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Test Methods for Determination of Air Content of Hardened Concrete

Master's thesis, for the degree of Building Technology in Engineering submitted for inspection.

Espoo, November 12th, 2018
Supervisor: Professor of Practice Jouni Punkki
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ABSTRACT OF THE MASTER'S THESIS

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Title: Test Methods for Determination of Air Content of Hardened Concrete

School: School of Engineering

Programme: Master´s programme in Building Technology

Field: Concrete Technology | Code: CE:thes

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Increased air content has been reported from drilled samples in the frost resistance concrete throughout Finland. Elevated air content has been measured at up to 15 percent which has resulted in inadequate compressive strength in various structures. However, the test method which is used to determine the air content in hardened concrete is not standardized. This thesis presents the results of measurements of air content in fresh and hardened concrete by using different methods and techniques. However, the absolute or true air content in concrete is always unknown. Therefore, the results do not show the correctness of measurement but the correlations between them. This thesis focuses on the measurement of air content in hardened concrete with different methods. The aim of this study was to draw a correlation between the methods and evaluate the performance of each method compared to a standardized method.

A research was carried out in the *Literature Review,* which consisted of the hypothesis of air voids, the influence of air content, factors affecting the air content, and the methods for measurement of air content in hardened concrete. The *Laboratory Work* comprised of the preparation of nine different concretes in three groups of water-cement ratios and different air contents ranging from 2% to 10% by volume. A total of sixteen cores were drilled from each cast block. Their densities were measured. From the theoretical density and measured density, the Calculated method was conducted to measure air contents. A total of 65 cores, from the nine concrete, were examined with the Pressure Saturation method. A Thin Section round-robin test was organised for 54 samples from the middle of the blocks.

Based on the results, the Calculated method has good correlation with fresh concrete 0.98 R^2 with ± 1.4% of error from the average within a standard deviation of nine blocks. However, this method is giving a false result if the concrete is inhomogeneous and cannot be used in in-situ cases since the mix-design of the concrete is not necessarily known. The Pressure Saturation method had a good correlation with fresh concrete and Calculated method with R^2 of 0.96 and 0.98. The standard deviation of the method shows that the maximum error which was conducted is ± 1.2% from the mean value. Thin Section within a round-robin test analysis proved that the results are unreliable due to problems with a relatively large variation of results regarding total air content. This is due to the high coefficient of variation of entrapped air (27% to 129%) in certain concretes. However, the average total air content results of Thin Section have a good correlation between the fresh concrete air content and Pressure Saturation.

Date: 12.11.2018 | Language: English | Number of pages: 65 + 22

Keywords: Air content, density, Calculated method, Thin Section, Pressure Saturation

Preface

This thesis is a review of previous experiences and research on the measurement of air content, and identification of field problems in measurements. In addition, the laboratory work was carried out between February and June of 2018 at the concrete laboratory of Aalto University in the School of Engineering.

Special thanks goes to my supervisor Professor of Practice Jouni Punkki and advisor Dr Fahim Al-Neshawy for helping me in this research investigation. I would like to thank those outstanding individuals who gave me assistance in the thesis. Thanks to laboratory manager Jukka Piironen, Mr. Janne Hostikka, laboratory technician Pertti Alho, M. Sc Teemu Ojala and M. Sc Soma Janka.

I would like to give thanks to Aalto University for the supporting this thesis financially. Also, I would like to thank the following petrographic analysis laboratories: Betonialan Ohuthiekeskus FCM Oy, Contesta Oy, Eurofins Expert Services Oy, Kaakkois-Suomen Ammattikorkeakoulu Oy / KymiLabs, KiwaLab, Labroc Oy, Pohjois-Suomen Betoni- ja Maalaboratorio Oy, Vahanen Rakennusfysiikka Oy, and WSP Finland Oy for participating in the thin section round-robin test analysis.

Espoo, November 2018
Mohammad Hossein Ramadan

Table of contents

List of figures

List of tables

Abbreviations

HCP	Hydrated cement paste
w/c ratio	Water-cement ratio
Co	Compressive
P Saturation	Pressure Saturation
AEA	Air entrained agent

1 Introduction

Air content is essential for the durability of concrete in a cyclic freezing and thawing environment. Accurate measurements of air content are therefore necessary for evaluating the performance and durability of concrete in an outdoor environment. If the amount is more or less than the target value it can be problematic. As the air content in concrete increases, the compressive strength decreases substantially (1% of air content reduces 5% of strength. Typically, frost resistant concretes have a target design value of 4-6% air content (Concrete Association of Finland, 2016).

1.1 Problem statement

In recent years, the air content of hardened concrete has been investigated in Finland, and elevated air content has been reported due to factors that are affecting the air content in fresh concrete. The highest air content drilled from structures has exceeded 15% (Al-Neshawy and Jouni, 2017). However, the test method which is used to determine the air content in hardened concrete is not standardized. In addition, there are no requirements for the air content of hardened concrete.

1.2 Research objectives

The aim of this thesis was to analyse the air content in hardened concrete with different methods including the Calculated method which is conducted from the density of hardened concrete, Pressure saturation, and Thin Section method.

The objectives of this thesis were:

1) to draw a correlation between test methods mentioned above for the determination of air content in hardened concrete with the standard methods used for fresh concrete
2) to find out the influencing factors that affect the test methods
3) to evaluate the measurements of air content by Thin Section with a round-robin test.

In order to achieve these objectives:

1. A literature review was carried out including (i) the measurement methods of air content of hardened concrete and (ii) identification of their field challenges.
2. In addition, the laboratory work was carried out on nine different concretes mixes in three groups of water-cement ratios and different air contents ranging from 2% to 10% by volume. A total of sixteen cores were drilled from each cast block. Their densities were measured. From the theoretical density and measured density, the Calculated method was conducted to measure air contents. A total of 65 cores were examined with the Pressure Saturation done among the nine concretes. The round-robin test was organised for 54 samples from the middle of the blocks.

1.3 Thesis outline

Chapter 1 Introduces the research background, needs, objective and approach.

Chapter 2 Reviews the nature of air voids in concrete. In addition, it covers the factors affecting the air content in fresh concrete. Lastly, it describes the principles of the methods of measuring the air content.

Chapter 3 Describes the laboratory work with respect to measuring air content regarding the Calculated method, Pressure Saturation, and Thin Section. This chapter describes the material selection, design of concrete, testing on fresh concrete, casting, curing and drilling. Finally, the chapter presents the procedures and formulas used for the methods which are mention above.

Chapter 4 Shows the results of different densities of hardened and fresh concrete and shows the air content measured by different methods.

Chapter 5 Analyzes the test results of fresh and hardened concrete and finally compares the results of those methods.

Chapter 6 Presents the discussion on the analysis and finally concludes the thesis with future directions.

2 Literature study – nature of air content in concrete and measuring methods of air content in hardened concrete

2.1 Voids in hydrated cement paste (HCP)

Voids are spaces, empty or filled with pore solution in the hydrated cementitious materials (Westermarck, 2000). Various types of voids with their sizes in the hydrated cement paste (HCP) are illustrated in Figure 2-1. These voids have an important influence on the properties of concrete.

The various types of voids in concrete can be classified into three main types: interlayer space, capillary voids and air voids.

1. Interlayer space voids are the solid to solid distance of Calcium Silicate Hydrate (C-S-H) layers; in the old literature they are called Gel pores or Micropores. Interlayer space voids are too small to have an adverse result on permeability and strength of concrete. The size of interlayer spaces voids ranges between 0.001 µm and 0.005 µm (1µm=0.001mm).
2. Capillary voids are the spaces unfilled by solid components of the HCP. Capillary voids depend on the initial separation of cement particles, which is controlled by the water-cement (w/c) ratio. The size of capillary voids range between 0.001 µm and 1µm (Mehta *et al.*, 2013).
3. Air voids consist of entrained and entrapped air voids. The size of entrained and entrapped air voids range between 70 µm to 1 mm and 1mm to 10 mm respectively (Federal Highway Administration, 1997).

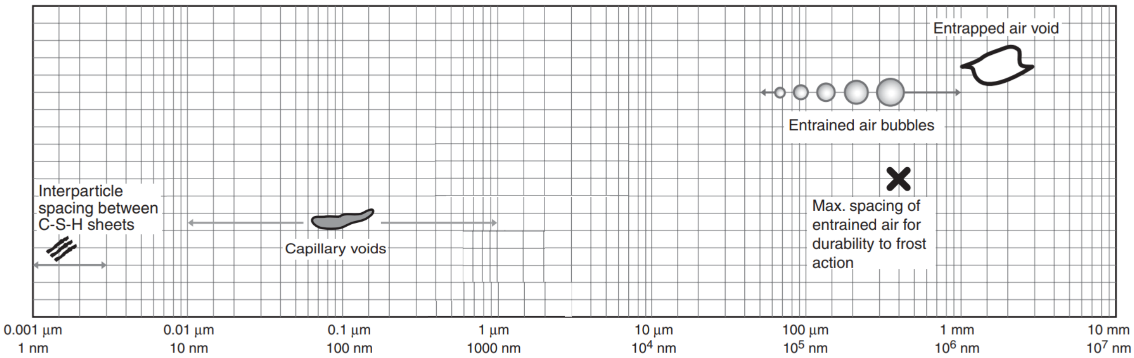

Figure 2-1 Dimensional range of voids in a hydrated cement paste (Mehta et al., 2013).

Air content is an extremely influential aspect of current concrete mix design criteria that greatly affect the performance and durability characteristics of the concrete. The air content is the cumulative volume of a large number of air voids with different sizes within a specific volume of concrete. These sizes range from microscopic bubbles to larger, unevenly shaped pockets (Lamond, Lamond and Pielert, 2006).

Entrapped air voids are empty pores formed during the mixing and compacting of the concrete. All voids that are more than 1 mm and up to several millimetres of diameters are defined as entrapped air voids regardless of their shape. Shell properties around the entrapped air voids change with the different water-cement ratio. With high w/c ratio, the air void shells are porous, while at the low w/c ratio, the shells are filled with hydration products (Moreira Canut Thesis, 2011). According to NTBuild-368, 1991, the volume of entrapped air voids is reported to be about 2% of the volume of the material. Trapped air with a large diameter of air pockets can be detrimental to the concrete quality by creating surface defects (bug holes) and reducing strength.

Entrained air is air purposely entrained through the addition of admixture to the mixture to stabilise a particular percentage of air voids. This is the key to avoiding damage from freeze-thaw forces (Lamond, Lamond and Pielert, 2006). Recently, it has become recommended for nearly all types of concrete in order to ensure proper resistance to freezing and thawing that is exposed to water and de-icing chemicals see Figure 2-2 (Al-Neshawy and Punkki, 2017).

