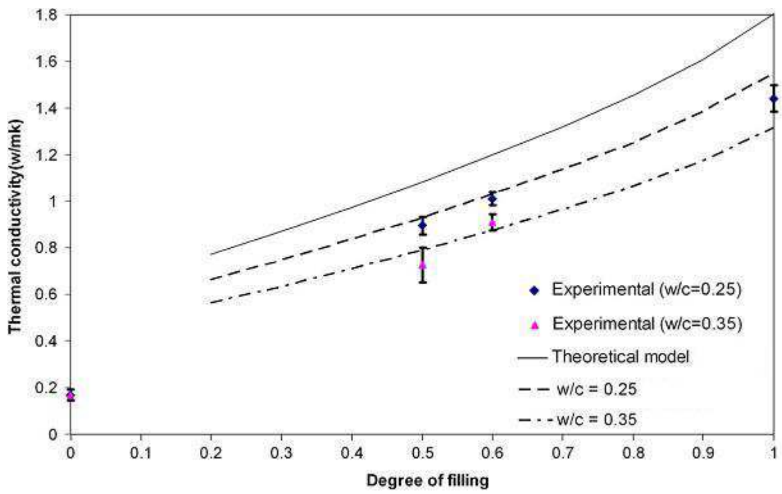

Figure 2.7: Thermal conductivity for experimental and theoretical results [8]

It can be seen from Fig. 2.7 that the values of the thermal conductivity increase with the increase of DF and the decrease of w/c ratio.

Furthermore, the plot indicates that the theoretical values of thermal conductivity are larger than those found experimentally, therefore inaccuracy of the mathematical model is depicted. However, the trends are similar. Moreover, the curves differ with different values of w/c. A conclusion can be drawn that thermal conductivity is sensitive to w/c. For higher w/c thermal conductivity is lower, because surplus water evaporates during drying and leaves cement paste more porous than in the case of lower w/c ratio. As described in previous chapters, higher porosity means lower thermal conductivity as air is a poor conductor.

The final conclusion of this analysis is that thermal conductivity is a function of water/cement ratio and volume fraction and thermal conductivities of the components. However, in reality the parameters of air permeable concrete are more difficult to predict. As can be seen from the cross-sectional view of an APC sample (Fig. 2.8), the location of components is random and irregular. Consequently, the relation between the parallel and serial flow of heat is unknown, so the mathematical model for the thermal conductivity is difficult to develop.

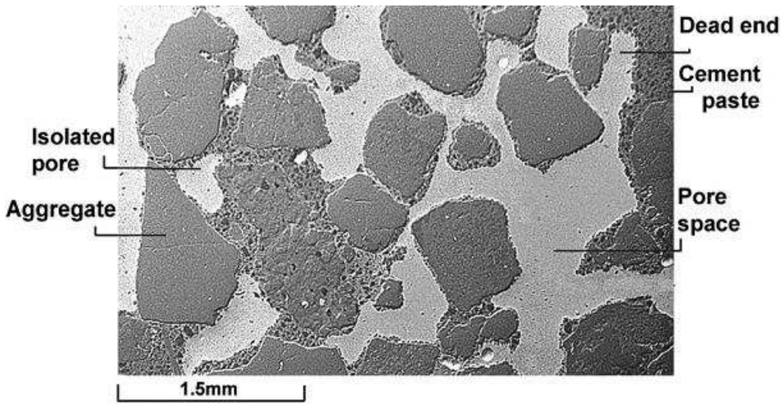

Figure 2.8: Cross-sectional view of APC [7]

The authors of the report [8] conclude that significant reduction of static thermal conductivity of APC is obtained (0.78–1.0$W/m \cdot K$, depending on the w/c ratio), compared to conventional concrete (1.4–2.0$W/m \cdot K$). The predictions of the dynamic U-factor are made, estimating it at 2.7$W/m2 \cdot K$ (with air flow velocity 0.002 m/s), which means 30% reduction in comparison to conventional concrete.

The research [8] resulted in a patent which gives information about a concrete mix design for creating air permeable and breathable concrete. However, the information given is of a more general nature and does not provide operative and specific guidelines for producing APC. Moreover, the patent suggests the possibility of enhancing the thermal properties of the APC by using Phase Changing Material (PCM). For this reason it has been decided to concentrate this study project on APC combined with PCM.

2.6 The idea behind the Phase Change Materials (PCM)

The building sector in the European Union consumes about 37% of the final energy (the amount of primary energy reduced by losses from conversion devices, transport etc [23]), which is more than the consumption in industry (28%) or transport sector (32%). Two-thirds of energy is used to provide thermal comfort in the buildings, either for heating or cooling. The energy consumption is particularly large in public buildings, such as offices or restaurants. Thus, there is a high necessity of reducing the use of energy in those sectors. [14]

The factors influencing the amount of energy used to provide the required thermal conditions are e.g.:

- climatic conditions of the region (temperature, wind speed, insulation);
- the structure of the building and the properties of building materials (wall thickness, insulation properties, window area);
- sources of heat (illumination, electrical devices, the number of people);
- the number of heat exchanges;
- the type of heating/cooling system.

Today's technologies of the constructions of buildings, especially office buildings, are based on lightweight materials which fulfill the requirements of thermal insulation, but on the other hand have very small thermal capacity. To increase the effective thermal capacity, without an adverse increase of the mass of a building, the idea of applying Phase Change Materials was created.

2.7 Phase Change Materials

The idea of Phase Change Materials was created in the 1960s, but its significant development has been observed just in the recent years.

Phase Change Materials are substances with high heat of fusion. While melting and solidifying they store and release large amounts of energy. Heat is absorbed when the material melts and its internal energy increases due to high temperature (in the daytime); heat is released when the material solidifies (due to low temperature in the night time), as the solidification is an exothermic process.

An important parameter of PCM is the thermal capacity (heat capacity). High thermal capacity means that the amount of energy which has to be provided to the material to change its temperature by a certain amount is relatively high. Heat capacity is represented by specific heat capacity (per unit of mass) or volumetric heat capacity (per unit of volume). In terms of building materials, high thermal capacity is important, as it ensures the constant temperature of the wall. In the following table (Tab. 2.2) the comparison of volumetric thermal capacities of different materials, together with their densities is presented. [15]

Table 2.2: Density and thermal capacity of different materials [15]

Material	**Density** $\rho[kg/m^3]$	**Volumetric heat capacity** $[MJ/m^3 \cdot K]$
water	1000	4.2
concrete	2300	2.3
steel	7800	3.67
plasterboard	1400	1.18
brick	1600	1.34
wood	600	0.96
PCM	870-1000	15-18.7

Some tests have been made to examine the impact of PCM on the changes of temperature in an office. A container with PCM was placed in the room above the dropped ceiling and the temperature was monitored during a working day. The results are presented in Fig. 2.9. Each diagram represents a different content of PCM for a unit of the room area. [16]

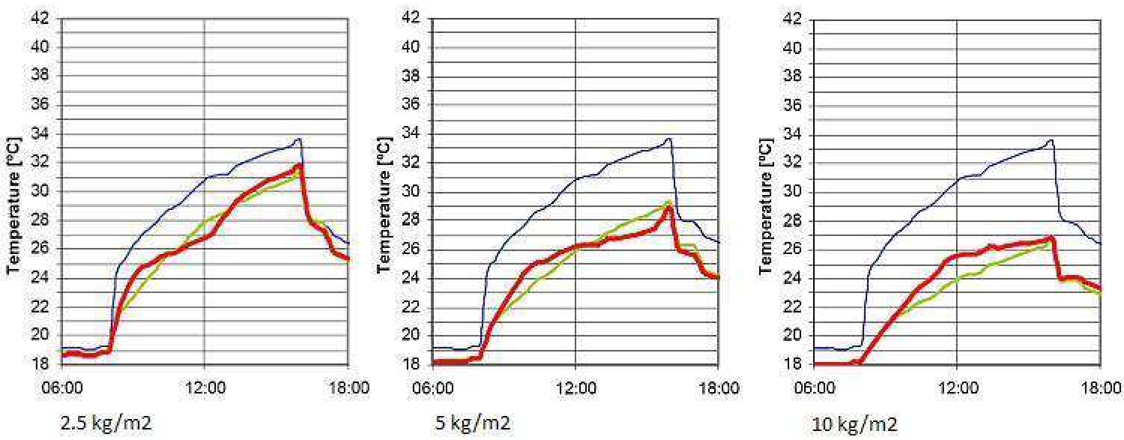

Figure 2.9: The impact of PCM on the temperature curve in an office [16]

The blue line represents the temperature in the office without the use of the cooling system. The increase of temperature is caused by the office equipment and the presence of humans.

The red and green lines show the temperature after placing a container with PCM. The tests were made for two materials whose phase change (in this case melting) takes place in temperature interval : DT2 ($24 - 26°C$, red line) and DT14 ($18 - 32°C$, green line).

A significant decrease of the maximum temperature in the room is noticeable. Therefore, the indoor thermal comfort can be increased by means of PCM, without using any cooling system.

Some methods have been developed to incorporate PCM into the buildings structure, e.g.: direct incorporation of PCM to cement paste, immersion of porous elements (bricks) with PCM or laminated glass-wool boards with a thin layer of PCM. [15] In this report the influence of PCM on the properties of cement paste and concrete will be analysed. Section 5.2.2 develops the idea of incorporation of PCM in air permeable concrete in order to obtain a special concrete that would act both as a load bearing structure and a heat storage unit.

2.8 Applications of APC

Although the attention of this report will not be focused on the computation of the U-value for the APC, for the sake of completeness this section aims to explain some possible utilizations of the APC especially concerning the construction requirements in terms of U-values.

The U-value is defined as the inverse of the thermal resistance as written in Eq. 2.1.

$$U = 1/R \tag{2.1}$$

$$R = d/\lambda \tag{2.2}$$

The thermal resistance (Eq. 2.2 [27]) defined as the ratio between the thermal conductivity (λ) and thickness (d) (e.g. of a wall), is highly influenced by the overall thickness of the wall: a large thickness means high values of R and therefore low values of the U-factor. Indeed, although with APC it is possible to obtain better results in terms of thermal conductivity than with normal concrete, this does not allow to build an external wall just by means of APC: the U-value would not be sufficiently low to meet the requirements imposed by the standards.

Table 2.3 shows a qualitative comparison between the U-values calculated for three different types of walls. It can be seen that a wall made just of APC can not be used as external wall as the code requirements for the U-value are close to zero (e.g. $U_{max} = 0.3$ [24]), yet it can be used as an internal wall where the codes do not prescribe such low U-values.

Material	λ $[\frac{W}{m} \cdot K]$	**d [m]**	**R**	$Wall_1$	$Wall_2$	$Wall_3$
Mineral wool	0.037	0.2	0.44		$\surd$	$\surd$
Trad. concrete	1.7	0.4	5.41			$\surd$
APC	0.9 [8]	0.4	1.2	$\surd$	$\surd$	
Air	0.025	0.03	0.24		$\surd$	$\surd$
U-value				2.27	0.14	0.15

Table 2.3: U-Value for two different kind of walls

Figures 2.10and 2.11 present the examples of possible applications of APC with PCM.

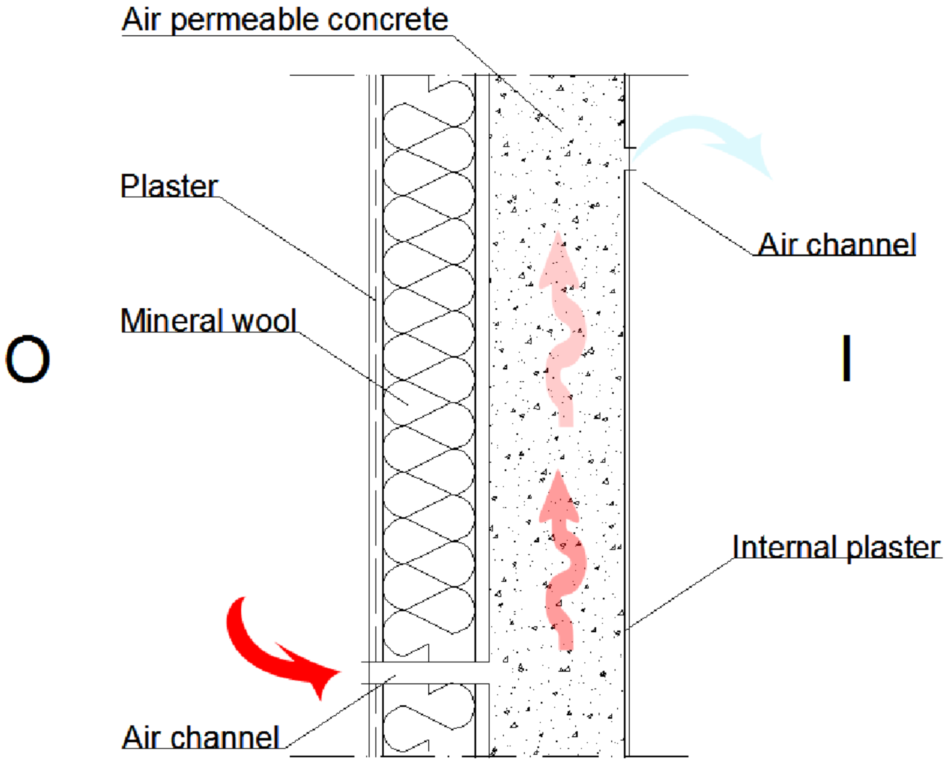

Figure 2.10: Example of application of a PCM-containing APC wall with high external temperature

Figure 2.10 shows a possible application of the APC with PCM. The outdoor air is cooled down and the wall is heated. The heat is stored by the PCM and it is released once the temperature drops below the fixed PCM melting point.

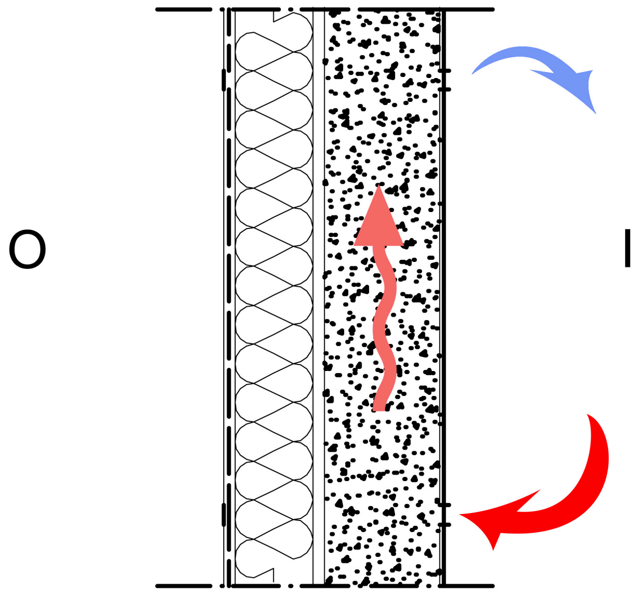

Figure 2.11: Example of application of an APC wall with low external temperature

Figure 2.11 illustrates how the wall can be used for cooling down the air without any exchange with the external environment. For instance the PCM would store the extra heat produced by working machinery (e.g.:computers, television...)during the day and release it in the night when the room temperature is decreased.

It has to be noticed that if there is not enough pressure difference between the internal and external areas, it might be needed to force the flow through the air channels by using fans or similar devices. Yet, it is beyond the scope of this project and therefore it will not be investigated.

Chapter 3

The objective of the research

The main objective of the research is to develop the background for production of air permeable concrete by identifying the influence of the main parameters on the most important properties of the concrete: porosity, permeability and compressive strength. Particularly, in order to analyse the problems embraced in the project the following aspects have been chosen to be described in the report :

- Analysis of basic properties of cement paste and concrete, such as water/cement ratio, rheology, porosity, compressive strength and thermal conductivity;
- choice of mix designs of APC with PCM, regarding the spread tests and recommendations;
- development of the mixing and casting procedure;
- establishment of the methods of measurements of porosity, permeability, compressive strength and performance of the tests;
- calculations of the parameters;
- comparison of the compressive strength of APC with and without PCM;
- comparison of obtained results with results from the research made by Imbabi et al. [8].