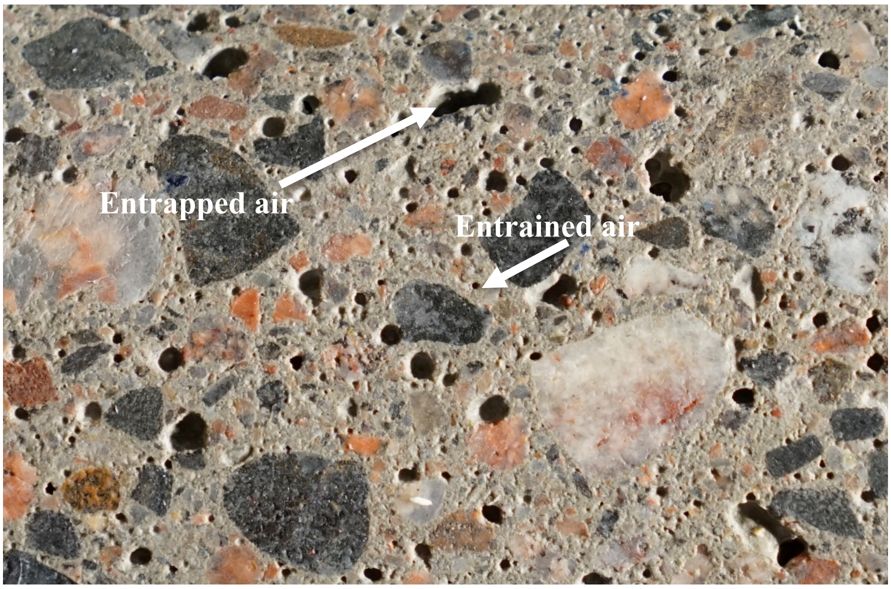

Figure 2-2 Surface image of drilled concrete with entrained and entrapped air voids.

2.2 Effect of air content on the performance of concrete

The existence of air voids suspended initially in the mix of water among the solid particulate components of the concrete influences the behavior of the material in both fresh and hardened concrete. Incorporating air voids into concrete affects several characteristics in fresh and hardened concrete. To what degree air voids can affect the concrete depends on the total volume, size, spreading of the air voids, and on the material properties of the concrete. Air content affects fresh concrete properties such as workability, bleeding tendency, consistency and density. Workability increases as a result of a large number of microscopically small voids, which are well dispersed through the cement paste. This is because sufficient small air bubbles can separate the solid particles in the mix. As a result, water content can be decreased depending on the aggregate gradation while maintaining the same slump value. Cohesion occurs when entrained air is used causing the creation of small air pockets or voids when a mutual attraction occurs between microscopic bubbles and Portland cement grains. This phenomenon anchors the air voids to stop their loss from fresh concrete due to buoyancy and also causes a helpful cohesion to the mix that lowers segregation, bleed over and settlement. Air content effects hardened concrete properties such as the strength, density, and frost resistance (Lamond, Lamond and Pielert, 2006).

2.2.1 Effect on Strength

As the air voids occupy the area between the cement grains, cement paste becomes more porous which reduces the strength and density of the concrete. When equal cement and water ratios exist, the strength decreases due to the increase of air content. There exist different estimated rules which suggest that for each 1% increase in air content, the strength reduction is 3–5% for the four-week compressive strength (Concrete Association of Finland, 2016).

2.2.2 Effect on durability

The air entrained admixture was developed in the 1930s; it was a significant advance in concrete technology. It was an accident by Jackson that led to the discovery that introducing air into the concrete can be an important factor in determining the durability of concrete (Aïtcin and Flatt, 1968).

Frost resistance is the main reason for adding air entraining admixture to mix designs, but there are side effects that are mentioned above. Air voids in concrete converge the system of fine pores in the solidified cement since the biggest of the capillary pores are normally, smaller than the base diameter of air voids. Water, that has been absorbed stays in the smaller areas, will tend to move in the direction of the air voids only when there is pressure caused by quick freezing. The air voids stay unfilled and ready to secure either ice or unfrozen water when a solidifying cycle starts under typical conditions.

To be able to achieve the improvement in frost resistance concrete, not only the total amount of air bubbles is essential but also the quality of the air bubbles.
Three parameters characterise the concrete air void system:

1. The total fraction of air voids in the concrete equates to the air void content.
2. The surface area of air voids divided by the volume of air voids is distinguished as the spacing factor.
3. Specific surface is calculated with the average distance from any point in the paste to the edge of the nearest void.

Concrete with excellent frost resistance has a decent quality of air bubbles, low enough spacing factor, and relatively high specific surface, and moderately high air content (Lamond, Lamond and Pielert, 2006).

2.3 Stability of air content in concrete

The elevated air content in frost resistance concrete can be associated with the many factors. Air content is influenced by many variables which can be grouped into four categories including concrete materials and mix design, production procedures, construction practice and environmental conditions. Each category has many variables that can influence the air content of concrete. The variables are presented in Figure below (Whiting and Stark, 1983).

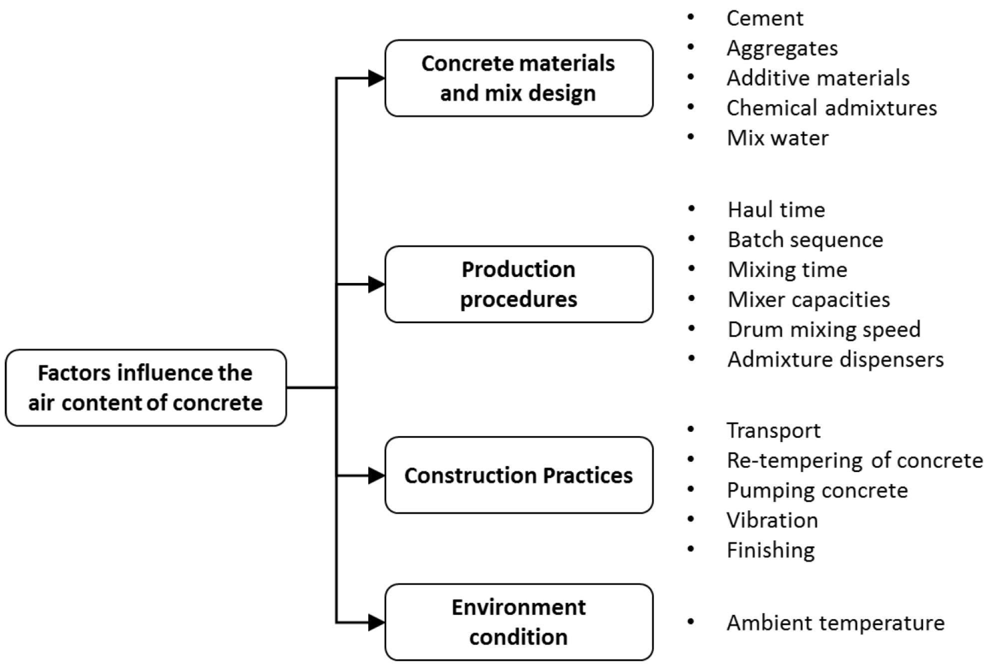

Figure 2-3 Factors influencing the air content (Whiting and Stark, 1983).

Regarding elevated air (15%) in the frost resistance concrete in Finland, Al-Neshawy and Punkki, 2017, investigated the reasons for elevated air content. Based on the report, the reason for the elevated air content was due to several factors that affect the phenomena. The *Air content potential* is the maximum air content that concrete can reach. The Air content potential depends on the concrete composition, water-cement ratio, type of cement, cement content and depends on the admixture combination. This includes the dosages of the superplasticizer and air entraining agent. In addition, the report reveals that the consistency of concrete affects the phenomena.

The time of mixing, 60 to 90 seconds, is short for air entraining agents to reach the Air content potential. Relatively long initial mixing is needed to be able to avoid an extensive increase of air content after initial mixing by transportation and pumping or casting. It is less critical if less dosage of AEA is used with longer mixing time or more effective mixing. Figure 2-4 shows that the same air content can be accomplished with lower AEA dosage and longer mixing time.

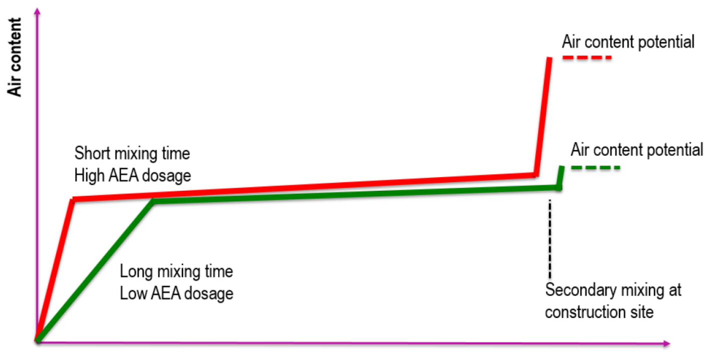

Figure 2-4 Influence of mixing time and the AEA dosage on the increase of air content after mixing (Al-Neshawy, Jouni, 2017).

2.4 Available air content measuring technique

In the following sections, the thesis studies the concepts of the methods that are utilized for measuring the air content in hardened concrete. The methods include:

- Calculated method based on the saturated density
- Pressure Saturation method
- Petrographic examination - Thin Section method.

2.4.1 Concept of Calculated method

The term "Calculated" as used here refers to the calculation of the air content of fresh and hardened concrete through the density of fresh and hardened concrete respectively. The density of concrete is the key factor for this method. The density of concrete has a linear correlation with the air content. Keeping all other aspects constant, density will be reduced with an increase in the voids space volume in the concrete specimen, regardless of the shape, or size. According to Lamond, Lamond and Pielert, 2006 the density test cannot distinguish differences between air void size or system in the hardened concrete and bleeding water channels, aggregate voids or capillary voids. However, according to Lamond, Lamond and Pielert, 2006 a concrete sample which absorbed water upon immersion for a period of time, or in other words when it is fully saturated, most of the capillary channels and cracks are filled with water. Therefore, mainly air voids including aggregate, entrained and entrapped voids are kept unfilled. This results in a method by which the air content can be calculated in this way.

The density expresses the unit weight of concrete per unit volume. However, two different densities are used to measure the air content by the Calculated method, which consists of the theoretical density and the measured density (bulk density). Robust Air introduces the formula based on *ASTM C 138 "Standard Test Method for Density (Unit Weight), Yield and Air Content of Concrete (Gravimetric)"*. The calculation can be seen in equation 3.

2.4.1.1 Measuring technique Calculated method

2.4.1.1.1 Theoretical density

The theoretical density is normally a laboratory determination. The value of the theoretical density is assumed to remain constant for all batches made using identical component ingredients and proportions. The theoretical density is calculated by the total mass of all the materials in the batch divided by the total absolute volume of the component ingredients in the batch. The absolute volume of each element in cubic meters is equal to the mass of that element in kg divided by 1000 multiplied by its specific gravity. Total absolute volume is the addition of each of the ingredients including water, cement, aggregates, air and any admixtures liquid materials used (ASTM C138/C, 2007).