The project work is aimed to provide the proper recipe for air permeable concrete with reliable results of its properties.

The parameters taken into account during the process of establishing the mix design and the process of the laboratory work are:

- maximum grain size and grain size distribution of the aggregate;
- water/cement ratio of the cement paste;
- degree of filling of the voids between the aggregate particles;
- rheology of the fresh cement paste, including the effect of the addition of SPA and PCM;
- mixing and casting procedure, particularly the method and duration of vibration; curing method.

The scheme in Fig. 3.1 aims to clarify the objective of this research project. A brief description of the scheme will be given shortly.

The starting point for the study is the research [8], introduced in Chapter 2. Following the recommendations given in [8] and [22] as well as experimental work performed in the laboratory to examine the properties of cement paste, the mix designs and casting procedure of APC will be chosen. This level of analysis is represented in blue in Fig. 3.1.

The next level of the analysis is represented in yellow in Fig. 3.1. The mix designs and mixing procedures are aimed to achieve satisfying parameters of APC such as porosity, permeability and compressive strength. Once the specimens of APC are ready the parameters will be examined. However, the study on thermal properties (thermal conductivity and U-factor) will not be developed in this report.

The last step, represented in red in Fig. 3.1 will examine the influence of PCM on the properties of APC. The parameters of APC with and without PCM will be compared.

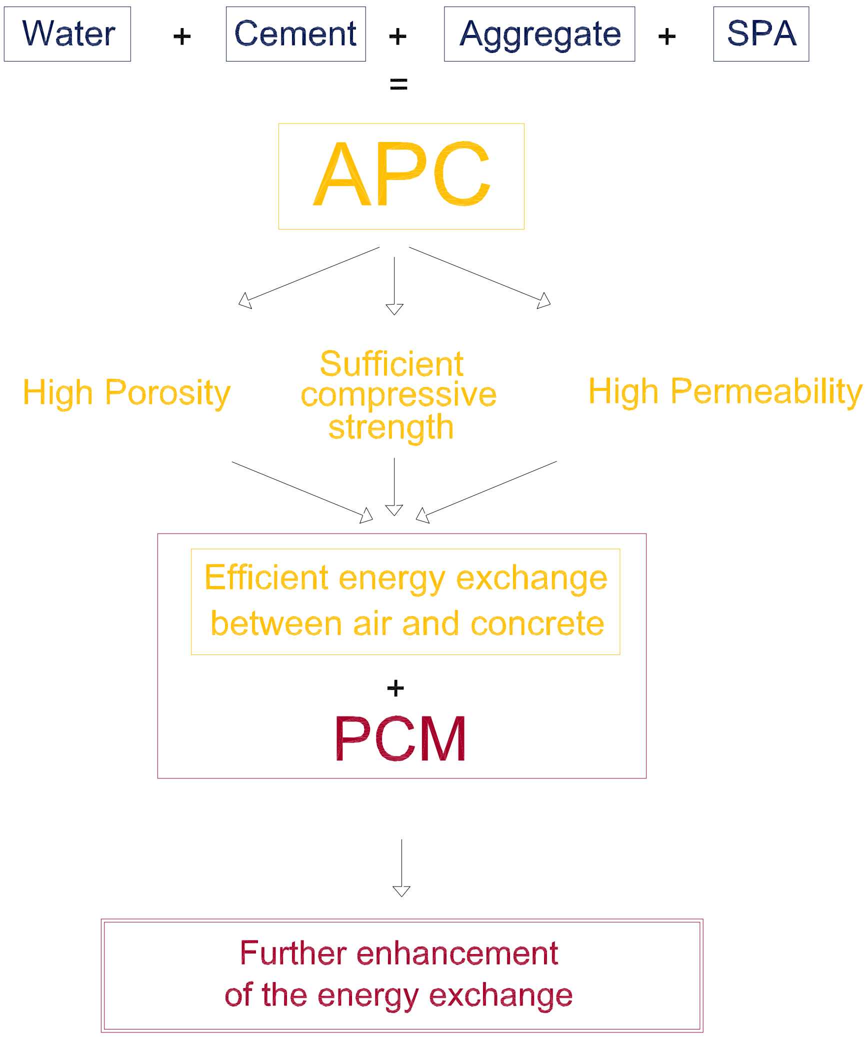

Figure 3.1: Scheme of the aim of the study

Chapter 4

Properties of cement paste and concrete

Traditional concrete, also known as regular concrete is composed of cement (usually Portland cement), aggregate, water and air. The cement mixed with water is subjected to the process of hydration. The products of reaction in time create a hardened cement paste, which becomes the bonding agent of aggregate particles in concrete.

The aggregate resists compressive stresses and provides the volume to concrete. The aggregate consists of fine aggregate (sand) and coarse aggregate (stones). Admixtures (i.e. accelerators, retarders, water-reducers, etc.) can also be added to achieve certain characteristics or special properties.

4.1 Water to cement ratio (w/c)

The water to cement ratio is the ratio between the initial mass of water and the mass of cement used in the concrete mix. The hydration of cement takes place in the presence of water and results in the formation of hard and firm cement paste, which becomes the bonding agent of the aggregate. For the sake of brevity 'w/c' will be used to refer to the water/cement ratio.

Regarding the cement paste, the w/c influences directly the course of hydration of cement. Full hydration is only possible with $w/c \geq 0.44$. With lower values of w/c, the degree of hydration and the volume fraction of the components of cement paste, i.e. unhydrated cement, gel solids, gel water, capillary water and air can be computed by means of Powers diagram, as described in section 4.3.1.

The w/c influences the compressive strength of cement paste and concrete and determines concrete durability. High w/c ensures good workability of the concrete mix, but lowers its compressive strength and durability. With lower w/c the situation is reversed: high compressive strength is related to poor workability. In this case the plasticizer is needed to enable the casting of concrete. Further explanation of the relation between w/c and compressive strength is presented in section 4.5.

While the amount of cement can be directly measured as the quantity of material introduced into the mixer, the amount of water needed for the hydration has to be adjusted according to the moisture content of the aggregates. If the aggregates are saturated but, instead of having a dry surface (optimal situation) they have a wet surface, this excess water has to be considered in the total amount of water needed for the hydration of the cement paste. In the same way, the water content present in the admixtures has to be taken into consideration in the computation of the w/c ratio. [4]

4.2 Rheology of cement paste

Rheology describes plastic deformation and flow of a material. The rheology of cement paste is an important property that determines the workability of concrete. The rheology can be mainly described by the plastic viscosity and the yield stress of the cement paste. Plastic viscosity defines how resistant the paste is to flow under external stress and therefore determines the speed of the flow and the size of the spread. The following figure (Fig. 4.1) presents the difference between the spread of high and low viscous material. The yield point determines the stress under which cement paste starts to move. [12]

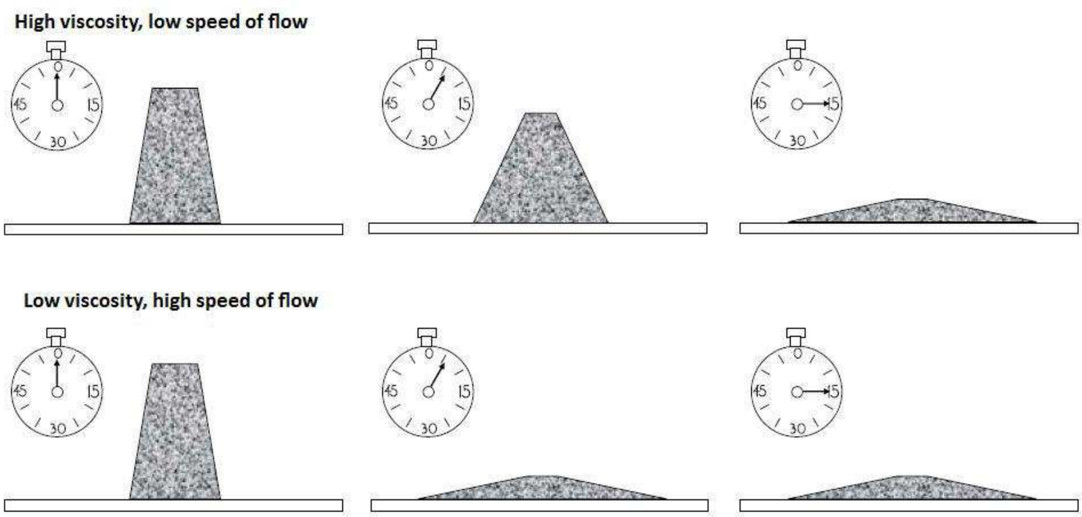

Figure 4.1: An example of flow with high and low viscosity [12]

Rheology can be described by means of fluidity of cement paste, which is tested by the spread test. The test of the rheology of the cement paste was performed using the spread cone. The laboratory work concerning rheology is described in section 5.2 .

4.3 Porosity

Porosity (P) is the ratio between the volume of pores in a material and the total volume of the material; it is usually expressed as a dimensionless fraction or in percent (Eq. (4.1)).

$$P = \frac{V_p}{V_{tot}} \tag{4.1}$$

Where:

V_p - the volume of pores,

V_{tot} - the total volume.

By the term ”pores” three different types of voids are defined, as there are three levels of porosity in concrete: coarse pores, capillary pores and gel pores. Figure 4.2 gives a schematic representation of this division.

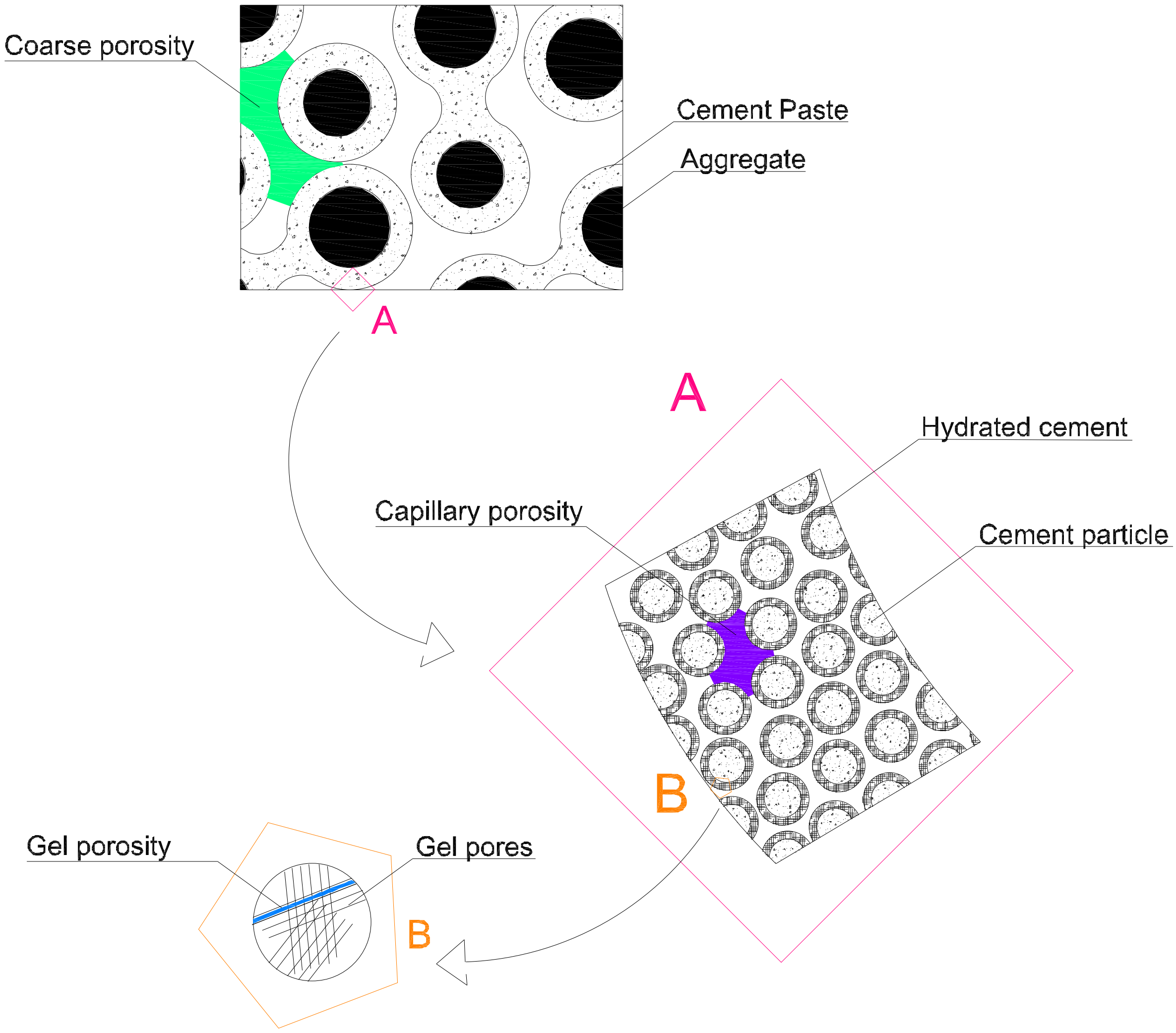

Figure 4.2: Schematic representation of the three degrees of porosity

Coarse pores, represented in green in the first scheme in Fig. 4.2, are the voids present between the aggregate particles covered with cement paste. They are the largest ones and, in the case of APC, they can be seen with the naked eye.

Capillary pores, represented in violet in the second scheme in Fig. 4.2, are the voids between the single particles of cement within the cement paste. Their size vary from 2 nm to 5 μm. They depend on the w/c and the degree of hydration. At any level of hydration, the total volume of cement paste which is not filled with the products of hydration, is represented by the capillary pores. Capillaries are filled with water or air. As the hydration proceeds, the volume of capillary water decreases and the volume of empty capillaries (filled with air) increases. [3]

Gel pores, represented in blue in the third scheme in Fig.4.2, are the pores present in the cement gel. The model of cement gel consists of randomly placed layers of particles, i.e. gel solids (C-S-H - calcium silicate hydrate) and physically bound water in between, i.e in the gel pores, which occupy 28 % of the total volume of the gel. Their size varies from 0.5 to 2 nm. [3]

Capillaries and gel pores of cement paste are called the intrinsic porosity of concrete. The intrinsic porosity is further explained in the following section (Sec. 4.3.1).

Porosity significantly influences the compressive strength of both cement paste and concrete. The relation between those parameters will be described in section 4.5.

4.3.1 Intrinsic porosity

As mentioned in the previous section, there are 3 types of pores in the structure of concrete: voids between the particles of aggregate, capillaries in cement paste and gel pores. Capillaries and gels pores of cement paste are defined as the intrinsic porosity of concrete. Because of the small size of those pores (2 nm - 5 μm - capillaries, 0.5 to 2 nm - gel pores), their contribution to overall porosity of concrete will be neglected in further calculation.

The amount of capillary and gel pores in cement paste can be read from Powers diagram. Powers diagram shows the relation between the volume fraction of each phase of cement paste (i.e. unhydrated cement, gel solids, gel water, capillary water and air filled pores) and the degree of hydration. An example of Powers diagram is presented in the Fig. 4.3.