The most influential component that alters the density by the greatest amount is the aggregate. According to Lane *et al.*, 1998, the bulk specific gravity and mass for the aggregate components is based on the saturated, surface-dry condition. Aggregates have significant influence on the density of hardened concrete since they occupy 60–80 % of the volume of most concrete mixes. Also, the specific gravity of aggregate is approximately one-third greater than cement paste. Actual specific gravity for cement should be determined by the C188 test method for each manufacturer (Lamond, Lamond and Pielert, 2006).

2.4.1.1.2 Measured density

The density of fresh and subsequently hardened concrete of a particular mix design is expected to be similar, however they do not have to be identical. The relationship of fresh and hardened concrete densities depend on some factors including the characteristics and mix proportion of aggregate, the degree of consolidation, volume changes, sampling, curing and the age of concrete.

The consistent densities usually indicate consistency in all phases of concrete. This is because the density of hardened concrete is the function of densities of the initial ingredients, mix proportions, air content, degree of hydration, degree of consolidation, volume changes, initial and final water content and subsequent loss or gain of water. Depending on the features, density can be an effective indicator of the consistency of raw materials, mixing, batching, placing, sampling, and testing. A significant difference in density can indicate a change somewhere in the process. For example, if the casting of concrete is not correct, this factor leads to the segregation in concrete (Lamond, Lamond and Pielert, 2006).

Density of hardened concrete can be measured based on the standard *SFS-EN 12390-7:200.* The sample that is received for the test is dried or otherwise conditioned. To be able to achieve the saturated density, the specimens are immersed in water so that the permeable pores are filled. Weight measurements are repeated after immersion and once the specimen is fully saturated. The weight divided by the volume relationship can be determined for water saturated density (ASTM C138/C, 2007).

2.4.1.2 Precision of measured density

Procedural factors can influence the results of the density of hardened concrete of the specimen. The volume of the sample is determined by the "displacement method." It means the difference between the weight in the air and the weight in water. The buoyancy effect of the water, plays the role of the displaced volume and the density of the water depending on the temperature of the water.

Another way to measure the volume can be when the dimensions of the specimen are accurately obtained and the shape of the specimen is highly regular. However, with standard concrete cylinders, significant errors can occur by the unevenness of unclosed ends and out-of-roundness. The standard illustrates the precision data for the determination of saturated density of cubes made from the same sample of concrete in the range 2 300 kg/m3 to 2 400 kg/m3. This indicates that variability occurs when sampling, making and curing the cubes. The repeatability value *r* indicates the difference between two test results conducted by one operator using the same apparatus within the shortest feasible time interval with the same specimen. Reproducibility value *R* indicates two operators each using their own apparatus with the same samples (ASTM C138/C, 2007).

Table 2-1 Precision data for saturated density measurement in hardened concrete (ASTM C138/C, 2007).

Test method	Repeatability conditions		Reproducibility conditions	
	S_r kg/m^3	r kg/m^3	S_R kg/m^3	R kg/m^3
By calculation using measured dimensions:				
100 mm cubes,	*13,9*	*39*	*20,5*	*57*
150 mm cubes.	*9,9*	*28*	*20,5*	*57*
By water displacement:				
100 mm cubes	*6,5*	*18*	*12,8*	*36*
150 mm cubes	*6,4*	*18*	*10,6*	*30*

2.4.1.3 Relationship of air content and density

The following figure shows the approximate range of densities and air content represented by different concretes. According to this figure the approximate density range for the air entrained concrete is between 2225 and 2600 kg/m^3. The lowest density is placed by cellular concrete with an air content of 25 % and highest.

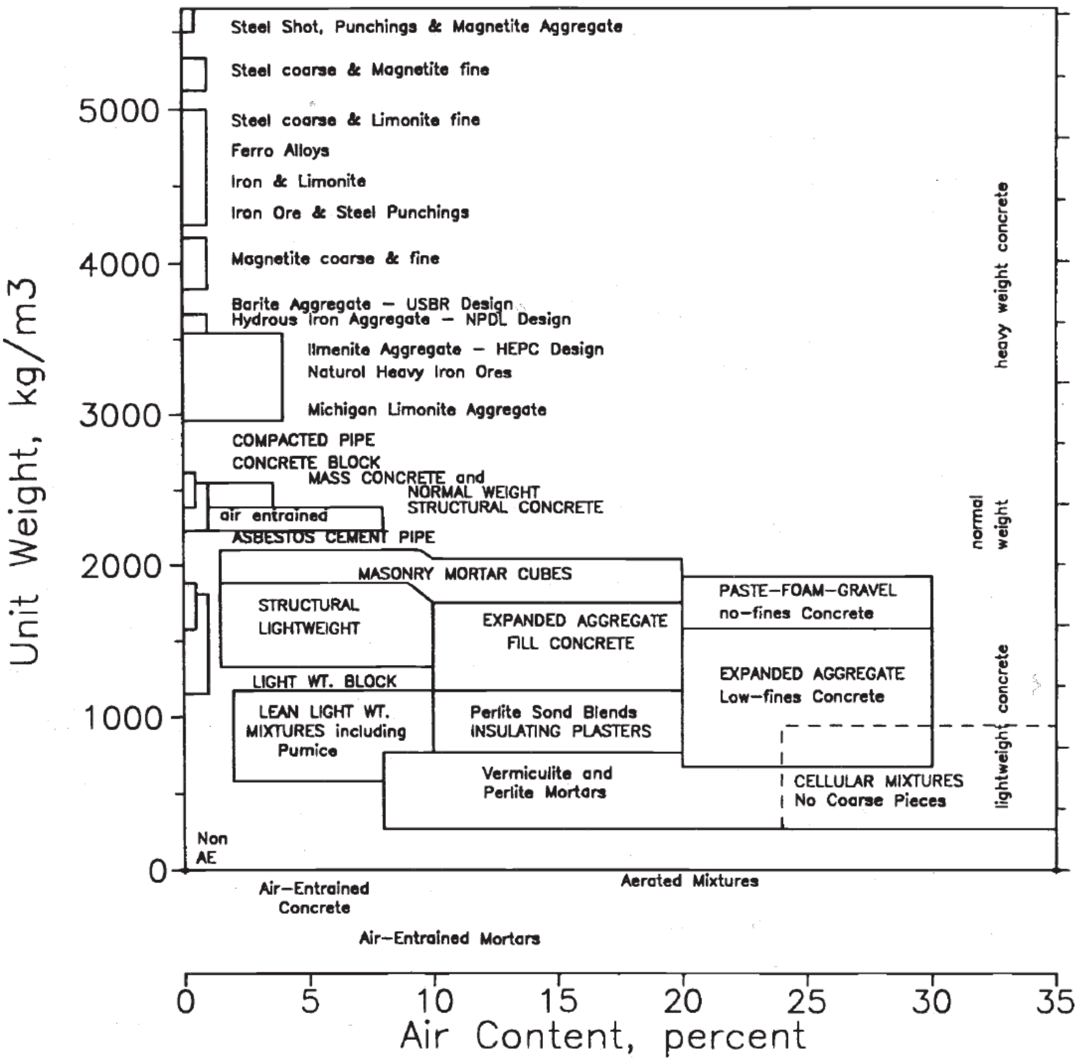

Figure 2-5 Density block diagram (Lamond, Lamond and Pielert, 2006).

2.4.2 Concept of Pressure Saturation method

An old Finnish standard *SFS-4475:1988 Pressure Saturation* was used as an official quality control method for frost resistance concrete. This Standard was withdrawn from the Finnish Standard Association in 2009 (*SFS Online Product*; Talakokula *et al.*, 1988). This method determines the total air content and porosity of concrete by a pressure saturation apparatus.

In dried, hardened concrete all of the internal voids are air-filled, including capillary pores in the hardened cement paste, bleed water channels, voids in the aggregate particles, water gain voids, micro cracks and entrained and entrapped air. Some of the volume, but not all, of these voids can be measured by the weight of the absorbed water once a dried sample is immersed for a period of time in such a way that air does not become trapped in the specimen (Lamond and Pielert, 2006). The determination of air content by the Pressure Saturation method depends on the ratio of permeable and impermeable voids of the concrete.

The “permeable voids” are the voids that absorb water upon immersion. They are voids that are directly on the surface of the specimen or connected to the surface by capillary voids or by drying and shrinkage cracks. Other voids do not fill with water upon immersion which includes some of the aggregate pores, a portion of the capillary void system and entrapped and entrained air voids. These are termed as “impermeable pores.” When determining voids content by absorption methods, one cannot distinguish among the various types of voids present and the final result is termed “total permeable voids” (Popovics, 1985).

The illustration of the permeable voids which are water filled is shown in Figure 2-6 (Penttala, 1999).

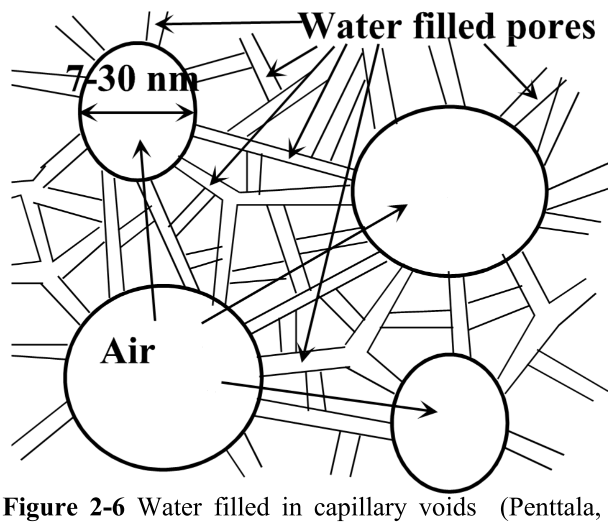

Figure 2-6 Water filled in capillary voids (Penttala, 1999).

According to the standard, *SFS-4475/4/,* the action of water filling of the total permeable voids is called capillary suction. The capillary rise depends on the void size, surface tension of water and the contact angle between the absorbing material and water. Figure 2-7, represents the ideal case of water absorption curve with respect to the square root time in the x-axis and capillary suction in the y-axis. The figure shows an oven dried specimen that was saturated until all the total permeable voids were filled with water.

There is a slowdown of suction after the nick point. The nick point on the curve represents the slow filling of interlayer spaces of the cement gel (Punkki, j. and Shellevold, 1994).

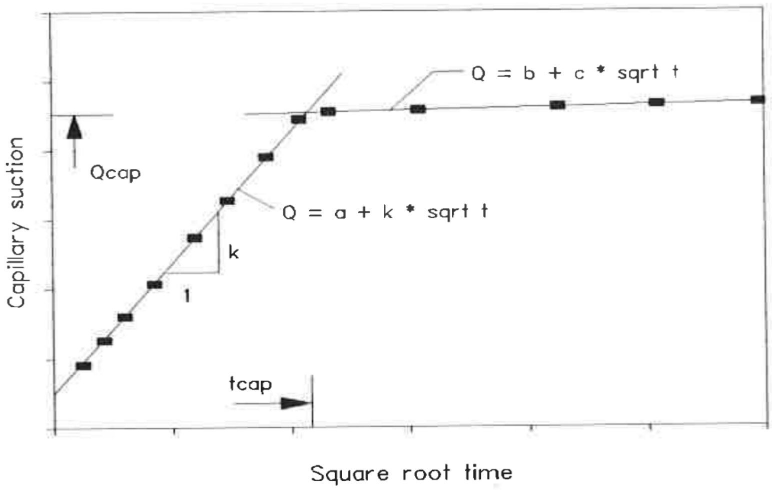

Figure 2-7 An ideal water absorption diagram (Punkki, 1994).