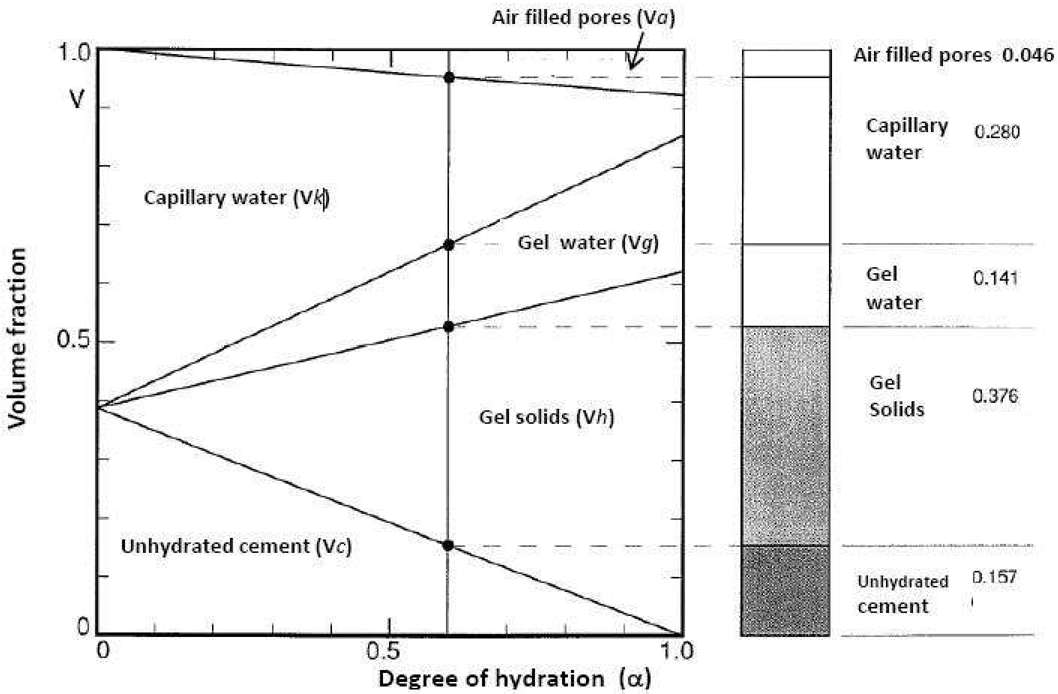

Figure 4.3: Example of Powers diagram [17]

To calculate the exact volume fraction of each phase at a certain stage of hydration, the following equations can be used [17]:

Air filled pores:

$$V_{air} = 0.2(1 - p) \cdot \alpha \tag{4.2}$$

Capillary water:

$$V_{cw} = p - 1.4(1 - p) \cdot \alpha \tag{4.3}$$

Gel water:

$$V_{gw} = 0.6(1 - p) \cdot \alpha \tag{4.4}$$

Gel solids:

$$V_g = 1.6(1 - p) \cdot \alpha \tag{4.5}$$

Unhydrated cement

$$V_c = (1 - p) \cdot \alpha \tag{4.6}$$

Where:
α - the degree of hydration,
p - initial porosity of the cement paste:

$$p = \frac{\frac{w}{c}}{\frac{1000}{3150} + \frac{w}{c}} \tag{4.7}$$

4.4 Degree of Filling

The degree of filling (DF) represents the amount of cement paste which fills the spaces between the aggregate particles. It is defined as the ratio between the volume of cement paste and the volume of voids in the aggregate (Eq. (4.9)). The latter is represented by the natural porosity of the aggregate (NP), which determines the amount of voids between the particles of aggregate (Eq. (4.8)). Further explanation of the natural porosity can be found in Sec. 5.3. [8]

$$NP = \frac{V_{voids}}{V_{tot}} \tag{4.8}$$

$$DF = \frac{V_{cement.paste}}{NP} \tag{4.9}$$

4.5 Compressive strength

4.5.1 Compressive strength of cement paste

The properties of cement paste have a strong effect on the quality and the parameters of concrete. Cement paste bonds together the aggregate particles, so in order to obtain a certain compressive strength of concrete, the "bonds" of cement paste (Fig. 4.4) must have an adequate strength.

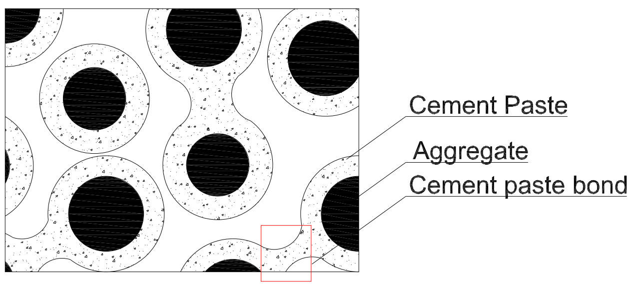

Figure 4.4: "Bonds" of cement paste in the model of concrete

The crucial factor influencing the strength of cement paste is the porosity. The relation between the porosity and the compressive strength is shown in Fig. 4.5.

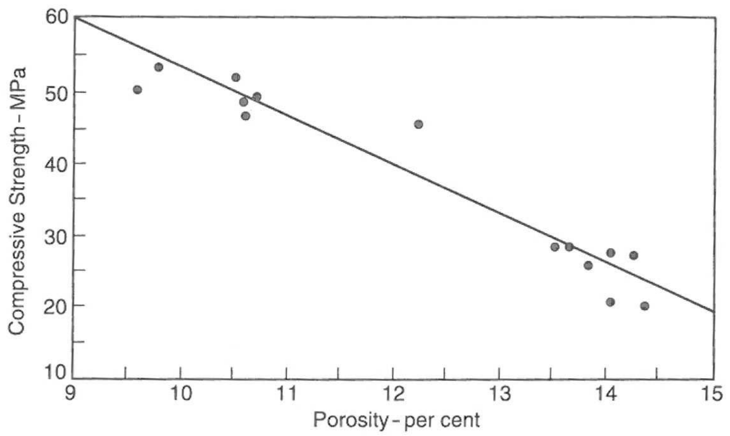

Figure 4.5: Relation between the compressive strength and the porosity of mortar, calculated from the volume of voids larger than 20 nm in diameter. [3]

The influence of pores smaller than 20 nm was found to be insignificant. It can be seen that the compressive strength of cement paste decreases with increase of porosity. However, not only the total porosity influences the compressive strength, but also the distribution of the pores in the structure of cement paste. At the same values of porosity, smaller pores contribute to higher compressive strength.

As mentioned before, porosity directly results from the water/cement (Sec. 4.3). Therefore, the compressive strength of cement paste depends on the water/cement ratio.

4.5.2 Compressive strength of concrete

The strength of concrete is usually considered to be its most important parameter. In practice, structural design requirements for concrete mix are primarily based on the strength of concrete, as well as on its class.

The strength of concrete is mainly regarded as the compressive strength, as the tensile strength is fairly low; it is typically measured 28 days after the concrete has been cast. In the load-bearing elements the tensile stress is carried by the steel reinforcement, whereas the compressive stress is carried by the concrete.

The compressive strength of concrete is influenced mostly by the w/c and the degree of compaction. In [3] the influence of air voids on the compressive strength is not considered on the stage of hardened concrete, as fully-compacted mix contains only 1% of air voids. However, since APC is highly porous (porosity reaching 38%), the volume of voids becomes a fundamental parameter influencing its strength. When considering the structure of concrete, the porosity will be treated as the amount of voids between the aggregate particles. Capillary and gel pores are the intrinsic porosity in the micro- and nano– scale. Therefore, in the further research their effect on the properties of concrete will be treated as negligible.

By using the following equation (Eq. (4.10)), the compressive strength of concrete can be calculated as a function of the porosity:

$$f_c = f_{c,0}(1-p)^n[3] \tag{4.10}$$

where:

- f_c is the compressive strength ;
- $f_{c,0}$ is the compressive strength of concrete with no porosity;
- p is the porosity of concrete;
- n is a coefficient.

The compressive strength of APC varies significantly with the degree of filling. Because the degree of filling determines the amount of cement paste surrounding the aggregate particles, the clear conclusion can be drawn that the more cement paste is present in the structure, the stronger is the concrete. Thus, the higher the degree of filling, the higher the compressive strength. The results presented in [8] (Fig. 2.1) confirm that the compressive strength depends on the degree of filling.

4.6 Permeability

Permeability determines the flow of the fluid through a material under a pressure differential. Permeability is thus a parameter that gives a measure on how the material is permeable to a gas or a liquid. [3] The medium taken into consideration for this specific study is air.

Permeability is directly related to porosity. To ensure high permeability, not only the high porosity is necessary, but also the interconnectivity of the channels, to enable the transport of air through the concrete. If the voids are discontinuous, the permeability is low, even if values of porosity are high. However, it should be emphasized that the permeability of ordinary concrete and cement paste is much lower than the permeability of APC and therefore it does not play a significant role among other parameters of ordinary concrete.

The results of the test of the permeability of APC, made be Imbabi et al. [7] vary from 0.18 to 0.60 $m^2/Pa{\cdot}h$. The permeability of APC is thus about 24 times higher than in the case of traditional concrete [21]. Furthermore, following the results obtained by Imbabi et al. [8], it can be seen that the permeability is significantly affected by the degree of filling. With constant increase of the degree of filling, the permeability decreases severely. For example, with the lowest DF=0.5 permeability equals 0.60 $m^2/Pa \cdot h$, whereas with DF=0.7, permeability is much lower, i.e 0.18 $m^2/Pa \cdot h$. However, the permeability does not seem to be sensitive to the changes of w/c ratio, as its values are the same with the same DF but different w/c.

High values of permeability are desired in the case of APC. High permeability is a key parameter of the concept of dynamic insulation, which assumes heat exchange, ventilation and filtration through a wall made of APC, as described in the State of the art (Sec. 2.2).

4.7 Thermal Conductivity

The main parameter determining thermal properties of concrete is the static thermal conductivity λ. The importance of the thermal conductivity results from the fact that in service concrete provides a layer of thermal insulation which contributes to the overall thermal properties of the building envelope. Since concrete is a heterogeneous material, its thermal conductivity depends on the thermal conduction properties of its components and the volume fraction of each of the components, i.e. cement paste, aggregate and voids (air content).

Physically, the thermal conductivity defines the ability of the material to conduct heat and it is measured in Watts per Kelvin-meter. Thermal conductivity represents the quantity of heat flux that flows through unit area of a material plate of unit thickness in unit time, when the temperature difference of its opposite faces is 1 Kelvin. Generally, thermal conductivity depends on the density of the material and its porosity. High-density materials, e.g. steel, have high thermal conductivity, whereas low-density, porous materials (since air is a poor conductor), e.g. mineral wool, have low thermal conductivity and are thus used as insulators. In the following table examples of thermal conductivity of various materials is presented (Tab. 4.1). [3]

Table 4.1: Thermal conductivities of different materials [15]

Material	**Thermal conductivity** $\lambda[W/m \cdot K]$
Steel	58
Mineral wool	0.037
Conventional concrete	1.7
Air	0.025
Water	0.58

The research made by Imbabi et al. [8] focuses on the evaluation of effective thermal conductivity, as it is a crucial parameter for predicting the dynamic U-factor. As described in previous section 2.4, a certain model of heat flow in APC was created by combining two models of the arrangement of the material components, parallel and serial (Fig. 4.6). [8]

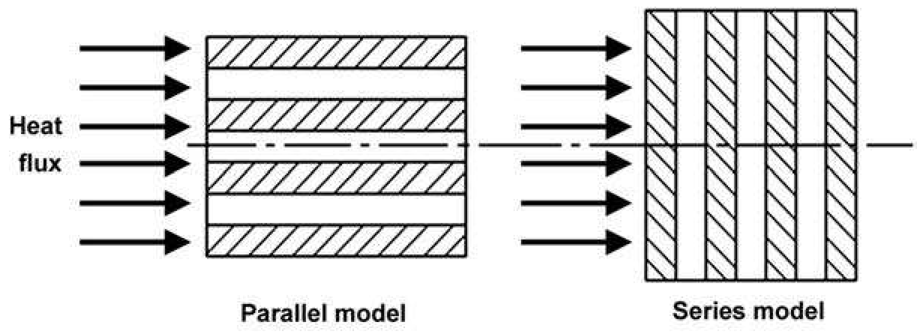

Figure 4.6: Parallel and series arrangement of a multiphase material. [8]

The results obtained by Imbabi et al. (Fig. 2.7, Sec. 2.5) indicate that indeed APC has lower values of thermal conductivity and that the values of the thermal conductivity depend on water/cement ratio (decrease of λ with the increase of w/c) and the degree of filling (increase of λ with the increse of DF).

Another parameter used to determine the thermal properties of the building envelope is the dynamic U-factor, also called overall heat transfer coefficient. The U-factor represents the heat flux which is transferred through a barrier per 1 K per unit area of the barrier (building envelope) in $W/m^2 \cdot K$, and can be predicted if the thermal conductivity is known. While the thermal conductivity is a characteristic of a material, the heat transfer coefficient refers to a particular barrier, such as a wall or a window. [8]

Despite the importance of the thermal parameters of APC such as thermal conductivity and dynamic U-factor, those properties will not be considered further on the report. Instead, the main focus of the report is manipulation of the mix design of APC in order to obtain sufficient porosity, permeability and compressive strength.

Chapter 5

Experimental work

In the following chapter the experimental work that has been done will be described. The materials used, the tests concerning the rheology of the cement paste, natural porosity of the aggregate as well as mixing, casting and curing procedures of concrete will be presented together with the description of equipment used in the laboratory. The tests were performed in the concrete laboratory at Aalborg University [1].

Different combinations of mix design were used and different combinations of the parameters (such as w/c, DF and amount of SPA and PCM) were considered. The parameters were chosen partly following the recommendations given by Imbabi et al. [8] and partly were based on the tests of rheology of cement paste and therefore the workability of concrete, performed during laboratory work, described in section 5.2. The amount of PCM was chosen following the recommendation of [19]. Further explanation concerning this issue is presented in Sec. 5.2.2.

[1] AAU, Institut for Byggeri og Anlæg, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

5.1 Materials

The following materials were used:

5.1.1 Cement

Rapid Aalborg Cement CEM I 52.5 N ($MS/LA/ \leq 2$). For Technical Data Sheet see the Appendix.

5.1.2 Water

Regular water for mixing of concrete and deaerated water for measuring the porosity.

5.1.3 Admixtures

Superplasticizer: Glenium Sky 680, BASF Construction Chemicals Denmark A/S. For Technical Data Sheet see the Appendix.
Viscosity Modifying Admixture: Rheomatrix 101, BASF Construction Chemicals Denmark A/S. For Technical Data Sheet see the Appendix.

5.1.4 Aggregate

Dansand A/S, Dansand nr. 6, 2-3.55 mm filter sand.

5.1.5 Phase Change Material

Micronal* DS 5039 X, BASF Construction Chemicals Denmark A/S. For Technical Data Sheet see the Appendix.

5.2 Rheology of cement paste

In order to find the most suitable mix design for APC, a study of the rheology of the cement paste was performed. The test was based on various w/c ratios and various amount of SPA.

The test set up consists of a spread cone (Fig. 5.1) which can contain a defined volume of cement paste. The measurements were done recording the diameter of the spread after 3 sec and at the complete stop of cement paste.