Impermeable pores are determined by the pressure saturation apparatus. Specimen is placed in the pressure saturation apparatus over 24 ± 2 hours under the water pressure of 15 ± 1.5 MPa. Pressure forces the water through the permeable voids and breaks the void's shells and fills the voids with the water according to the standard. The voids include the entrapped and entrained air voids, some of the aggregate pores, and some portion of the capillary void system.

The air content of concrete can be determined using the difference of the weight of water filled, permeated and impermeated voids divided by the volume of the permeated sample. The total porosity can be measured by adding the calculated air content to the suction porosity (Thakur and NATALE, 2009). The calculations can be seen in equations 5 and 6.

The suction porosity (capillary absorption) of the concrete can be determined by the difference of weight between the water filled, permeated sample and dry sample divided by the volume of the permeated sample. The calculations can be seen in equation 7.

2.4.3 Concept of Thin Section analyses of air voids

Petrography began in 1828 when Scottish physicist William Nicol invented the technique. The first investigation of concrete through Thin Section was in Denmark in the 1950s. The petrographic examination is a laboratory procedure that is unique. It relies highly on visual inspection of the samples. It requires sample preparation, microscopical equipment and operators with appropriate qualifications and experience. Using the microscope, the petrographer can determine the composition of concrete, assess its quality, and investigate the causes and extent of any deterioration. Petrographic techniques have been used in the various range of construction including concrete, building stone, soil, aggregate, cement, mortar and bitumen mixtures ('Goals for the Thin-Section Petrography of Ceramics', 2018).

Specimens received for microscopic analysis, often cores, are extracted from the structure or sample cast in the laboratory. When conducting tests for reference purposes or to determine compliance of hardened concrete in relation to the required specifications for the air-void system, it is suggested to utilize at least three different samples according to the ASTM C 457. The accuracy of the results are greatly enhanced when the average of the results are calculated from a minimum of three samples or more (Pigeon and Pleau, 1995).

2.4.3.1 Measuring procedure

For the Thin Section examination, three procedures are performed on each specimen which consist of the following:

I. Initial examination

Initial examinations are conducted with the naked eye utilizing a low-control binocular microscope at amplifications of up to x100. This allows for the observation and examination of specific features, for example, colour changes or micro-cracking. Additionally, it permits determination of the most suitable location for Thin Section (commonly 75 × 50 mm zone). With the guide of a zoom stereomicroscope (low power microscopy), extra data can be picked up from the specimens (Poole, Sims and St John, 2015).

II. Preparation of Thin Sections

Thin Section is made by first cutting a small piece from the concrete specimen using a non-deformational diamond saw. To ensure that it will not be harmed or damaged, the fragment might be injected with resin before separating. The sawn surface is then ground, either with grinding machine or by hand until the point that it is totally level Then it is appended to a glass slide with an epoxy or mounting medium. At the point when the medium has dried, the highest point of the specimen that is parallel to the slide is cut down to a thickness of 1– 2 mm. For protection, a glass cover is mounted over the Thin Section. ('Goals for the Thin-Section Petrography of Ceramics', 2018).

III. Microscopic examination

The main components of concrete and the porosity are classified and identified using the polarizing microscope which transmits polarized light through the mounted Thin Section.

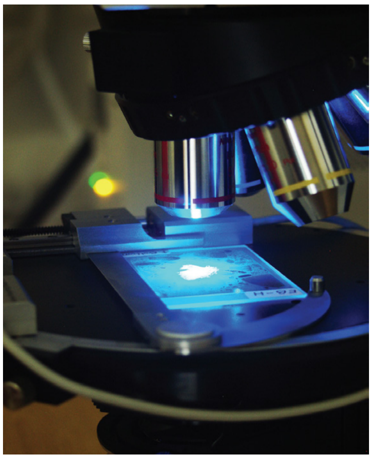

Figure 2-8 Thin Section examination (Poole, Sims and St John, 2015).

ASTM C 457 portrays two different strategies: (1) the linear traverse technique and (2) the modified point-count method. The nature of the measurement contrasts to some degree between the two methods, however, the end results are basically equal. Thin Section is performed by the modified point-count method. However, Technical Research Centre of Finland (VTT) used the TEST – R003-00-2010 which is almost equivalent to the modified point-count technique for only estimating the air content (Concrete Association of Finland, 2016). The modified point count method measures air content as the number of points falling on an air void divided by the total number of points in the grid. The modified point-count method is also used to estimate the volume proportions of all other constituents see Figure 2-9 (Lamond and Pielert, 2006).

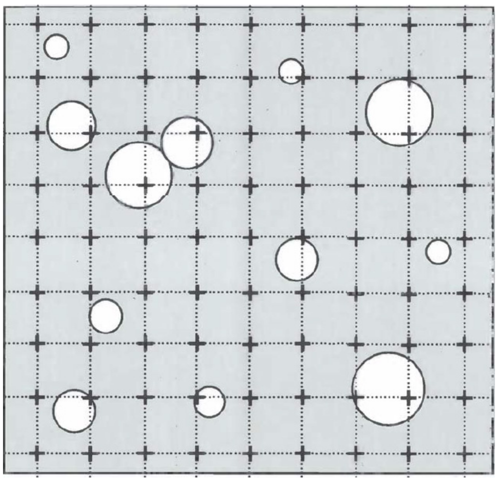

Figure 2-9 Representation of modified point count procedure (Lamond, Lamond and Pielert, 2006).

2.4.3.2 Precision and bias

The discourse of precision and bias that happens with ASTM C 457 incorporates the consequences of two examinations on precision (Wedding and Sommer, 1979). The precision and bias are measured on samples that are from the same set or either tested in the same or independent laboratories. In such a case that the same single sample is examined in the same laboratory under two independent measurements, the difference between the results are expected to be 0.82% of air content or less for 95% of the cases. Under the same conditions, the difference would reach 1.16% air content if two independent laboratories perform the measurements.

Another investigation by Sommer suggests that within the same laboratory the difference would be 1.61% or less of air content and 2.01% difference if the test is done in independent laboratories. The variation in air content increases in practice when the samples are chosen from in place concrete. The coefficient of variation also increases due to the surface preparation procedure belonging to each laboratory.

2.4.3.3 Source of variability and uncertainty in test results

The discussion of precision and bias reveals that the variability of results from the Thin Section analysis depends on the sample to sample, laboratories, operators, and on uncertainty of the results due to their statistical nature. This provides that the same laboratory investigation on the same sample performed again would produce a slightly different result even though the same operator is conducting the test.

2.4.3.3.1 Inherent statistical uncertainty

The Modified point-count procedure represents only a small fraction of air content for a small part of the concrete, therefore, the results are a statistical estimate that depends on a limited amount of observation. For example, if a portion of concrete is examined and that portion contains a set number of voids, the actual voids observed would represent only a fraction of the total. This uncertainty arises from the variability of the concrete, the number of voids measured, the area of concrete sampled, and on the breadth of the distribution of void sizes, and the area of cement pastes available (Lamond, Lamond and Pielert, 2006).

2.4.3.3.2 Sampling

The accuracy of the microscope testing would still vary based on the number of samples used even if the concrete placement being examined were homogeneous throughout. Because the results of the examinations are statistical estimates of the exact values, the error inherent in the reported values “decreases exponentially” based on the number of specimens (Pleau *et al.*, 1990).

2.4.3.3.3 Surface preparation

Based on information from Wedding and Sommer in 1979, the effects of the preparation of the specimens can by itself affect the results of the ASTM C 45 testing by up to 3% of air content.

2.4.3.3.4 Operator subjectivity

The most important and sensitive factor required in the microscopic testing of the air-void systems in concrete is the human brain itself and the use of the human eye as an input device. The time-consuming procedures and processes involved in this testing was imposing great stress to each of these. Although a lot of the machinery used in the testing was helpful in creating more efficient use of time and effort, the human observer and tester remain the critical component in decision making. Specifically, when to begin and end individual measurements of chord length, and whether the constituent under the crosshairs is coarse aggregate, fine aggregate, paste, or an air void. Often these decisions are difficult, such as when the crosshairs or traverse line is nearly tangent to a void or when insufficient surface preparation makes boundaries vague. Detailed observations are found in the notes and text of *ASTM C 457.* Operator bias can be especially critical in the modified point-count procedure when the crosshairs fall directly on the edge of an air void. Counting this as an "air" or "non-air" point is a subjective decision that can greatly alter the examination results.

2.4.3.3.5 Random deletion of large voids

ASTM C 456 indicates, "No specification is made for the distinguishment among water voids, entrained air voids, and entrapped air voids. Any such distinction is subjective because the various types of voids conform in size, shape, and other attributes". Some testing agencies nevertheless distinguish at least between coarse aggregate voids and entrapped-entrained air voids. However, VTT TEST-R003-00-2010 method separates the protective and compaction air voids. Air voids with a diameter of less than 0.8 mm are counted as protective voids (Concrete Association of Finland, 2016).

3 Experimental work

The objectives of the laboratory investigation were to measure the air content in fresh and hardened concrete (see Table 3-1). The laboratory tests were selected based on existing standards and literature studies for measuring the air content in fresh and hardened concrete.

The research investigation was carried out at Aalto University in the School of Engineering to evaluate the non-standard methods of measuring air content in hardened concrete and to explore the correlation between them. The laboratory work started with sixty mix design trials to determine the best mix design for nine types of concrete. These nine mix-designs consist of three different w/c ratios, and each w/c ratio included three air content classes.

The different tests and their standards that are adopted in this thesis are shown in the following Table.

Table 3-1 Standard codes for concrete laboratory tests.

Laboratory Test	Standard
Fresh Concrete	
Slump Test	SFS-EN 12350-2:2009
Gravimetric (Concrete Density) Test	SFS-EN 12350-6:2009
Air Pressure Meter Test	SFS-EN 12350-7:2009
CiDRA AIRtrac Test	-
Hardened Concrete	
Compacting and Curing	SFS-EN 12390-1:2000
Shape, Dimensions and other Requirements for Specimens and Moulds	SFS-EN 12390-1:2000
Cored Specimens	SFS-EN 12504-1:2000
Density of Hardened Concrete Test	SFS-EN 12390-7:2009
Pressure Saturation Test	SFS-4475:1988 (Old Finnish Standard)
Thin Section Test	-
Compressive Strength Test	SFS-EN 12390-4:2000

3.1.1 Material selection

In the mixtures, different cement contents were chosen for the different water-cement ratios. Plus Cement, produced by Finnsementti, was used in the concrete. The chemical compositions of the cement used are presented Table 3-2. These values were obtained from the cement manufacturer.