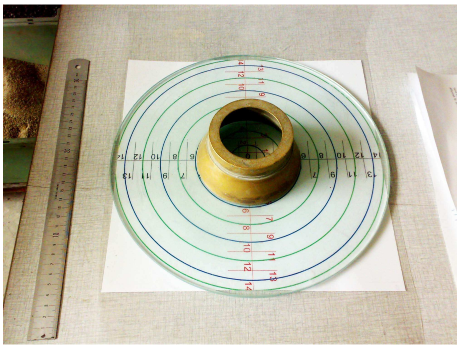

Figure 5.1: Spread cone

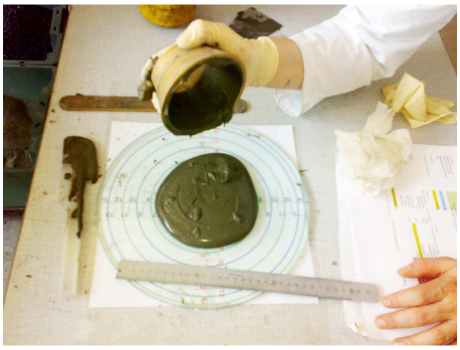

Figure 5.2: Spread cone test

Table 5.1 shows the results of the spread test done considering values of SPA of 0.5%, 1%,1.5% and 2% by cement mass and w/c ratio of 0.25, 0.30, 0.35. The designation used in the table is as following:

- m_c - mass of cement
- m_{SPA} - mass of superplasticizer
- m_{H_2O} - mass of water
- $3s$ - spread after 3 seconds
- *Stop* - spread at stop

Since the spread cone has the diameter of 100 mm, the spread of cement paste of 100 mm indicates no fluidity.

w/c	**SPA%**	$\mathbf{m}_c$ **[kg]**	$\mathbf{m}_{SPA}$ **[kg]**	$\mathbf{m}_{H_2O}$**[kg]**	**3s [mm]**	**Stop [mm]**
0.25	0.5	0.5	0.0025	0.1231	-	-
	1	0.5	0.005	0.1211	-	-
	1.5	0.5	0.0075	0.1192	112	112
	2	0.5	0.01	0.1173	140	156
w/c	**SPA%**	$\mathbf{m}_c$ **[kg]**	$\mathbf{m}_{SPA}$ **[kg]**	$\mathbf{m}_{H_2O}$**[kg]**	**3s [mm]**	**Stop [mm]**
0.30	0.5	0.5	0.0025	0.1481	112	112
	1	0.5	0.005	0.1461	150	160
	1.5	0.5	0.0075	0.1442	220	250
	2	0.5	0.01	0.1423	230	270
w/c	**SPA%**	$\mathbf{m}_c$ **[kg]**	$\mathbf{m}_{SPA}$ **[kg]**	$\mathbf{m}_{H_2O}$**[kg]**	**3s [mm]**	**Stop [mm]**
0.35	0.5	0.5	0.0025	0.1731	170	176
	1	0.5	0.005	0.1711	280	300
	1.5	0.5	0.0075	0.1692	300	400
	2	0.5	0.01	0.1673	320	400

Table 5.1: Mix design varying the w/c ratio and the amount of SPA

As depicted in Table 5.1, w/c of 0.25 with SPA content of 0.5 and 1 % could not be tested because the cement paste resulted to be impossible to work with (it was almost completely dry). For that reason w/c of 0.25 was not taken into consideration.

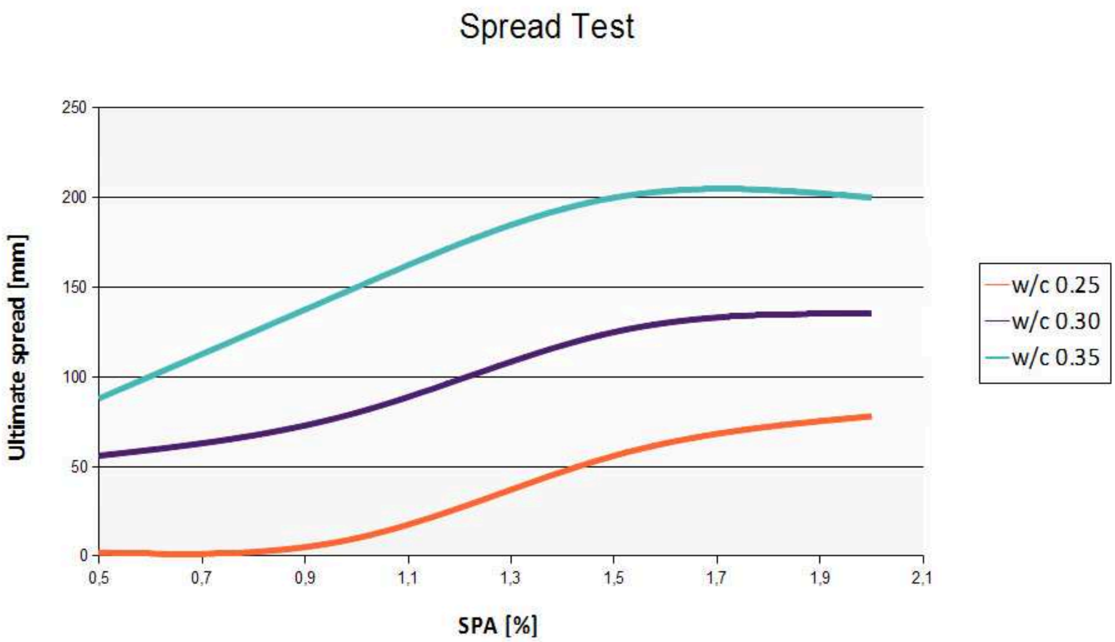

Figure 5.3: Spread test 'at stop'

Figure 5.3 shows that the curve relating the amount of SPA to the spread of cement paste rises steeply between 0.5 % and 1.5% of SPA and has an asymptotic behaviour for percentage higher than 2 (the limit value recommended by the producer). Indeed, using values of SPA higher than 2% would mean adding basically more water to the paste and having almost no SPA influence.

5.2.1 Viscosity Modifying Admixture

In order to test the flow of the cement paste with the Viscosity Modifying Admixture and study its influence on the rheology of cement paste, the RheoMATRIX BASF was added to the mix.

The aim of adding Viscosity Modifying Admixtures (VMA) is to control the rheology of the cement paste. The rheology of the cement paste was described in section 4.2. To obtain the proper rheology of the concrete, the balance between the plastic viscosity and the yield point has to be kept. The VMA increases the plastic viscosity of the mix and slightly decreases the yield point. To optimize the value of the yielding point, plasticizers are added. The effects of adding the VMA are e.g. the reduction of segregation of the particles in highly fluid concrete and reduction of the washout in the underwater concrete.[12]

According to the producer, RheoMATRIX ensures the homogenity of the mix, the balance between fluidity, workability and resistance to segregation and minimizes the necessary content of fine particles in the mix design.[13]

To observe the effects of RheoMATRIX (RM) on the rheology of the cement paste the most fluid mix was chosen to be modified in the laboratory. The results of the test are presented in the following table (Tab. 5.2):

Table 5.2: Comparison between the spread of cement paste with and without RheoMATRIX

w/c	**SPA [%]**	**RM [%]**	**Spread 1 [cm]**	**Spread 2 [cm]**
0.35	1.5	1	40	14
0.35	2	1.5	40	22

Where:

Spread 1 - the diameter of spread with SPA only

Spread 2 - the diameter of spread with SPA and RM

It can be seen that RheoMARTIX reduces the fluidity of cement paste significantly and thus can be used to modify the rheology of cement paste when necessary. However, since the test was made for the sake of completeness, it will not be considered in the following studies.

5.2.2 Viscosity adding PCM

The PCM used for the tests was $Micronal^{*}DS5039X$, produced by BASF [2]. Micronal is an aqueous dispersion containing microencapsulated spheres of wax covered with a layer of polymer. The content of solids varies from 41% to 43%. To have more precise results the percentage of solid content was determined experimentally and resulted to be 43%.

The first step to be done is to study the influence of the PCM on the rheology of the cement paste. For this purpose it has been decided to consider a fixed value of w/c and amount of SPA and vary the percentage of PCM. The recipe adopted for the experiment (see table 5.1 for details), is the one corresponding to a w/c of 0.35 and SPA=2%.

Figure 5.4 shows the results obtained by adding different contents of PCM to the cement paste. The first experimental point on the left of the graph corresponds to the unmodified cement paste (value showed in table 5.1) to be read as a reference point. While moving to the right it is noticeable that the higher the dosage of PCM the lower the value of the spread. Thus, the PCM has an evident influence on the rheology of the

[2]BASF SE Regional Business Unit Dispersions for Adhesives & Construction Europe, 67056 Ludwigshafen, Germany.

cement paste.

In this specific case adding the PCM to "too fluid" cement paste of the high w/c and the high content of SPA would have the effect of bringing the cement paste to lower values of spread and therefore lower fluidity.

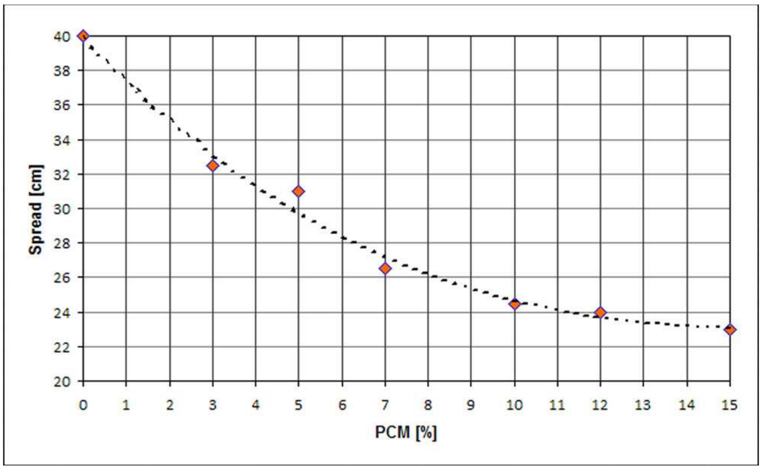

Figure 5.4: Workability of cement paste as a function of percentage of PCM

It can be concluded that to be able to work with PCM a high fluidity of the cement paste must be reached. The next step will be to add the aggregate to the cement paste and to analyse the samples of APC with PCM.

5.3 Natural Porosity of aggregate

Natural Porosity (NP) of the aggregate (also named as bulk density by [3]) determines the amount of voids between the particles of aggregate. It should not be confused with the intrinsic porosity which comprises the internal pores up to ones in nano-scale. Natural Porosity depends on how much space is left between solid particles and thus how densely the aggregate is packed. Therefore, NP depends on the size distribution and the angularity and shape of particles. For aggregate with wide scope of grading (e.g. 2 - 16 mm), fine aggregate fills the spaces between coarse aggregate and therefore NP is low. Reversely, for narrow size fraction (like the one used in the tests) NP is high, as there are no smaller particles that can fill spaces between larger particles.

Natural porosity of aggregate is an important parameter to be calculated as later it will be used to model the theoretical porosity of Air Permeable Concrete.

Measurement and calculation of Natural Porosity

To measure Natural Porosity, a glass cylinder of 2 litres was filled with aggregate and tapped slightly to ensure proper filling of the glass with the stones. Then the mass of the aggregate was measured (m_a). Then the cylinder was filled with water to the level of aggregate and the mass was measured (m_{aw}). The volume of water (V_w) which filled the voids of aggregate was compared to the total volume of aggregate ($V_a = 2litres$) and the natural porosity was calculated:

$$m_w = m_{aw} - m_a \tag{5.1}$$

$$V_w = \frac{m_w}{\rho_w} \tag{5.2}$$

$$NP = \left(\frac{V_w}{V_a}\right) \cdot 100\% \tag{5.3}$$

The density of aggregate ρ_a was calculated:

$$\rho_a = \frac{m_a}{V_a} \tag{5.4}$$

The results of calculations are as following:

NP=0.406

$\rho_a = 1490\frac{kg}{m^3}$

The results will be used for further calculations.

5.4 Concrete mix designs

The mix designs of APC chosen by following the recommendations by [8] and the results of tests concerning the rheology of cement paste with and without PCM, are presented in the following table (Tab. 5.3). The amount of SPA and PCM is expressed in percentage of the mass of cement.

case No.	w/c	DF	SPA [%]	PCM [%]
1	0.30	0.4	2	12
2	0.30	0.5	2	12
3	0.30	0.6	2	12
4	0.35	0.4	2	12
5	0.35	0.5	2	12
6	0.35	0.6	2	12

Table 5.3: Mix design of APC

5.5 Concrete production procedure

The first step that has been taken to ensure the reproducibility of the specimens and the homogeneity of the concrete was to define a standard and reliable mixing and casting procedure. A uniform method, applied during all tests, was essential to obtain comparable results of the tests.

5.5.1 Mixing procedure

Two different mixers were used for mixing the concrete. The mixer used for mixing first specimens turned out to be too small for mixing big portions of concrete (16 litres). Thus it was decided to used the bigger mixer, and in cases of small portions - the small mixer. Only the first mixer is equipped with a timer, in the case of the second mixer the time of mixing was measured manually. The following figure presents the mixers used (Fig. 5.5):

Figure 5.5: Mixer 1 (top), 2 (bottom)

The mixing procedure that has been applied consisted of the following steps:

1. Place the aggregate with the water required for the saturation in the mixer and mix for 2 minutes;

2. Add cement together with the water and the PCM and mix for 10 minutes;

3. Add the SPA and mix the concrete for 10 minutes;

The first step of adding the water to the aggregate is to obtain saturated and surface-dry state of the particles. It means that the intrinsic pores of the aggregate are saturated with water, but their surface is kept dry. This prevents the aggregate to absorb the water needed for the hydration of the cement paste and thus to cause decrease of the desired w/c. The amount of water needed for the saturation was assumed to be 0.4% of the weight of the aggregate, following the recommendation of [18]. Two minutes of mixing the aggregate with water were assumed to be sufficient to ensure proper saturation.

The figure below shows the fresh concrete obtained after mixing (Fig. 5.6).

Figure 5.6: Fresh concrete

5.5.2 Casting procedure

The mould used for casting the specimens are cylinders of the size of 100 mm in diameter and 200 mm in height. The moulds were properly prepared before casting, i.e. cleaned and greased to avoid blockage of the cement while casting. The used set of moulds with lids and clamps is shown in figure 5.7.

Figure 5.7: Moulds 100 x 200 mm

Once the concrete is ready to be cast the following procedure was adopted:

1. Fill in the moulds up to 4/5 of the height of the mould;
2. Vibrate the moulds for 15 seconds at 50 Hz;
3. Refill the moulds with concrete, apply a steel counterweight (3.6 kg) on top of the concrete and vibrate for 15 seconds at 50 Hz;
4. Fill the mould for the last time and seal the moulds with the lid ensuring that the lid adheres smoothly to the mould and that there is no space left between the lid and the edge of the mould;
5. Close the mould with the clamp.

The vibration of concrete is important to ensure that the concrete is properly compacted and fills in the mould. The time and the frequency of vibration was a study of [18] and was chosen following the recommendation by [18]. This issue was not considered as a part of this study as the chosen parameters of vibration performed properly.

The vibration was done on the vibration table and the moulds were bolted to the table during the vibration (Fig. 5.8).

Figure 5.8: Vibration table with moulds bolted on it

A significant compaction of concrete was noticed. The comparison of the state before and after vibration is shown in Figure 5.9: the level of the mould's filling decreased.

Figure 5.9: Mould with concrete before and after the first vibration

The step of placing a counterweight on top of concrete during the second vibration is made to avoid density differences between the top and the bottom of the sample. Because of the self-weight of the concrete, the bottom layer may have larger density that the top one. To avoid this situation and to balance the densities between the bottom and top layers, a steel cylinder of 3.6 kg (Fig. 5.10) is put on the top of concrete and the sample is vibrated. Thus, both layers (bottom and top) result being vibrated under weight.

Figure 5.10: A mould with steel cylinder counterweight on the top

Once the mould is filled and vibrated, it is closed and thus ready for the curing procedure. A ready mould is shown in the following figure (Fig. 5.11).

Figure 5.11: Clamping the mould

5.5.3 Curing procedure

After casting, the following steps are followed in order to cure the concrete:

1. Store the concrete for 24h at 20 °C;

2. Open the moulds and store the specimens in plastic bags at 20 °C.

The concrete is cured in plastic bags in order to avoid water losses and therefore prevent shortage of water needed for the hydration of the cement.

Chapter 6

Experimental work issues

Experimental work is often a challenge both in terms of the results obtained, in comparison with the expected ones, and in terms of the issues that could occur during performing the experiments.