Table 3-2 Properties of Plus Cement used in the test series (*Finnsementti | Suomalainen sementinvalmistaja*, no date).

Properties	Plus Cement, Finnsementti CEM II/B-M (S-LL) 42.5 N
1d Strength	15 MPa
7d Strength	39 MPa
28d Strength	49 MPa
Initial Setting Time	150 – 210 min
Soundness	0 – 1.5 mm
Fineness	420 – 470 m^2/kg
Chemical Composition	
CaO	65 %
SiO_2	21 %
Al_2O_3	4.7 %
Fe_2O_3	3.5 %
MgO	3.1 %
Lime Stone	6-15 %
Blast Furnace Slag	15-25 %

In this investigation, the granitic aggregate was washed, dried and graded by sieving. Seven different aggregate fractions were used in the mix design. The maximum size was 16 mm. The moisture absorption of the aggregates is assumed to be 0.4% by mass. The grading curve of the mix-designs is presented in Appendix A. The aggregation fractions are illustrated in Table 3-3.

Table 3-3 Aggregate fractions used in the concrete mix design.

Aggregate Type	Fraction	Size mm]
Filler	R 96	<0.125
Fine Aggregates	R 0.1/0.6	0.1-0.6
	R 0.5/1.2	0.5-1.2
	R 1/2	1-2
	R 2/5	2-5
Coarse Aggregates	R 5/10	5-10
	R 8/16	8-16

Tap water was used to create the concrete with a temperature of 20 ± 2°C.

The air-entraining agent and superplasticizer were added with recommended dosages. The amount that was used in each mix design is presented in Appendix A. The admixtures were stored in the bottle of polyethene at room temperature (+20 ± 2°C). The physical properties and dosage recommendation according to the information received from the manufacturer is presented in Table 3-4.

Table 3-4 Admixture used in the concrete mix designs.

Admixture Code	Manufacturer	Colour	Recommended Dosage/ Binder	Density, [kg/dm^3]
Ilma-Parmix	Finnsementti Oy	amber	0.05% - 0.1%	1.02
VB-Parmix		brownish	0.5% - 1.0 %	1.03

3.1.2 Mix design

The concrete mix-designs were calculated using the absolute volume method, and batches consisted of a volume of 130 dm^3 each. The absolute volume equation was used of proportioning of the concrete mixtures. The mixture consists of water, cement, aggregates, air and admixtures.

$$\frac{W_{cement}}{\rho_{cement}} + \frac{W_{aggregate}}{\rho_{aggregate}} + \frac{W_{admixtures}}{\rho_{admixtures}} + W_{water} + Air = 1\ m^3 \quad (1)$$

Where:

W	is the mass of the material, [kg]
ρ	is the density of the material, [kg/m^3]
Air	is the air content, [m^3]

The concrete mixtures were coded based on different water-cement ratios and target air contents. The concrete samples, that were later prepared, were supplemented according to the core numbers and disk numbers as presented in Figure 3-1.

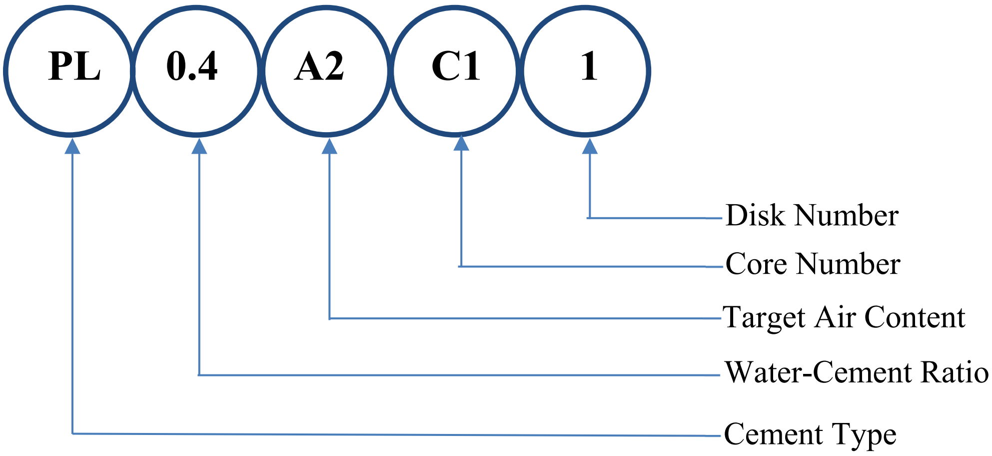

Figure 3-1 Description of mixture and sample coding used in this thesis.

The research investigation involves three water-cement ratios with low, moderate, and high air content. The reason for the selection of the different w/c ratio was to investigate if w/c ratio influences the results of air content in hardened concrete. The nine concretes mixtures were labelled according to Table 3-5.

Table 3-5 Concrete coding for different W/C ratios and Air Contents.

	Air content		
W/C ratio	**2%**	**5-6%**	**10-12%**
0.4 W/C	PL-0.4-A2	PL-0.4-A5	PL-0.4-A10
0.5 W/C	PL-0.5-A2	PL-0.5-A5	PL-0.5-A10
0.6 W/C	PL-0.6-A2	PL-0.6-A5	PL-0.4-A10

Each w/c ratio has different paste amounts and aggregate fraction portions. However, in each group of w/c ratio the amount of water and cement is the same, only the aggregate portion changes due to the replacement of aggregate to air as the air content in the mixtures increase. The amount of aggregate portion, water and cement in the nine mixtures concrete is presented in Table 3-6.

Table 3-6 The composition of the concrete mix design.

Concrete	**Concrete Composition [kg/m^3}**				
	Cement	**Water**	**Aggregates**		
			Filler	**R0.1-5**	**R5-16**
PL-0.4-A2	400	160	129	937	772
PL-0.4-A5	400	160	123	898	739
PL-0.4-A10	400	160	114	832	685
PL-0.5-A2	320	160	115	974	821
PL-0.5-A5	320	160	110	936	789
PL-0.5-A10	320	160	102	869	733
PL-0.6-A2	300	180	150	1108	619
PL-0.6-A5	300	180	144	1062	594
PL-0.6-A10	300	180	133	983	551

3.1.3 Mixing procedure

Fresh properties of concrete depend on multiple variables such as the following: the time of mixing, the speed of mixture, the amount of batch, the temperature of the concrete, the loading the batches, the water-cement ratios and the fraction portion. Therefore in this report, the guidelines of the Robust Air research (Jouni *et al.*, 2017) were used for this experimental investigation.

Figure 3-2 Mixer used for casting the concrete.

The drum of the mixer was moistened before any material was added. Loading the mixer starts with aggregate fractions of 2/5 – 8/16 and then cement powder is added to the mixture. Next, 1/2 – 0.1/0.6 is added, and finally the filler is added last.

The concrete mixing procedure is summarized in the following four steps:

Step 1: Dry mixing of an ingredient of concrete for 30 seconds.

Step 2: 80% of the water was added to the dry mix for another 30 seconds.

Step 3: 10% of the water was added together with an air entraining agent for another 30 seconds.

Step 4: Finally, 10% water was added together with the superplasticizer during the continuous mixing. The batch was mixed for up to a total of five minutes over all the steps to reach the air content potential.

3.2 Testing of fresh concrete

The properties of fresh concrete were determined during with CiDRA and right after the mixing procedure. Standard tests were done according to the list below.

- CiDRA AIRtrac is the air content measurement in real time, which is fixed into the bottom of the mixer (see Figure 3-3a). The measurement technique used was the following: (*Teemu Ojala Analyzing the air-entrainment of fresh concrete with an acoustic measurement system*, 2017).
- Workability by the Slump Test method (see Figure 3-3b).
- The gravimetric method using the density of fresh concrete accordingly: see above (Figure 3-3c).

$$A = \frac{(T - D)}{T} * 100 \quad (1)$$

Where: *A* is the volume percent [vol%] of air content in concrete,
D is the unit weight measurement of the concrete, [kg/m^3]
T is theoretical density with free-air bases in concrete, [kg/m^3]

$$T = \frac{M}{V} = \frac{M}{1 - A_t} \quad (2)$$

Where: *M* is the mass of all the materials in the batch, [kg]
V is the absolute volume of the ingredients in the batch, [m^3]
A is the target air content of the batch, [m^3]

By solving equations (2) and (3) for the air content (A), the air content can be determined:

$$A = \left(1 - \frac{D}{M} + \frac{D * A_t}{M}\right) * 100 \quad (3)$$

- “Air pressure meter” (see Figure 3-3d).

a) CiDRA AIRtrac b) Slump Test c) Gravimetric Method d) Air Pressure Meter

Figure 3-3 Different apparatus for testing of fresh concrete were used.

3.3 Preparation of specimen

Two types of concrete moulds were used in the investigation research.

- Timber mould was made with the dimensions of 500x500x150 mm^3. This mould was used for all casting concrete blocks. Each concrete block was demoulded one day after casting (see Figure 3-4).
- Concrete cubes cast into steel moulds with the dimension of 100x100x100 mm^3 were used to carry out the compressive strength test (see Figure 3-5).

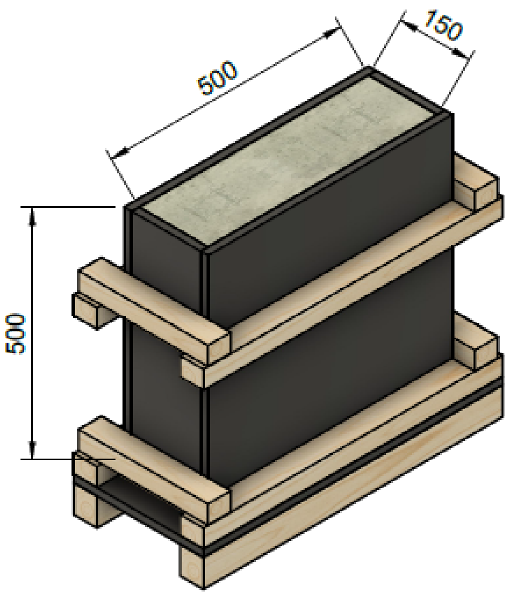

Figure 3-4 Concrete block for testing the air content measurements.

Figure 3-5 Concrete specimen for Compressive strength test.

All the test concretes were compacted for the same period of time and at the same height using the same poker vibrator. This was done to retain consistency through the different concretes. Before air content was measured with an air pressure meter, a layer of fresh concrete of 125mm was placed inside of an air pressure meter container. Then the poker vibrator was vertically inserted in the centre of the container for nine seconds. The second layer of 125mm was added and the vibrated with the same procedure and time period.