6.1 Aggregates

Generally issues were discovered at the beginning of the tests and therefore solved during laboratory work whereas some others are not: the latter case is what is going to be discussed in this section.

The mixers used for mixing the concrete, described in section 5.5.1, are of two kinds. The smaller one (Fig. 6.1) has been the one used the most and it is similar to those made for bakeries thus the blade is very close to the surface of the bowl during mixing. Since the amount of litres of cement paste made for each casting was not large, it has been decided that the smaller mixer was appropriate for mixing the concrete.

Figure 6.1: Small mixer

However, after having cast all the specimens needed for this study, some fine sand found on the bottom of the bowl created some doubts about the suitability of this mixer. For this reason a test of mixing pure aggregate was performed. Then it was examined if any change of the volume of the aggregates occurred.

The result of the test showed that after 10 minutes of mixing the volume of the aggregates decreased. As expected, larger stones were crushed and filled the spaced between the particles. Therefore the volume of sand and the size of the particles was changed. Yet, the most evident result could be seen with the naked eye: Fig. 6.2 shows some of the sand before the mixing whereas Fig. 6.3 shows the sand after the mixing. It is evident that the mixer crushes the aggregates and creates fine sand.

Figure 6.2: Aggregate before the mixing

Figure 6.3: Aggregates after the mixing

This problem might have affected the compressive strength, the porosity and the permeability. The compressive strength might be increased since fine sand would improve the connections between the aggregates and also increase the number of bonds. However, this statement is only a hypothesis and in the later study the analysis of the compressive strength of specimens made with normal and crushed aggregates will be made and the conclusion will be drawn (Sec. 7.3.4). On the other hand, porosity and permeability might give lower results since the fine sand would obstruct the pores. While the results of the compressive strength probably overestimate the real values which would be obtained using a proper mixer, the porosity and permeability are on the conservative side, and therefore can be considered reliable.

To have a better estimation on how much the mixing actually changes the granulometry of the aggregates the Natural Porosity was calculated and a sieve test and sieve analysis have been done.

6.1.1 Natural Porosity

The calculation of the Natural Porosity of the crushed aggregates was done using the same method as described in Sec. 5.3. Before the measurement the aggregates were mixed in the mixer for 10 min.

As expected, the presence of the small particles affected the Natural Porosity NP and the density ρ of the aggregates after the mixing. The results of the tests are presented in the following table (Tab. 6.1.1):

Aggregate	NP	$\rho[kg/m^3]$
before mixing	0.406	1490
after mixing	0.358	1523

Table 6.1: Natural Porosity and density of the aggregates before and after mixing

A noticeable decrease in the natural porosity can be seen. It can be explained by the fact that small particles, which are created during mixing and thus crushing the aggregates, fill the pores between larger particles. The whole structure of the aggregate becomes more compact and therefore the increase in density is noticed.

6.1.2 Sieve test

The test has been done by following this procedure:

- prepare the concrete and mix it following the same procedure used for casting the specimens;
- wash the concrete using a sieve of size 0.063 mm in order to separate the aggregates from the cement and SPA (Fig. 6.4);
- dry the aggregates at 105°C until they reach a bone dry condition (when the change in weight between two measurements is less than 0.1 %);
- weigh a certain amount of aggregates (c.a. 150 gr) and put them in the sieve set;
- put the set of sieves in the vibrating machine and vibrate for 20 min (Fig. 6.5);
- once the vibrating is done, separate the sieves and weight the content of aggregates present in each of the sieves;
- analyse the results and plot an aggregate size distribution curve.

Figure 6.4: Washing the aggregates in a fine matrix sieve after the mixing

Figure 6.5: Set of sieves in the vibrating machine

The same procedure has been applied to the 'raw aggregates' (condition before mixing) in order to compare the size distribution of the two sets of aggregates.

6.1.3 Sieve test result

The sieve test result, done on the aggregates before and after the mixing, has reported the expected behaviour: the aggregates have been highly crushed during the mixing. As can be seen from Figure 6.6, the aggregates have now a large size distribution, much larger than the original one (2 - 3.55 mm).

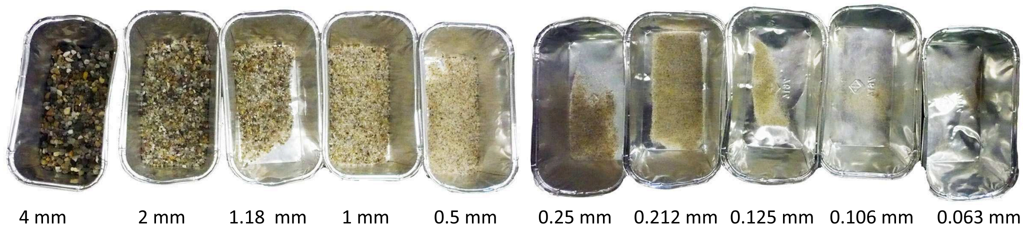

Figure 6.6: Aggregates after the mixing

In the following table reports the values of the sieve test. A plot of these results is given in Figure 6.7.

Sieve size [mm]	**Passing Agg**$_{mixed}$	**Passing Agg**$_{normal}$
4	100.000%	98.755 %
2	59.628 %	13.060 %
1.18	28.092 %	1.099 %
1	22.235 %	0.633 %
0.5	9.162 %	0.073 %
0.25	2.679 %	0.040 %
0.212	1.959 %	0.000 %
0.125	0.213 %	0.000 %
0.106	0.053 %	0.000 %
0.063	0.033 %	0.000 %

Table 6.2: Test results of sieve analysis

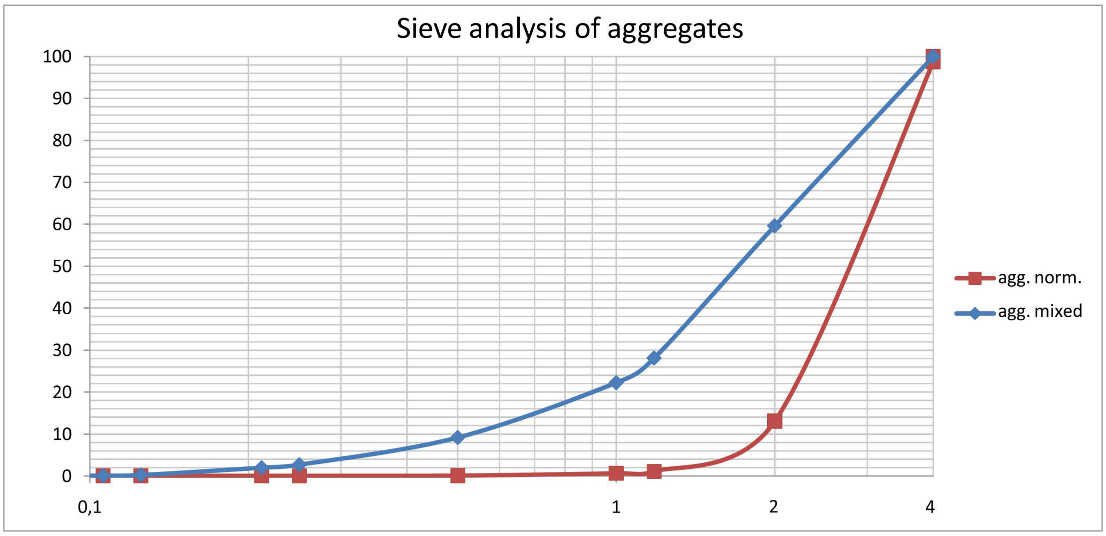

Figure 6.7: Aggregates after the mixing

From the graph (Fig. 6.7) it can be seen that the shape of the curves vary significantly and therefore the size distribution of the aggregates is changed. This issue certainly had a negative impact on the assumptions made for creating mix designs and the results of performed tests. However, it should be emphasized that the awareness of the existence of such a problem is equally important.

Chapter 7

Measurements of parameters of APC

In the following chapter the methods and procedures of measurements of parameters of APC will be presented. The tests performed on the specimens concerned:

- porosity;
- ultrasound pulse velocity;
- permeability;
- compressive strength.

7.1 Porosity of concrete

The porosity of concrete is described in section 4.3.

The hardened concrete has the form presented in Fig. 7.1. While observing the sample with the naked eye, high porosity can be noticed.

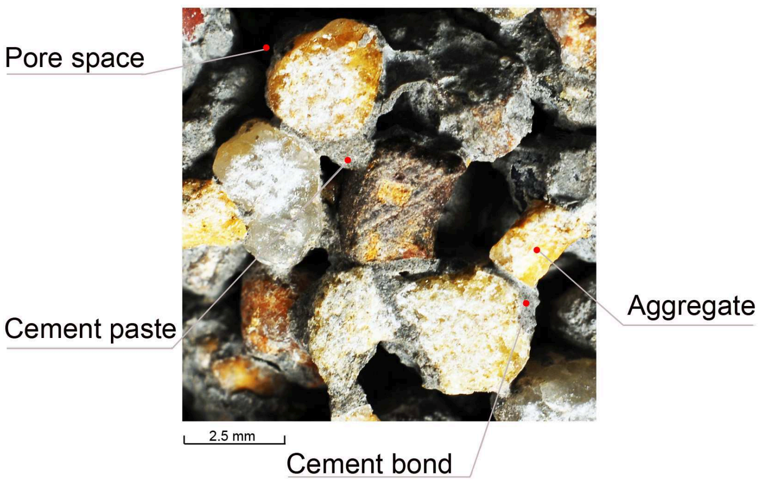

Figure 7.1: Piece of ready specimen

In this section the method of measuring the porosity of APC samples together with the results of the measurement will be presented. At this stage of the study capillary pores and gel pores representing the intrinsic porosity will be neglected.

7.1.1 Measurement set-up

The porosity of the samples has been measured performing the following steps:

1) Drying the specimen in the oven at 105°C. The specimen has been weighed before and during the drying process until the difference in weight between two measurements was $\leq 0.1\%$ per hour;

2) Placing the dry specimen in the desiccator (Fig. 7.3) and with a vacuum pump (Fig. 7.2) extract the air and therefore reduce the pressure by 98-99%. In such a way it is ensured that all the air inside the specimen is sucked out and all the voids are air-free. This will guarantee that once water will be introduced in the desiccator all the voids will be filled with water and there will be no air stuck inside the specimen.

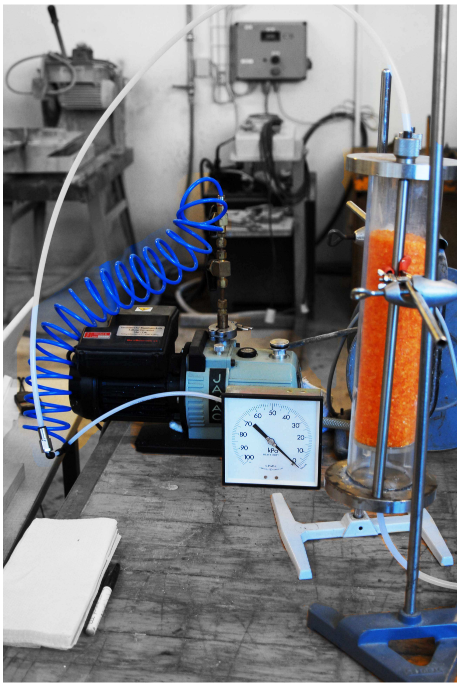

Figure 7.2: Vacuum pump set-up

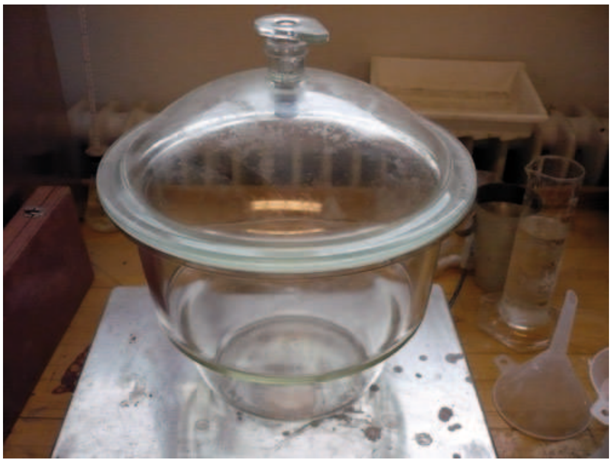

Figure 7.3: Desiccator

3) Introducing de-aerated water being careful not to release the vacuum inside in the desiccator. In this manner the water will be absorbed by the specimen and will fill in all the air voids.

4) Once the water covers the whole specimen the desiccator can be opened and the room pressure is re-established.

5) Weighing the specimen submerged in water so that it is still saturated in water.

6) By computing the mass difference between dry and submerged specimen, due to the Archimedes' principle, the porosity is calculated directly. The calculation is presented in the following section (Sec. 7.1.2). To ensure the validity of this method the porosity has also been determined in another manner using a pycnometer. This has been done by calculating the volume of water filling in the voids, the result obtained was confirming the validity of the first method (the two results differed only by 0.16 %).

7.1.2 Experimental results

The measurement of porosity was performed at all cast recipes (1-6) on entire cylinders. Specimen of recipe 1 was later cut into five smaller sections (where section A is the top one and section E is the bottom one) and the porosity was measured also on those sections. Evaluating the values of porosity for smaller sections is a means of checking whether the aggregate distribution is homogeneous and the voids are equally distributed.

Calculation of the results

Porosity is the ratio between volume of voids V_v and the total volume of the specimen V_{tot}:

$$porosity = \frac{V_v}{V_{tot}}$$

The volume of voids equals the total volume minus volume occupied by solids V_s:

$$V_v = V_{tot} - V_s$$

Volume of solids, according to Archimedes law, is the difference between the mass of dry (m_{dry}) and submerged (m_{wet}) specimen, divided by water density ρ_w:

$$V_s = \frac{m_{dry} - m_{wet}}{\rho_w}$$

V_{tot} was calculated from the exterior dimensions of the specimen.

Following given formulas, the porosity was calculated and the results are presented in the following table.

case	w/c	DF	PCM [%]	m_{dry} [g]	m_{wet} [g]	Porosity [-]
1	0.30	0.4	2	2749.40	1703.60	0.33
2	0.30	0.5	2	2901.51	1786.66	0.29
3	0.30	0.6	2	2878.00	1772.15	0.30
4	0.35	0.4	2	2775.76	1720.22	0.33
5	0.35	0.5	2	2827.48	1744.41	0.31
6	0.35	0.6	2	2964.40	1819.58	0.27

Table 7.1: Measured porosity of cases 1-6

The results of measured porosity of a cut specimen of case 4 are presented in the following table (Tab. 7.2):

Case	m_{dry} [g]	m_{wet} [g]	Porosity [-]
A	550.95	339.88	0.33
B	510.95	315.35	0.38
C	495.83	306.14	0.40
D	482.33	298.11	0.41
E	498.41	301.44	0.39
Entire	2744.87	1720.22	0.33

Table 7.2: Measured porosity of sections of the specimen of recipe 4; A - top, E - bottom of the specimen

It has been noticed that except for the top section, the results for the sections are higher than the result for the entire specimen. It might be caused by the fact that during casting the specimens the top layer of the specimen has been precisely filled with fresh concrete in order to adjust the lid to the mould accurately. Thus, the potential voids have been clogged with paste. On the other hand, the sections B, C, D have larger values of porosity, probably due to the fact that while cutting the specimen, their top and bottom surfaces were "opened" and this might have increased the porosity of those sections. Nevertheless, the porosity seems rather uniform and the conclusion can be made that the specimen is homogeneous, except for the top part.