The poker has a diameter of 25 mm. The Wacker Neuson vibrator has a low vibrating output power of 1.5 kW. Therefore, the vibration of the concrete required a long time period for proper compaction (see Figure 3-7).

The eight litres of concrete was vibrated for 18 seconds for the container of the Air Pressure Meter. Therefore, the vibration time for one cubic meter of concrete is 18*(1000/8) = 2250 s/m^3. The concrete block has a volume of 37.5 dm^3 and must be vibrated for 2250*0.0375=84.375s. The blocks are vibrated in twelve compaction points. The height is divided into four layers of 125 mm each and each layer also with three vibrating points. (see Figure 3-6). Each section was subjected to a vibration duration that was calculated as follows:

$$\frac{1}{12 \text{ quadrants}} * 84.375\text{s} = 7.03\text{s} \approx 7 \text{ s} \tag{4}$$

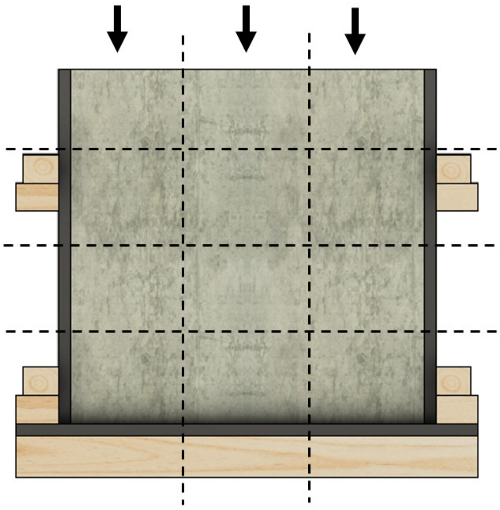

Figure 3-6 Concrete block compaction points.

The vibration of each cube sample for compressive strength test was done by a table vibrator for the duration of two seconds (see Figure 3-8).

Figure 3-7 Vibration used for vibrating the concrete block and Air pressure meter container.

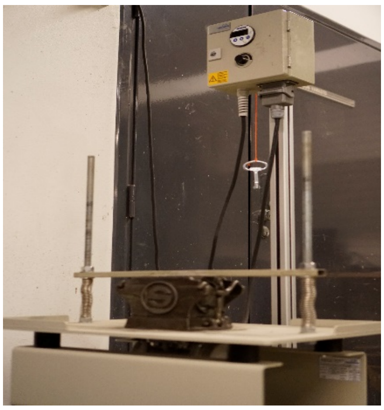

Figure 3-8 Vibration table used for vibrating cube.

Curing of all specimens was done in a controlled environment laboratory (20 ± 2 °C). After casting the concrete, the concrete was covered with a plastic sheet for 24 ± 2 hours to prevent evaporation of water. After 24 ± 2 hours the specimens were demoulded. Concrete cubes were placed in a chamber room with RH=95% for a total of 28 days. Concrete blocks were placed underwater in plastic containers for a total of 28 days.

Figure 3-9 Concrete blocks, one day after casting.

Figure 3-10 Curing tanks.

3.4 Preparation for testing in hardened concrete

For the research investigation, 144 cores were drilled from nine concrete blocks. Laboratory work with hardened concrete started with the concrete taken out of the water tank before 28 days. First, each of the sixteen cores were identified. The coding convention was based on the location of the core starting on the bottom left and continuing to the upper right side. The sixteen concrete cores were drilled from each block in the dimensions of 98 mm x 150 mm (See Figure 3-12). After the cores were drilled from the blocks, they were placed under water in a container in the laboratory room (20 ± 2 °C).

Figure 3-11 Concrete block preparation for drilling.

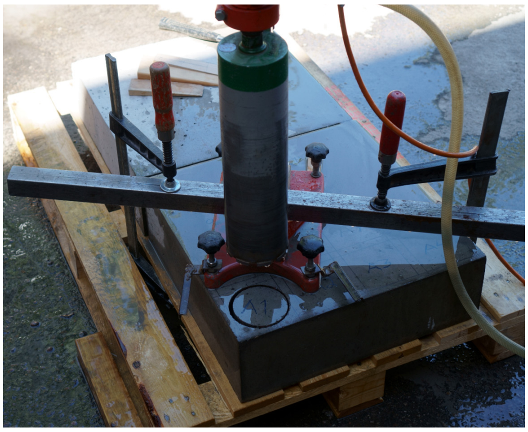

Figure 3-12 Drilling of concrete blocks.

3.4.1 Water saturated density calculation

Specimens were taken out for Water Saturated Density tests before 28 days. Density tests of the blocks and cores were measured according to the standard of SFS-EN 12390-7:2009.

The following procedures were followed:

a. Visual inspection was done for all the cores for any sign of segregation.
b. Adjust the temperature of the water to the 20 ± 2 °C.
c. By using the underwater weight scale the weight was determined (see Figure 3-13 and Figure 3-14).
d. Wiping the surplus water from the surfaces using a paper towel and then the weight of the samples in the air was determined.

By having the measured density of hardened concrete, the air content of concrete was calculated according to the same formula as (4).

Figure 3-13 Measuring the water saturated density of concrete block without cores.

Figure 3-14 Measuring the water saturated density of cores.

After the cores were tested by Saturated Density, the selected cores for the Thin Section, Pressure Saturation and compressive strength test were sawn in the laboratory. More details of saw-cuts for each method are explained in the following sections.

Figure 3-15 Saw-cut used for the experimental work.

3.4.2 Pressure Saturation test

The Pressure Saturated test started after the 28th day. Selected cores for Pressure Saturation were sawn into four slices of 20 mm thick concrete disks with a diameter of 98 mm (see Figure 3-16).

Figure 3-16 Four disks are used for Pressure saturation test.

The preparation procedure for the Pressure Saturation test was done according to the modified standard of SFS-4475:1988. Test method had the following stages:

1. *Drying of concrete samples*

The specimens were placed in the oven at a temperature of 105 degrees for a period of 24 ± 2 hours. The drying was controlled until constant weight was achieved. The specimen was checked to see if the weight change of the concrete did not exceed 0.05% of the specimen weight over the period of 24 ± 2hours (see Figure 3-17a).

2. *Measurement of the specimen after cooling*

After the concrete reached constant weight, the specimen was placed in a vacuum-sealed box for 24 ± 2 hours to cool down, and then the weight of the sample was measured at room temperature (see Figure 3-17b).

3. *Saturating the specimen*
    a. ¼ of the height of the specimen was immersed into a water reservoir with the temperature of 22 °C.
    b. Over the next two hours water was added to the reservoir to ½ the height of the specimen.
    c. Over the next two hours, water was added into the reservoir until it reached ¾ height of the specimen in a way in which air did not become trap inside of the specimen.
    d. After the following day, the water was added into the reservoir until the disks were covered entirely inside the water. The specimen was stored under water until the weight of the sample did not change over a period of 24 ± 2 hours with the difference being less than 0.05% of the weight of the sample (see Figure 3-17c).

4. *Weighting the saturated specimen*
    a. After the concrete was saturated, each sample was wiped with a paper towel to remove the surplus water on the entire surface. Afterwards, the weight of the sample in the air was measured.
    b. Weighing the specimen under water using the underwater weighing scale (see Figure 3-17d).

a) Oven with 105°C was used for drying samples. b) Vacuum sealing the hot samples. c) Saturating the samples. d) Weighing of samples in air and under water.

Figure 3-17 Preparation of Pressure saturation test.

5. *Water Pressure Saturation*
   a) The specimens were placed in a Pressure Saturation apparatus. It was linked to compressed air from an assembly line being pumped into a compressor. As a result, the liquid was pressured into sealed, bolted vessels with the specimens submerged under water with until the water pressure of 15 ± 1.5 MPa for 24 ± 2 hours.
   b) Once the pressure was released from the vessel, each of the specimens were immediately wiped with a paper towel of surplus water over the entire surface and the weight of the sample was measured in the air (see Figure 3-18).

Figure 3-18 Pressure saturation apparatus.

According to data collected in the earlier steps, the following parameters can be calculated as follows:

Air content in hardened concrete:

$$A_{Air} = \frac{W_{pr} - W_{sat,air}}{V} * 100\ \% \qquad (5)$$

Total porosity of hardened concrete: $$A_{total} = \frac{W_{pr} - W_{dry}}{V} * 100\ \% \qquad (6)$$

Suction porosity of hardened concrete: $$A_{suction} = \frac{W_{sat,air} - W_{dry}}{V} * 100\ \% \qquad (7)$$

Where:

W_{pr}	is the weight of the sample in the air after pressure saturation, [g]
$W_{sat,air}$	is the weight of the capillary saturated sample in the air, [g]
$W_{sat,sub}$	is the weight of the capillary saturated sample under water, [g]
V	is the “volume” of the sample =$W_{sat,air}$ - $W_{sat,sub}$ [g]
W_{dry}	is the dry weight of the sample in the air, [g]

In addition to this report, the density of the specimens is calculated using the following formula (the result is represented in Appendix D).

Saturated density of hardened concrete: $$\rho_{sat} = \frac{W_{sat,air}}{V} * 1000\ \frac{kg}{m^3} \qquad (8)$$

Dry density of hardened concrete: $$\rho_{dry} = \frac{W_{dry}}{V} * 1000\ \frac{kg}{m^3} \qquad (9)$$

3.4.3 Thin Section method

Aalto University organised the Thin Section round-robin test analysis for this research investigation in Finland. Nine laboratories volunteered to be a part of round-robin test analysis investigation for Thin Section properties. The participating laboratories are well represented in Finland for void analysis. The laboratories are included:
dun

- Betonialan Ohuthiekeskus FCM Oy
- Contesta Oy
- Eurofins Expert Services Oy
- Kaakkois-Suomen Ammattikorkeakoulu Oy / KymiLabs
- KiwaLab
- Labroc Oy
- Pohjois-Suomen Betoni- ja Maalaboratorio Oy
- Vahanen Rakennusfysiikka Oy
- WSP Finland Oy

Entrained air mixed-designs were part of the investigation as shown in Table 3-7. Selection of cores for the Thin Section were based on the density of full cores in the middle section of concrete blocks which were close to each other in an effort to maintain similar properties (see Figure 3-20). Concrete cores were sawn into halves, and the saturated density of each sample was measured (see Figure 3-19). Afterwards, each sawn core was sent to the laboratories. The purpose of the test series is to find out how to scatter the method, not the differences between laboratories. Laboratories are not identified, but they are presented in the format Lab-A, Lab -B. The order is not the same as the list above. Samples, which were sent to the laboratories, were labelled in such a way that the information regarding the mixed-design was not disclosed.

Table 3-7 The concrete mixtures used for Thin section analysis.

Entrained Mix Design	
PL-0.4-A5	PL-0.4-A10
PL-0.5-A5	PL-0.5-A10
PL-0.6-A5	PL-0.4-A10

Figure 3-19 Saw-cut for Thin section samples.