7.1.3 Theoretical results

Theoretical porosity was calculated for cases 1 - 6 to compare it with the laboratory results. Taking into consideration that porosity is the ratio between the volume of voids in the concrete to the total volume of the specimen, the following procedure was applied:

$$p = \frac{V_{ac}}{V_{tot}} \tag{7.1}$$

where:

p - porosity of the specimen, [-]

V_{ac} - volume of the voids in concrete specimen

V_{tot} - volume of the specimen, equal to the bulk volume of the aggregate

The volume of voids is the volume of air in the aggregate $V_{a.agg}$ reduced by the volume occupied by cement paste V_{cp} (Eq. (7.2)).

$$V_{ac} = V_{a.agg} - V_{cp} \tag{7.2}$$

V_{cp} - volume of cement paste

$$V_{cp} = \frac{m_c}{\rho_c} + \frac{m_w}{\rho_w} + \frac{m_{SPA}}{\rho_{SPA}} \tag{7.3}$$

m_c, m_w, m_{SPA} - mass of cement, water and superplasticizer, respectively

$\rho_c, \rho_w, \rho_{SPA}$ - density of cement, water and superplasticizer, respectively

Knowing that

$V_{tot} = V_{a.agg} + V_s$

$V_{a.agg}$ - volume of voids in bulk aggregate,
V_s - volume of solid particles in aggregate,

from the definition of natural porosity of aggregate NP:

$$V_{a.agg} = NP \cdot V_{tot} \tag{7.4}$$

$$V_s = (1 - NP) \cdot V_{tot} \Rightarrow V_{tot} = \frac{V_s}{1 - NP} \tag{7.5}$$

$$V_s = \frac{m_s}{\rho_s} \tag{7.6}$$

m_s - mass of solid particles, equals to the mass of aggregate used
ρ_s - density of solid particles

The combination of presented equations results in the following equation for calculating the porosity of concrete (Eq. (7.7)):

$$p = \frac{V_{ac}}{V_{tot}} = \frac{\dfrac{\left(\dfrac{m_s}{\rho_s}\right)}{1 - NP} \cdot NP - \left(\dfrac{m_c}{\rho_c} + \dfrac{m_w}{\rho_w} + \dfrac{m_{SPA}}{\rho_{SPA}}\right)}{\dfrac{\left(\dfrac{m_s}{\rho_s}\right)}{1 - NP}} \tag{7.7}$$

The results of the calculation of theoretical porosity will be presented in the following section.

7.1.4 Comparison of experimental and theoretical results

The experimental and theoretical porosity have been computed and compared. The results are reported in the following table (Tab. 7.3).

Case	w/c	DF	Experimental [-]	Theoretical [-]
1	0.30	0.4	0.33	0.32
2	0.30	0.5	0.29	0.31
3	0.30	0.6	0.30	0.29
4	0.35	0.4	0.33	0.33
5	0.35	0.5	0.31	0.31
6	0.35	0.6	0.27	0.28

Table 7.3: Comparison of experimental and theoretical porosity

The results of experimental measurements and theoretical calculations do not indicate any significant discrepancy. Therefore, the applied test method was correct and accurate.

To support the results of the measurement of the porosity, the comparison of experimental and theoretical values of concrete density was performed. The calculation of the experimental density ρ_{lab} was done using the formula (Eq. (7.8)):

$$\rho_{lab} = \frac{m_{dry}}{V} \tag{7.8}$$

Where:

- m_{dry} - the mass of the dried specimen;

- V - the volume of the specimen, calculated from external dimensions.

The theoretical values were taken from the mix designs.

In the following table the values of theoretical ρ_t and experimental ρ_{lab} densities are presented (Tab. 7.4):

Case	w/c	DF	$\rho_{lab}[kg/m^3]$	$\rho_t[kg/m^3]$
1	0.30	0.4	1750	1745
2	0.30	0.5	1847	1816
3	0.30	0.6	1832	1886
4	0.35	0.4	1767	1739
5	0.35	0.5	1800	1807
6	0.35	0.6	1887	1876

Table 7.4: Comparison of experimental and theoretical density

It can be seen that results are consistent and do not vary significantly. It supports the uniform values of experimental and theoretical porosity and indicates that the amount of closed pores is negligible.

7.2 Permeability

High permeability is a desired parameter of APC, as the idea of breathable concrete is basically based on the permeation of air through the interconnected channels of the concrete structure. Furthermore, since the permeability of traditional concrete is negligible, the challenge of not only obtaining high permeability, but also measuring it by a reliable method was faced during the research.

The subject of measurement of permeability of APC was extensively developed in [21]. The set-up made by Daniels and Norgaard [21] was used and the method of measurement and calculation of the permeability were adopted, following the guidance by [18]. In this section the equipment of the set-up and the method of the measurement will be described as well as the results of the tests.

7.2.1 Measurement method and set-up

According to the definition, permeability is a measure of the flow of a fluid through a material. Thus, to measure permeability two basic parameters need to be tested: an air flow and a pressure drop over which this air flow occurs.

The basic idea of examining the permeability of APC was to measure the pressure drop of the air passing trough a specimen at certain rate of L/min. Each end of the specimen was installed in a chamber and put into the pressure box. The pressurised air was then supplied to chamber 1. To ensure that leakage of the air will not occur, the pressure in the box was equalized with the pressure in chamber 1. Finally, as the air passed through a specimen, the pressure difference between chamber 1 and chamber 2 was measured. The scheme of the set-up is shown in Fig. 7.4:

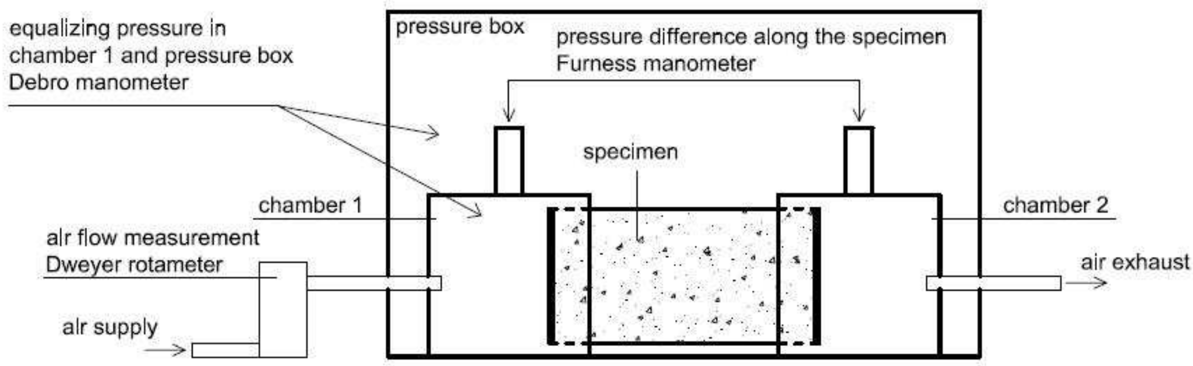

Figure 7.4: Schematic representation of the set-up

The following procedure was applied to perform the test:

1. **Preparation of the specimens**

   Firstly, the top layer of each specimen was cut to ensure that any inhomogeneity of the concrete, induced on the stage of casting, would affect the permeability. To prevent the air from moving through the sides of the cylinder, the specimens were rolled with 3 layers of tape. With such a sealing, the air should move from one end - through the specimen - to the other end. Ready specimens are shown in Fig. 7.5.

Figure 7.5: Set of specimens sealed with tape and ready for the test

2. **Installing the specimen in the pressure box**

   To ease place the chambers at the ends of the specimen, the tape at the ends of the cylinder and the rubber gaskets inside the chambers were wetted with water and soap. Then the chambers were put tightly on the ends of the specimen and placed together inside the pressure box. The box was closed with a wooden lid and hinges attached to the lid. Ready set-up is shown in Fig. 7.6.

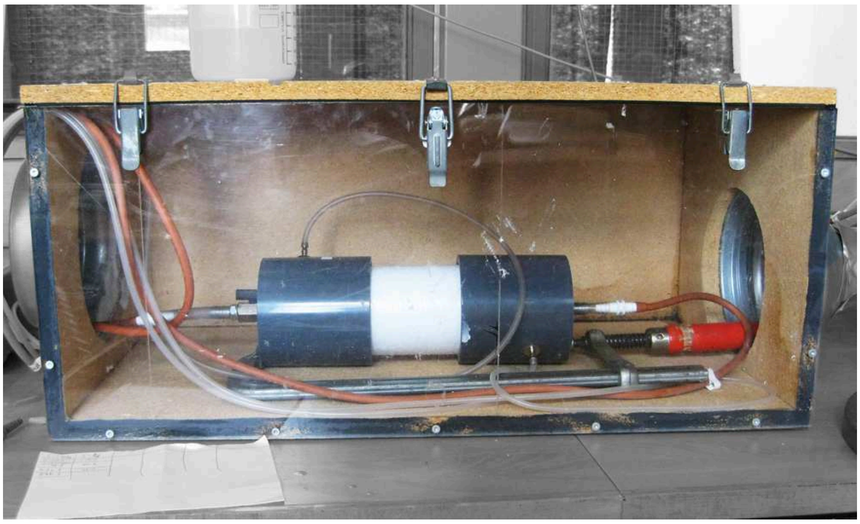

Figure 7.6: Pressure box with a specimen installed in the chambers

3. **Applying pressurised air**

   Before entering the box, the airflow was measured using a rotameter (Fig. 7.7). Four values of the airflow were applied during one test: 2, 4, 6 and 8 L/min. In order to prevent the leakage of air from the specimen (which was very possible to happen, due to the rough edges of the cylinder and shape imperfections), the air pressure in the pressure box was regulated until it would reach the same value as the pressure of air entering the specimen in chamber 1. This step was derived from basic fluid dynamics, which states that the flow of a fluid will occur when there is a pressure drop. Since the pressure of air in the box and in chamber 1 is equalized, no flow should occur.

   The pressure in the box was regulated using Debro micro manometer (Fig. 7.8).

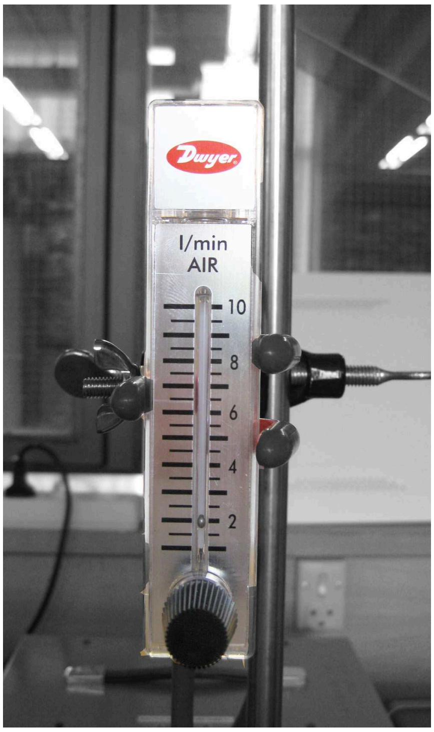

Figure 7.7: Dweyer rotameter

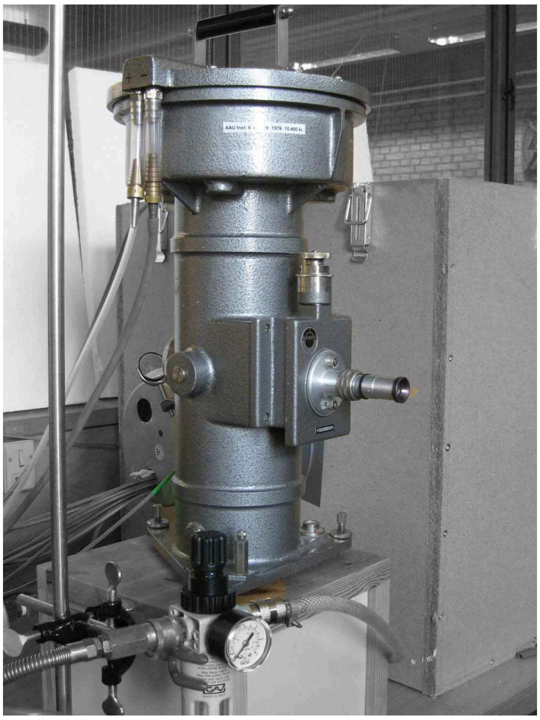

Figure 7.8: Debro micro manometer 43701

4. **Measurement of the pressure drop across the specimen**

   Once the pressure equilibrium in the box and chamber 1 was achieved, the pressure difference across the specimen was measured by Furness micro manometer FCO510 (Fig. 7.9). The high accuracy of the manometer (0.01 MPa) is important, as this reading was the one directly used to calculate the permeability.

   The leakage which might have occurred between chamber 2 and the box was not of any significance, as the air has already flown through the cylinder and the pressure difference has been measured.

Figure 7.9: Furness micro manometer FCO510

7.2.2 Results

The formula to calculate the permeability k was derived from Darcy's law (Eq. (7.9)):

$$k = \frac{q}{A}\mu\frac{L}{\Delta p} \tag{7.9}$$

However, the flow in Darcy's law is assumed to be laminar (which is not correct in the case of APC); also the dynamic viscosity μ was removed. The formula takes the following form (Eq. (7.10)):

$$k = \frac{q}{A}\frac{L}{\Delta p^n} \tag{7.10}$$

Where:

- q - air flow [L/min];
- A - cross-sectional area [mm^2];
- L - length of the specimen [mm];

- Δ p - pressure difference between chamber 1 and chamber 2 [Pa];
- n - pressure exponent, depending on the type of the flow; here $n = 0.5$ as a turbulent flow was assumed.

The results of the tests are presented in the table (Tab. 7.5):

w/c	DF	Porosity [-]	k [m^2/Pah]
0.30	0.4	0.33	0.34
	0.5	0.33	0.44
	0.6	0.31	0.37
0.35	0.4	0.27	0.18
	0.5	0.29	0.30
	0.6	0.30	0.17

Table 7.5: Measured permeability

The plot of the results, showing the relation between the permeability and the degree of filling for two different w/c ratios, is presented below (Fig. 7.10, 7.11):

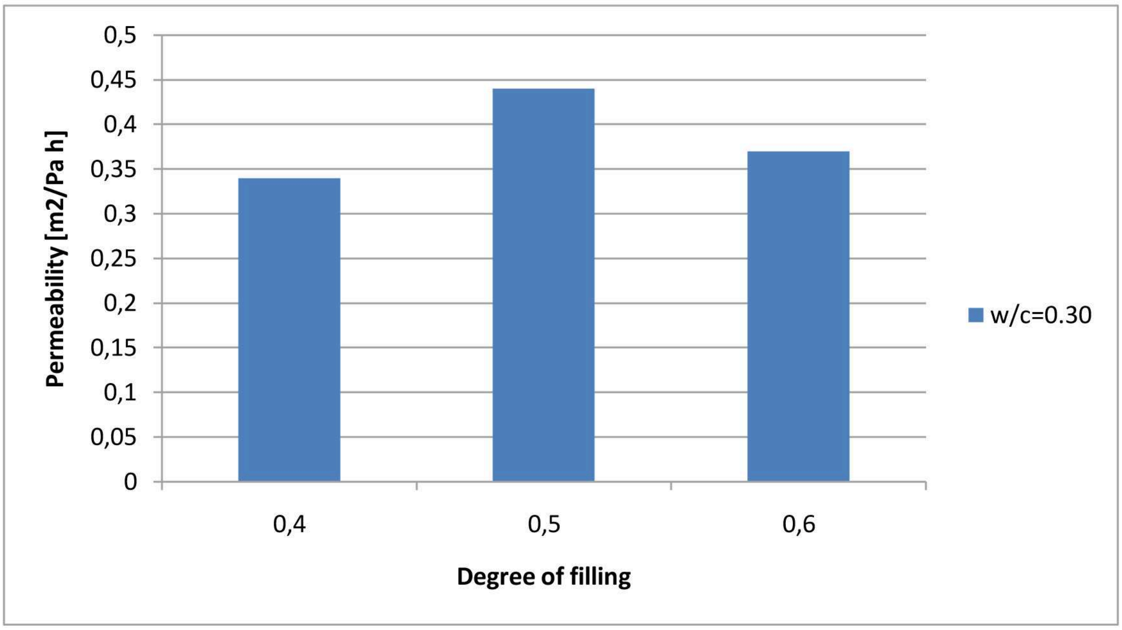

Figure 7.10: Relation between permeability and degree of filling for w/c=0.30

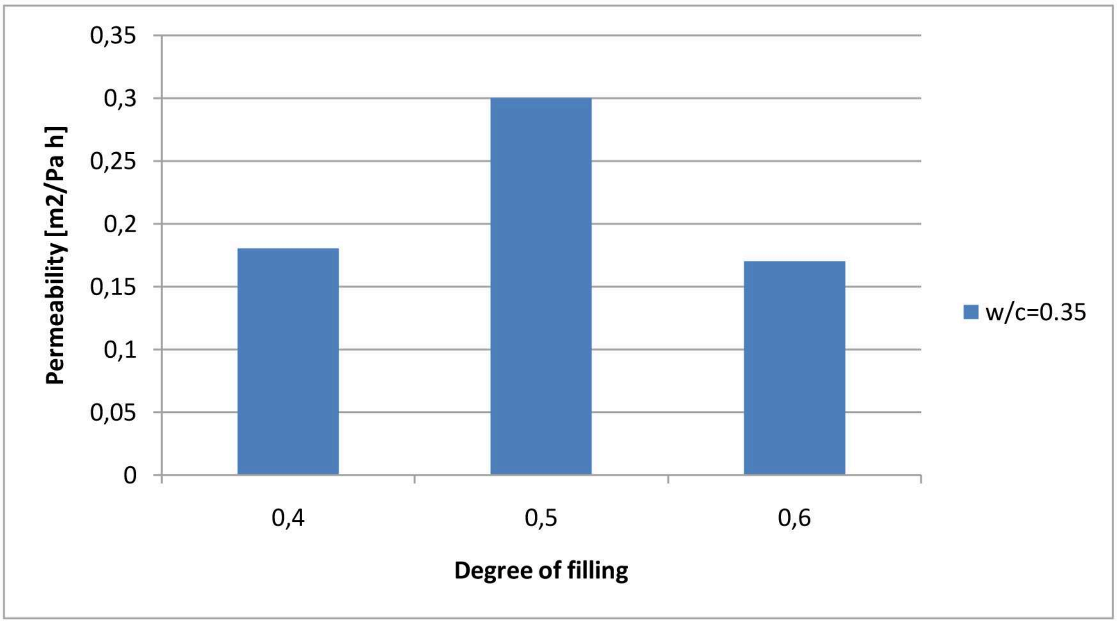

Figure 7.11: Relation between permeability and degree of filling for w/c=0.35

The results are only partly consistent with the expectations. Intuitional knowledge suggests that the lower degree of filling, the higher the permeability, due to large amount of open channels. However, in both cases of w/c ratio, the opposite behaviour is noticed, in terms of case DF=0.4. The permeability is not only lower than permeability of specimens with DF=0.5, but also with DF=0.6, which is a very surprising result. The explanation of this issue might be found in relating it with the problem of the aggregate crushed by the mixer, described in Sec. 6. This issue might have been significantly influential when it comes to specimens with high porosity and low degree of filling, such as ones with DF=0.4. It is possible that small aggregate particles, which are created during mixing from crushing bigger particles, clog interconnected channels and therefore prevent the proper permeation.

In the case of DF=0.5 and DF=0.6 the results are as expected: the higher degree of filling, the lower the permeability.

The inconsistency of the results might have been caused also by difficulties in readings of the measurement. The fluctuations of the readings were significantly affecting the procedure of the measurement and therefore might have affected the results.

7.3 Compressive strength

The compressive strength and the parameters which influence it are described in Section 4.5. In this section the tests of compressive strength of APC with different combinations of mix designs will be presented. The tests were made also for APC with and without PCM.

7.3.1 Set-up

The testing machine that has been used for measuring the compressive strength (f_c), is Tonipact 3000 compressive strength tester (Fig. 7.12).

Figure 7.12: Tonipact 3000 compressive strength tester

Due to the special porous geometry of the APC some aggregates could loosen even while applying low pressures resulting in the stop of the testing machine. Thus, it has been needed to run the test until the complete crush of the specimen was reached (Fig. 7.18). The force has been applied at a constant rate of $1kN/s$.

The compressive strength has been calculated by converting the maximum value reported by a voltmeter directly connected to the machine (Fig. 7.14) into a force using a calibration Excel spread-sheet file (Fig. 7.13). Then the force has been divided by the area of the specimen and adjusted in order to take into account that the samples' dimensions are smaller than the standard ones (150 mm x 300 mm).

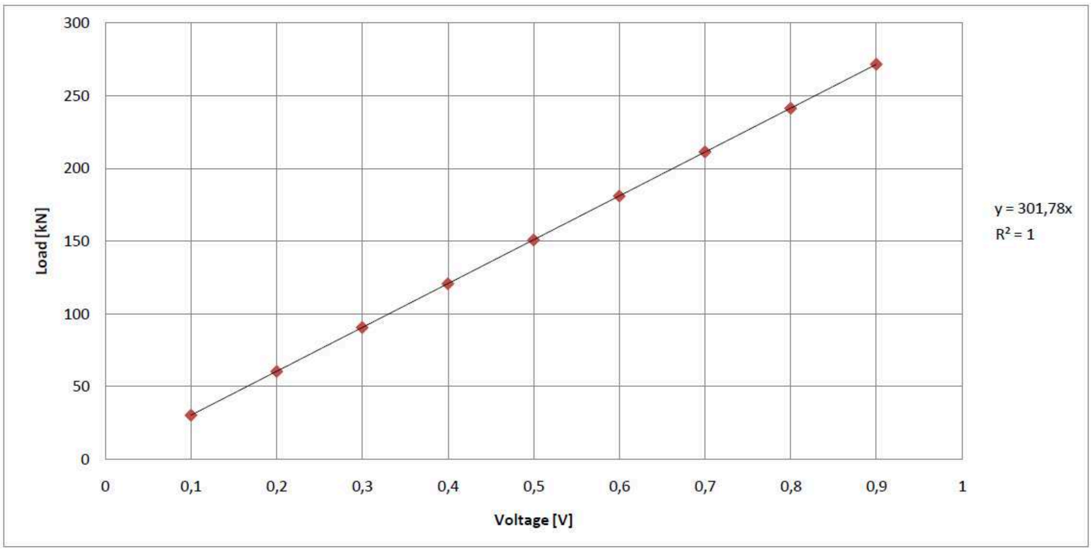

Figure 7.13: Voltmeter calibration graph [18]

Figure 7.14: Set-up ready for the test

The formula used for calculating compressive strength f_c from the values of the loading F applied during the tests is presented below (Eq. (7.11)):

$$f_c = \frac{F \cdot 301.78 \cdot 1000}{A \cdot 1.04} [18] \tag{7.11}$$

where:

- 301.78 - the coefficient taking into account the calibration of the testing machine;
- 1.04 - the coefficient taking into account non-standard dimensions of specimens;
- A - the area of the cross-section of the specimen, $A = 7854mm^2$.

For each recipe, three compression tests were performed and the mean value was calculated.

7.3.2 Test Results

Firstly, it has been decided to plot the development of the compressive strength. This has been done considering recipe 2 and recipe 5 (section 5.4); the results are shown in graphs (Fig. 7.16, 7.15). The DF is kept constant (DF=0.4)whereas the w/c varies (respectively 0.35, 0.30).

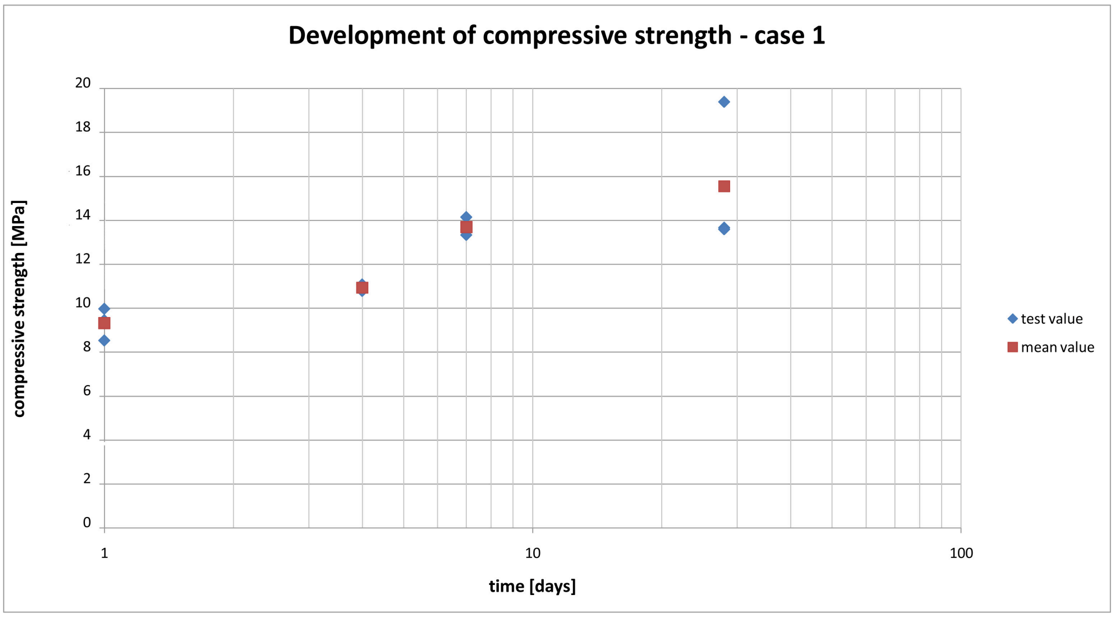

Figure 7.15: Compressive strength development graph for recipe 5 (w/c=0.35, DF=0.4), with PCM

	f_c 1_{day} [MPa]	f_c 4_{days} [MPa]	f_c 7_{days} [MPa]	f_c 28_{days} [MPa]
	8.5	7.4	14.0	13.7
	9.5	10.8	14.2	19.4
	10.0	11.1	13.3	13.6
Mean (f_{cm})	9.3	10.9	13.7	15.6

Table 7.6: Measured compressive strength for development graph in Fig. 7.15

The development of the compressive strength (Fig. 7.15) shows a smooth increase of f_c with time. It is necessary to observe that for further calculations the attention will be put primarily on the 7_{days} compressive strength mainly for two reasons: reduce the time between the casting and the testing and because the 7_{days} f_c can already give a feeling on the resistance of the APC and allow the comparison of the results.

In table 7.6 the value in blue represents a sample that had an unusual crushing mode and therefore the result has been rejected.

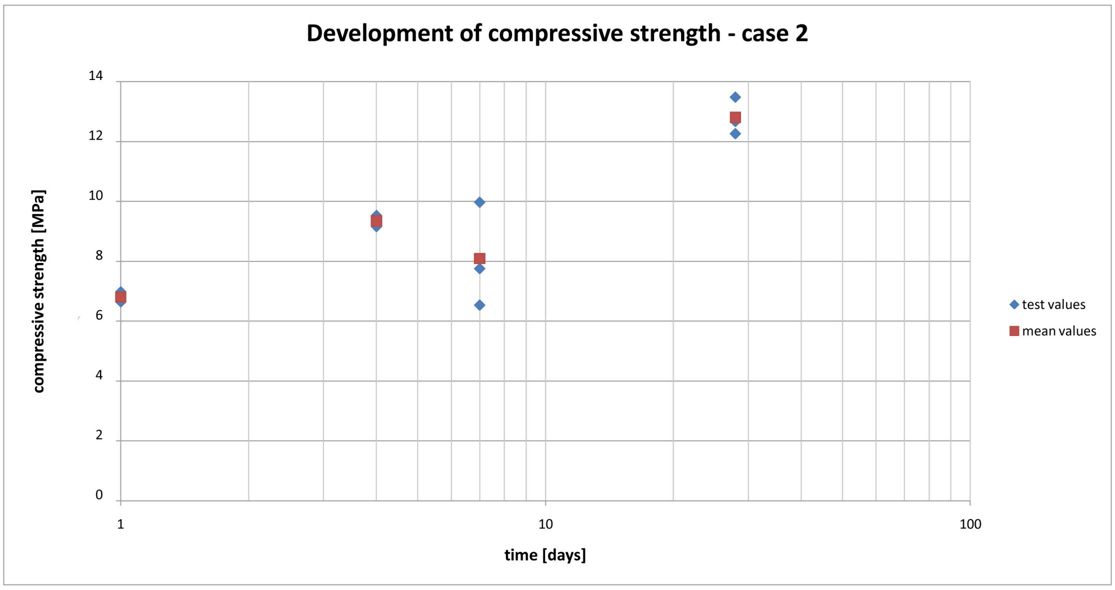

Figure 7.16: Compressive strength development graph for recipe 2 (w/c=0.30, DF=0.4), with PCM

	$f_c\ 1_{day}$	$f_c\ 4_{days}$	$f_c\ 7_{days}$	$f_c\ 28_{days}$
	6.7	4.3	6.5	12.7
	6.8	9.2	7.8	12.3
	7.0	9.5	10.0	13.5
Mean (f_{cm})	6.8	9.3	8.1	12.8

Table 7.7: Measured compressive strength for development graph in Fig. 7.16

Graph 7.16 has a similar trend to graph 7.15 although the values of the 7_{days} f_c do not show a reliable behaviour. A hypothesis on this result could be that different mixers were used for casting APC. Indeed, both recipes have been mixed using the large mixer except for the 7_{days} specimens of recipe 2 which have been mixed using the small mixer. This might have compromised the quality of the aggregates and therefore the compressive strength. Further details will be given in chapter 6.

In table 7.7 the blue value represents a sample that had an unusual crushing mode and therefore has been rejected.

Figure 7.17: Fracture lines at failure

Figure 7.18: Fracture lines while reaching the maximum f_c

Figures 7.17 and 7.18 show the crushing behaviour of APC. It can be seen that the aggregates covered in cement paste crumble apart as the maximum compressive strength is reached. Yet it is noticeable, especially in Fig. 7.18, that the fracture lines follow the general behaviour of regular concrete. Indeed there is the formation of two cones at the ends and detachment of material from the central zone.

After having plot the compressive strength development for the APC with PCM, it has been decided to evaluate the influence of the water/cement ratio and the degree of filling on the compressive strength with constant amount of PCM. Thus, in addition to the results of recipes 2 and 5, presented in section 7.3.2, the results of recipes 1, 3, 4 and 6 will be analysed.

Water/cement ratio	**Degree of filling**	**Mean compressive strength f_{cm} $[MPa]$**
0.30	0.4	8.1
0.30	0.5	14.8
0.30	0.6	15.3
0.35	0.4	13.7
0.35	0.5	18.7
0.35	0.6	18.4

Table 7.8: Measured 7_{days} compressive strength with PCM

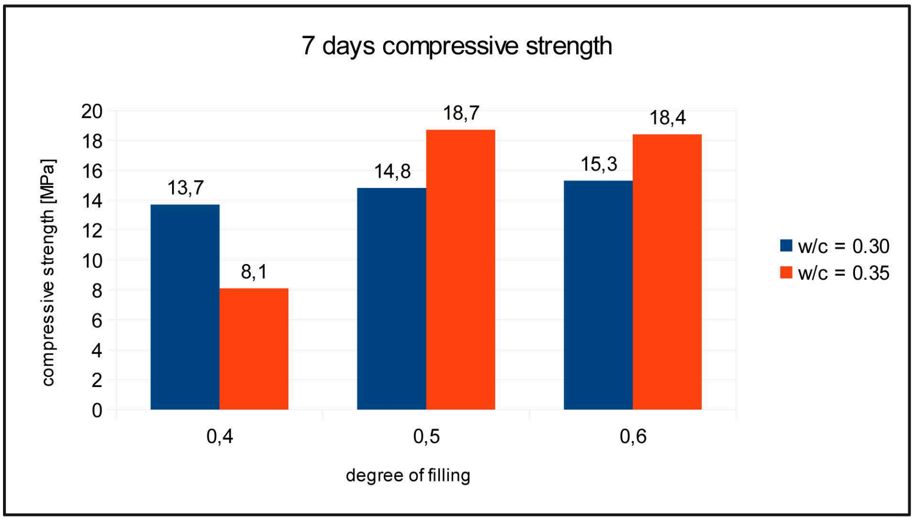

Figure 7.19: Plot of the 7_{days} compressive strength with PCM

Excluding the result of the 7_{days} compressive strength of w/c=0.35 and DF=0.4 (commented in the previous section), an unexpected behaviour is noticed: the results with higher strength are those corresponding to a higher water cement ratio. From the theory the results should be the opposite: the higher the amount of water the lower the strength of the concrete.