Figure 3-20 Thin section selection based on density in the middle of block.

3.4.4 Compressive Strength test

3.4.4.1 Compressive Strength test of drilled specimens

Based on the density of each core in each block, the cores were selected for the Compressive Strength Test. To be able to represent the average density of block three cores in each block were selected for the test in which the average of these three cores was equal to the average density of the entire block. The Compressive Strength Test was done according to the standard of *Testing hardened concrete* SFS-EN 12390-4:2000. According to the standard, the dimensions of the core should be 1:1. Therefore, the selected cores were saw-cut on both sides and each side was 24 mm (see Figure 3-21 right). After the sawing, the specimens were ground by about 2mm on each side in order to have the concrete perfectly flat on each side (see Figure 3-22).
Samples were taken out from a water tank after 28 days and kept at room temperature for three days to dry out, and then the Compressive Strength test was performed on each core sample (see Figure 3-23). The strength results have been changed to be equivalent to 150 mm cubic strength.

3.4.4.2 The Compressive Strength of lab specimen

The samples were taken out of the chamber room after 28 days. Three specimens were tested on each block at that time (see Figure 3-21 left). Strengths results have been changed to be equivalent to 150 mm cubic strength.

Figure 3-21 Compressive strength tests for lab and drilled specimens.

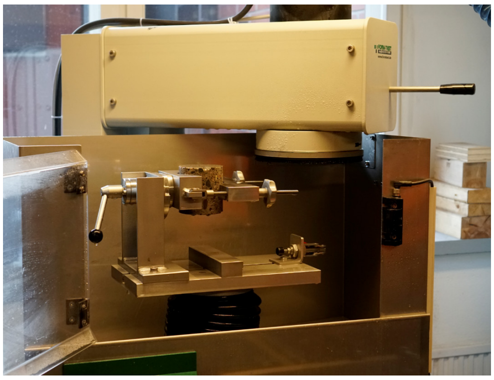

Figure 3-22 Grinding machine used for flatted the samples in order to avoid the error for results of Compressive strength test.

Figure 3-23 Compressive strength test used for measuring the strength of concrete.

4 Experimental results

The Experimental Results chapter is divided into three parts.

1. Results of fresh concrete properties, which is the key parameter of indication of the air content of concrete.
2. Results of the density of hardened concrete cores to assign them to different test methods.
3. Results of air content of hardened concrete for the nine blocks with three different methods used to determine the air content of hardened concrete.

4.1 The result of fresh concrete measurements

The results of the air content of the Gravimetric method, Air Pressure Meter, CiDRA AIRtrac Measurement and Slump Test are represented in the current section. The tests are performed according to the standards and study case of other researchers as mentioned in section 3.2 The figures below illustrate the air content and slump value according to the range of water-cement ratios categories, which are with low, moderate, and high air content.

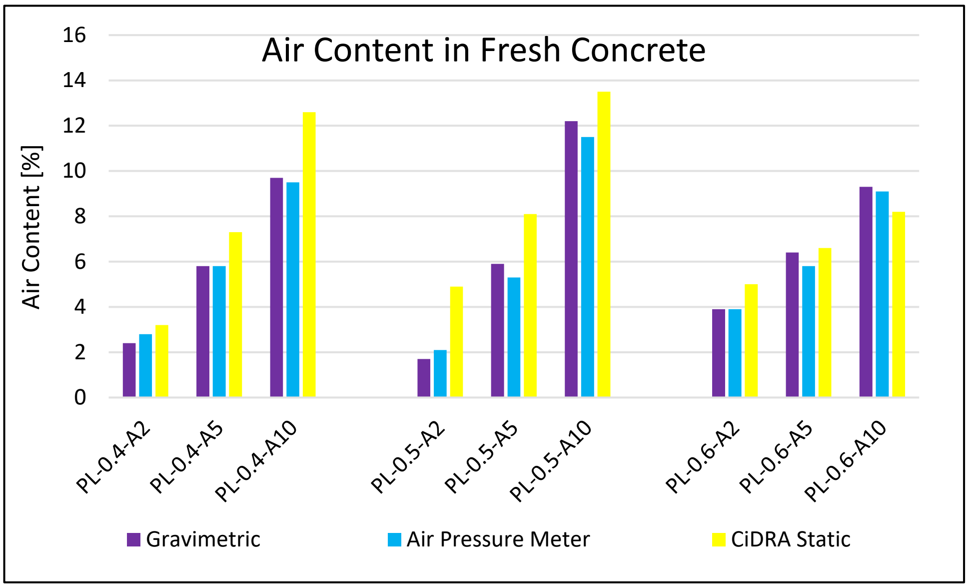

Figure 4-1 Result of air content of fresh concrete for nine mixtures.

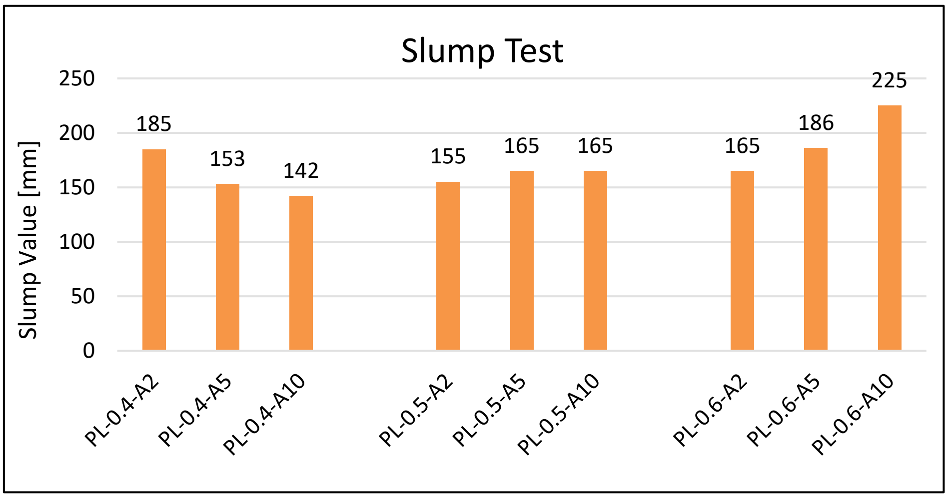

Figure 4-2 Results of Slump test values for nine mixture.

4.2 Result of Hardened Concrete Measurement

4.2.1 The Density of Hardened Concrete

This section describes the density difference of fresh and hardened concrete and is described with the following equation:

Density differences:

$$\rho_{\text{Differences}} = \rho_{Hardened} - \rho_{Fresh} \left(\frac{kg}{m^3}\right) \quad (10)$$

Where: $\rho_{Hardened}$ is the saturated density of hardened concrete, [kg/m^3]
ρ_{Fresh} is the density of fresh concrete, [kg/m^3]

The densities of hardened concrete vary from core to core. However, the fresh density in each block is assumed as a constant value. The result of each method can be found in Appendix B. The water saturated density of hardened concrete and density of fresh concrete were measured according to standards as described in chapter 3. The results are illustrated in the figures using both numeric and colour variations. The contour colour-fill is done with an application named Origin. On the right side of the figures below, the density is depicted based on both a numeric and colour representation. As the density of hardened concrete decreases, the colour becomes lighter and vice-versa. As the concrete is more dense (lighter colour), there is less air or it is segregated. The selection of each test method of each core is based on the density of that core. The test method of each core is named on the core in each figure in this section.
Figure 4-3 to Figure 4-5 are illustrating the air content of A10 with 0.6, 0.5 and 0.4 water-cement ratios.