An explanation to this behaviour could be that the cement paste, due to its low content of water, cannot cover the aggregates homogeneously and therefore there is not sufficient amount of the cement bonds that are needed to give strength to the whole matrix. The same behaviour has been noticed in the study of [21].

7.3.3 Comparison of the results

This section is intended to analyse whether the PCM have an influence on the compressive strength of the samples.

Due to the fact that PCM changes the rheology of the cement paste by increasing its viscosity (Sec. 5.2.2), it has been decided to modify the mix designs to obtain a rheology of the cement paste that would give the same results in terms of fluidity. Therefore, to obtain the same values of the spread of the cement paste with and without PCM, it has been needed to reduce the amount of SPA. The modification is presented in the following table (Tab. 7.9). The amount of SPA is expressed in percentage of the mass of cement. For samples with PCM, the amount of PCM is 12% of cement by weight.

Water/cement ratio	**Degree of filling**	**SPA with PCM** [%]	**SPA without PCM** [%]
0.30	0.4	2	1.5
0.30	0.5	2	1.5
0.30	0.6	2	1.5
0.35	0.4	2	0.75
0.35	0.5	2	0.75
0.35	0.6	2	0.75

Table 7.9: Comparison of the amount of SPA with and without PCM

Table (7.10) shows the result of the compressive strength at seven days of all recipes (1-6) both for APC with and without PCM.

Water/cement ratio	**Degree of filling**	f_{cm} **with PCM** $[MPa]$	f_{cm} **without PCM** $[MPa]$
0.30	0.4	8.1	8.7
0.30	0.5	14.8	16.0
0.30	0.6	15.3	19.3
0.35	0.4	13.7	14.8
0.35	0.5	18.7	19.7
0.35	0.6	18.4	14.4

Table 7.10: Comparison of the compressive strength with and without PCM

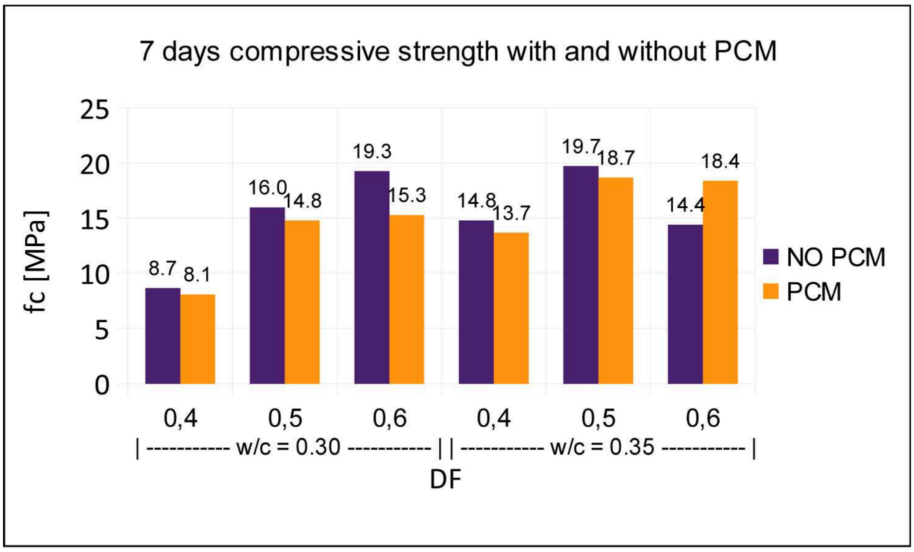

Figure 7.20: Compressive strength with and without PCM

As can be seen from Figure 7.20 the effect of the PCM on the compressive strength is evident. Apart from the last case which behaves differently, all the other tests showed a similar behaviour: the strength without the PCM is higher. A conclusion can be drawn that the cement paste with PCM has a weaker matrix. This is due to the fact that the small spheres of PCM are encompassed in the cement paste and since they are not able to bear any load, they weaken the concrete.

7.3.4 Influence of experimental issues on compressive strength

The analysis of the influence of the type of the mixer and the size of the aggregates was performed on the specimens of recipe 2. It resulted from the fact that due to the schedule some specimens were mixed in the big mixer (on 14.04.2011, specimens for 1, 4 and 28 day compressive strength tests) and some were mixed in the small mixer (on 17.05.2011, specimens for 7 day compressive strength test).

As described in Section 7.3.2, p. 70, the 7_{days} compressive strength has an unexpected value of 8.091 MPa. Indeed, it seems doubtful that the 7_{days} compressive strength has a lower value than the 4_{days} compressive strength. Since the casting procedures have been the same for all the specimens described in this report, the only reason that could explain this behaviour is the crushing effect that the mixer has on the aggregates during the mixing procedure.

Yet, while considering the development curve (p. 70), it is clear that the measured 7_{days} compressive strength has as a lower result than expected. This can be considered a good outcome in terms of safety: the results obtained mixing the concrete in the small mixer are therefore on the conservative side. Nevertheless, for the sake of reliable research a quantitative analysis should be carried out.

Chapter 8

Comparison with literature

As far as the experimental work in the concrete laboratory is concerned, some unexpected issues appeared, such as problems with the mixer crushing the particles of the aggregate. This issue is believed to affect the results causing some inconsistencies. Moreover, it can be concluded that the production of the specimens with repeatable results is extremely difficult and the importance of the laboratory issues (i.e. devices, materials, procedures) should be emphasized. Therefore, the perfect uniformity of parameters of APC (such as the one obtained by Imbabi et al. [8]) can hardly be expected.

Since the idea for the project was induced by the interest in research [8], the comparison of the results of parameters of APC obtained in this project and by Imbabi et al. will be performed in this section.

As can be seen in the following figure (Fig. 8.1), the values of compressive strength are relatively high, from 14.4 to 19.7 MPa for APC without PCM. Although PCM seems to weaken the strength of concrete, the results for compressive strength for APC with PCM are still high (from 14.8 to 18.7 MPa). The results obtained by Imbabi et al. are significantly lower (the difference between 4.0 and 11.2 MPa for APC without PCM).

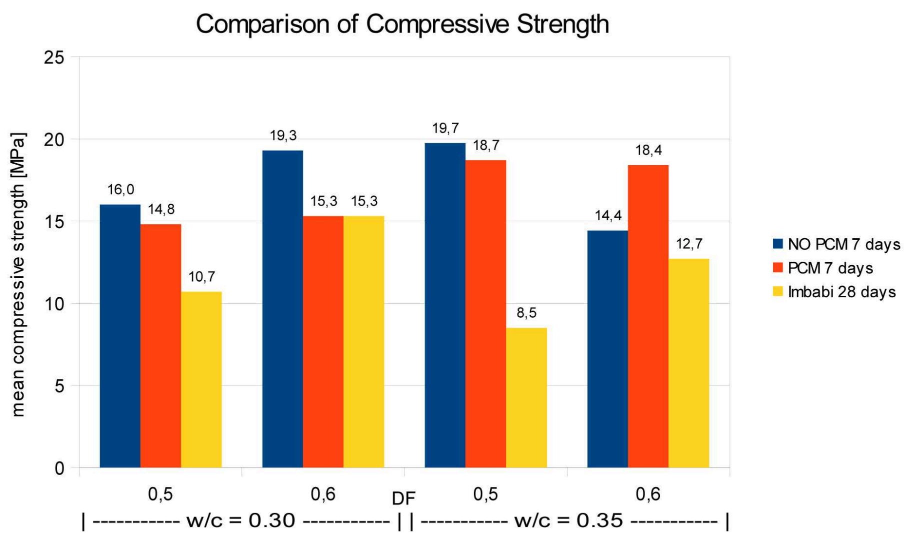

Figure 8.1: Comparison of results of compressive strength with results by Imbabi et al.

As far as the porosity is concerned (Fig. 8.2), the results differ to rather insignificant extent (from 1 to 3%). Nevertheless, the repeatability of the values of the porosity for specimens with the same degree of filling (0.5) obtained in [8] could not be confirmed in this study.

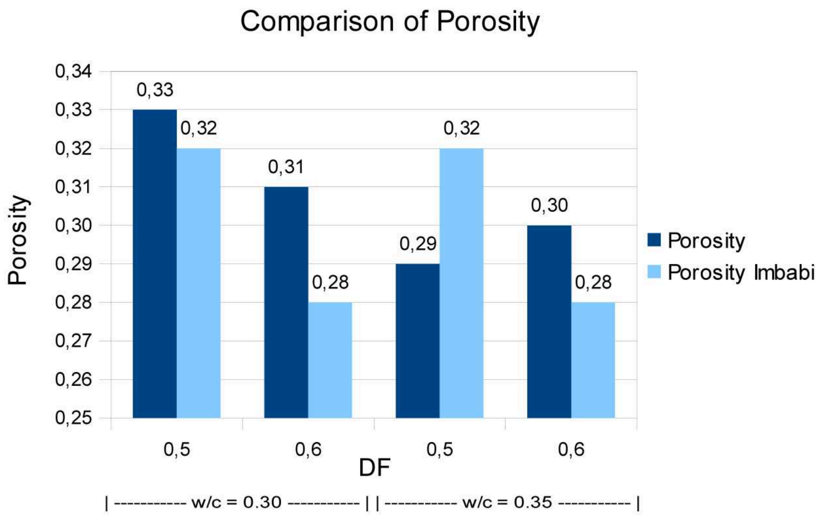

Figure 8.2: Comparison of results of porosity with results by Imbabi et al.

The values of the permeability are similar only in case with $w/c = 0.30$ and $DF = 0.6$, in all other cases the results are considerably lower (Fig. 8.3). It might be caused by the fact that no recommendations for measurement were given in [8] and that the set-up used in the project might have been different.

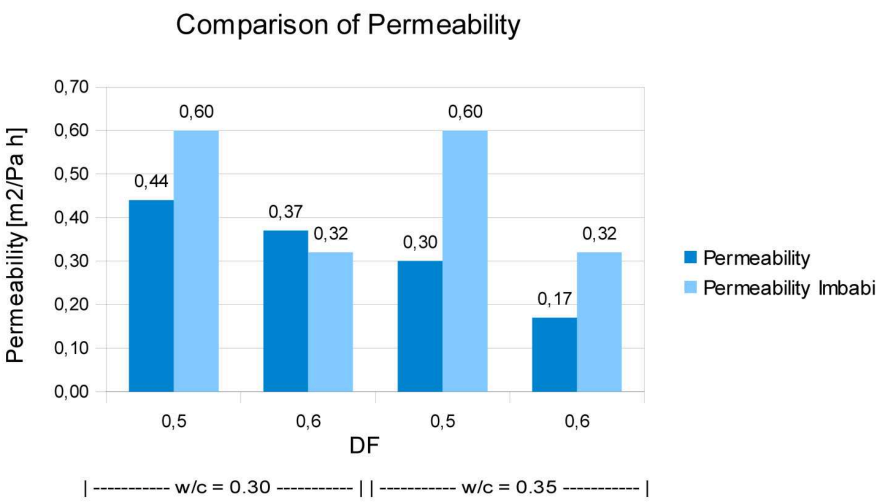

Figure 8.3: Comparison of results of permeability with results by Imbabi et al.

Chapter 9

Conclusions

Within the project "Air Permeable Concrete" the theoretical analysis and experimental tests have been performed and notable results have been found. The issues selected for the project to be analysed embraced developing the background for the production of air permeable concrete (APC), including mix designs for APC as well as mixing, casting and curing procedures. Furthermore, the project aim was to define the influence of the parameters of APC on the main properties of concrete and to evaluate the impact of Phase Change Materials on the parameters of APC.

Considering the main objective of the report, which is the definition of recommendations for the production of APC, satisfying results were obtained. Six different recipes were tested, covering two water/cement ratios (0.30 and 0.35) and three different values of the degree of filling (0.4, 0.5, 0.6) for each water/cement ratio. A narrow fraction of the aggregate was used (2 - 3.55 mm). The amount of super-plasticizer (SPA) and Phase Change Material (PCM) was found in order to ensure the proper workability of concrete. The amount of SPA was established as 2% (by weight of cement) and PCM was investigated at a dosage level of 12% (by weight of cement). Moreover, the mixing, casting and curing procedures were established and the recommendations for vibration time and frequency were given (Sec. 5.5.2).

Regarding the parameters of APC, the methods of the tests were established and the porosity, the permeability and the compressive strength of the specimens of APC were examined. The tests gave satisfactory results, although in some cases the inconsistency and unexpected trends were noticed; the most relevant results are presented below.

Two water/cement ratios have been studied and a proper cement paste was obtained: this ensures an appropriate distribution of the cement paste around the particles of the aggregate.

The amount of super-plasticizer has been a very important parameter to manipulate for obtaining the proper cement paste. The percentage of SPA used has been defined by means of the spread tests with and without PCM.

Adding the PCM to the cement paste resulted in a drastic change in the rheology of the cement paste, thus large amount of SPA was needed. Furthermore, the additive of PCM resulted in the decrease of the compressive strength.

The process of compacting the specimens has been noticed to be an important step of the casting procedure. Varying the frequency and the time of vibration can highly influence the results.

The compressive tests done on the six different cases of APC reported good values of the compressive strength and therefore the recipes used for producing APC are suitable for designing concrete for load bearing structures.

The recipes used resulted in very satisfactory values of the porosity: indeed the theoretical and the experimental values are uniform. This outcome is also supported by the computation of the theoretical and experimental concrete density. Thus, it can be stated that closed pores are very limited and the interconnectivity of the channels is obtained.

The results of permeability showed a noticeable inconsistency. The set-up used for the measurements, due to the difficulty of reading the pressure drop, proved to be inaccurate. Indeed, since the test on the porosity demonstrated that there are almost no closed pores, permeability was expected to be increasing with the increasing values of porosity. Nevertheless, the values of permeability are relatively high and are expected to ensure the desired permeation of the air.

The project resulted in the establishment of mix designs of APC, which together with the application of recommended methods of mixing, casting and curing enable obtaining Air Permeable Concrete with satisfactory properties. Moreover, the results of the project can be considered as a strong basis for further studies on APC.

Chapter 10

Future work

Due to time limitations, not all areas of interest have been analysed. Therefore, the following fields of concern are highly recommended to be a subject for future work:

- investigate the compaction process, especially concerning the vibration procedure for future full scale production;
- analysis of the influence of PCM on porosity and permeability of APC;
- establish a permeability set-up that would give more reliable results;
- analysis of thermal properties of APC with and without PCM;
- further development of technical issues concerning the application of APC in the buildings;
- tests of the properties of APC performed on the specimens mixed in a proper mixer;
- tests should be done to estimate the influence that a different grain size distribution would have on the properties of the APC.

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Chapter 11

Appendix

The appendix contains the technical data sheets of the following materials:

1. Rapid Aalborg Cement CEM I 52.5 N;
2. Superplasticizer Glenium Sky 680;
3. Viscosity Modifying Admixture: Rheomatrix 101;
4. Phase Chande Material: Micronal* DS 5039 X.