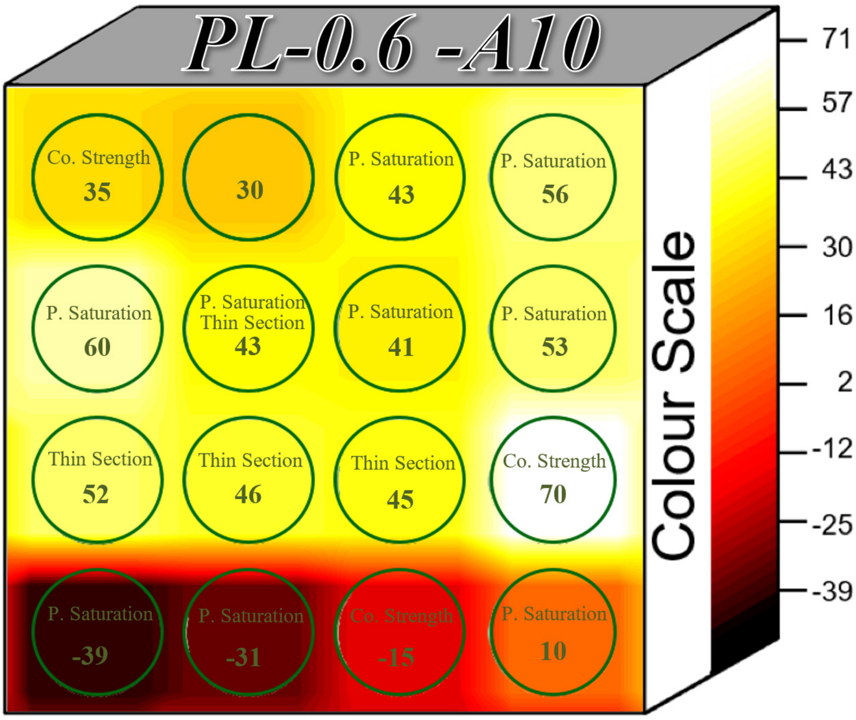

Figure 4-3 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

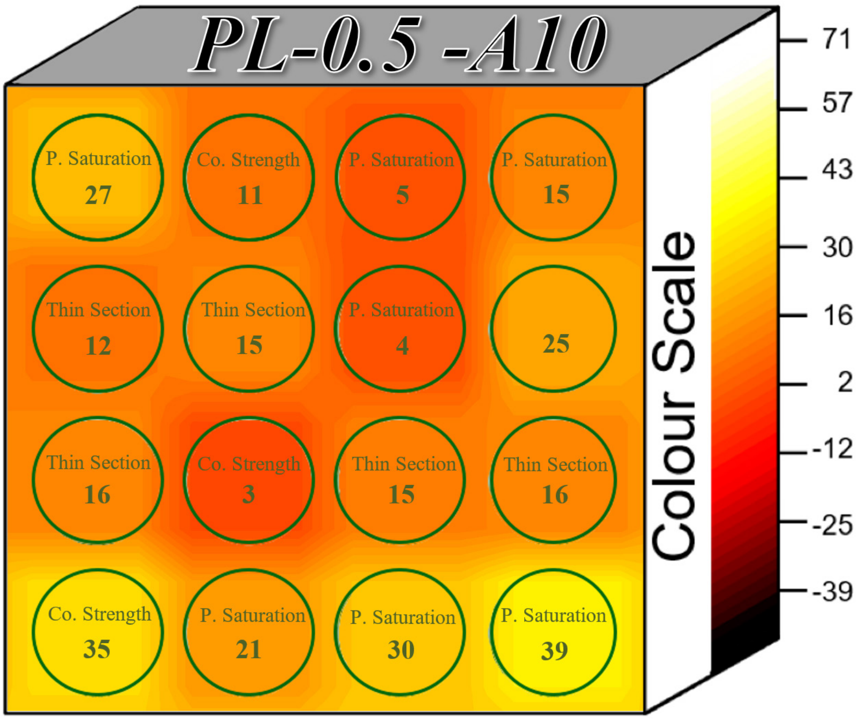

Figure 4-4 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

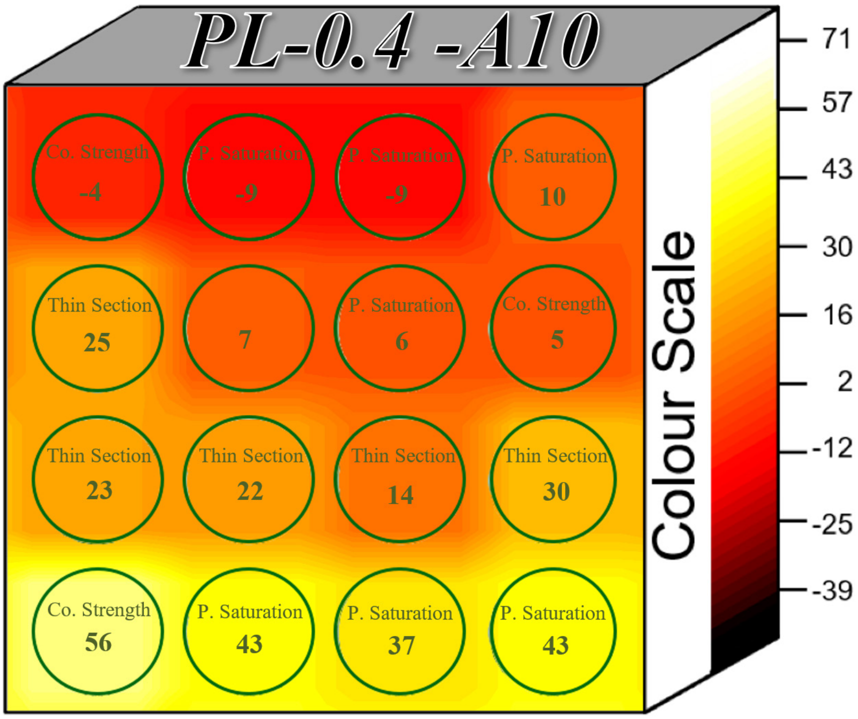

Figure 4-5 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

Figure 4-6 to Figure 4-8 are illustrating the air content of A5 with 0.6, 0.5 and 0.4 water-cement ratios.

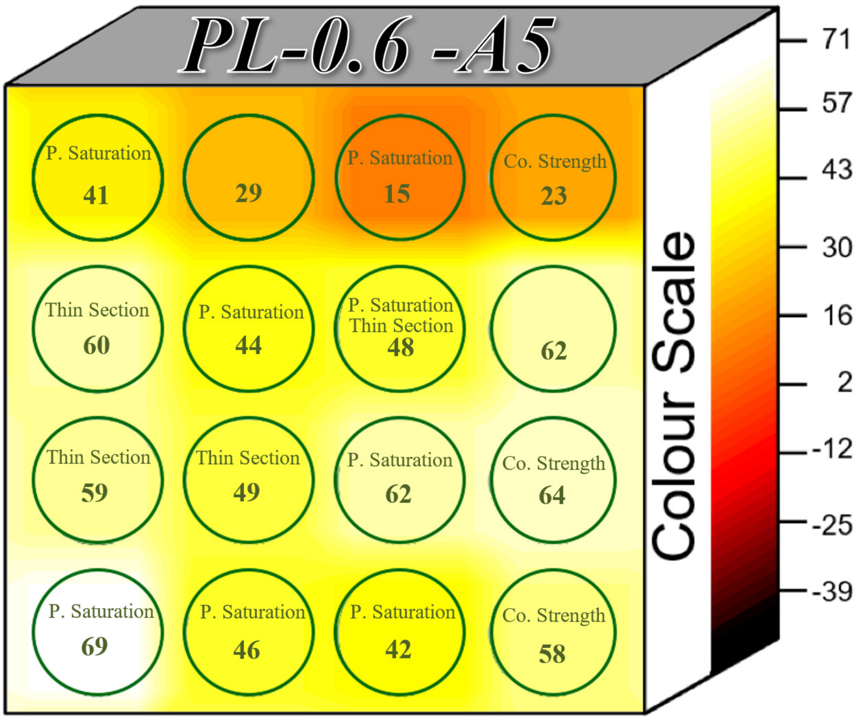

Figure 4-6 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

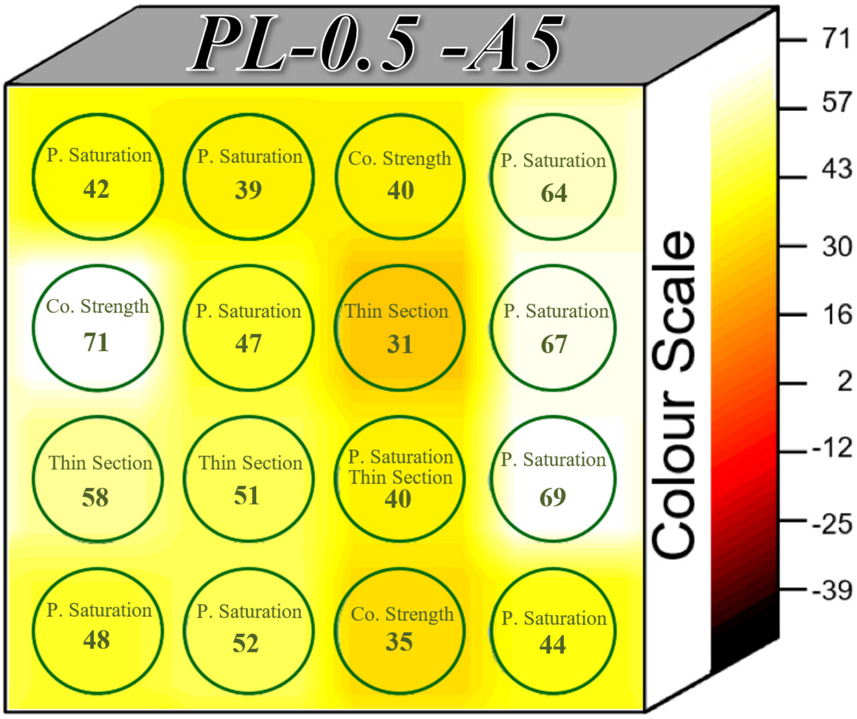

Figure 4-7 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

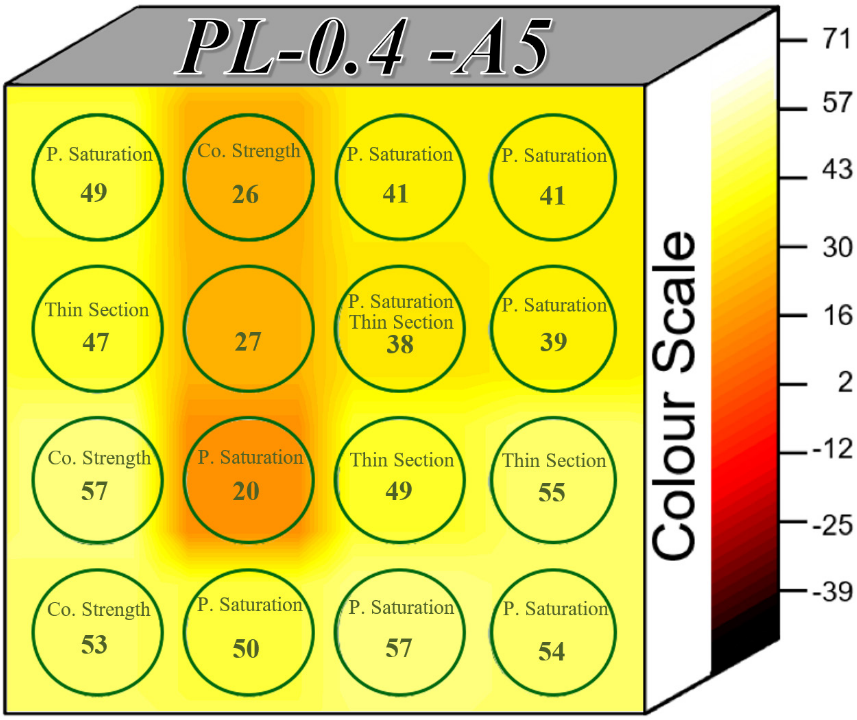

Figure 4-8 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

Figure 4-9 to Figure 4-11 are illustrating the air content of A2 with 0.6, 0.5 and 0.4 water-cement ratios.

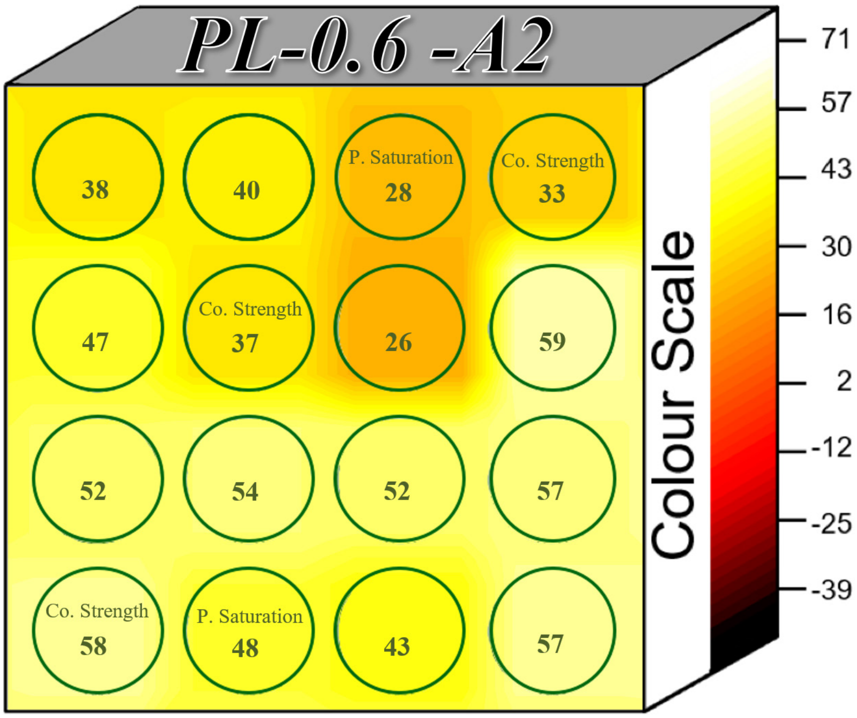

Figure 4-9 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

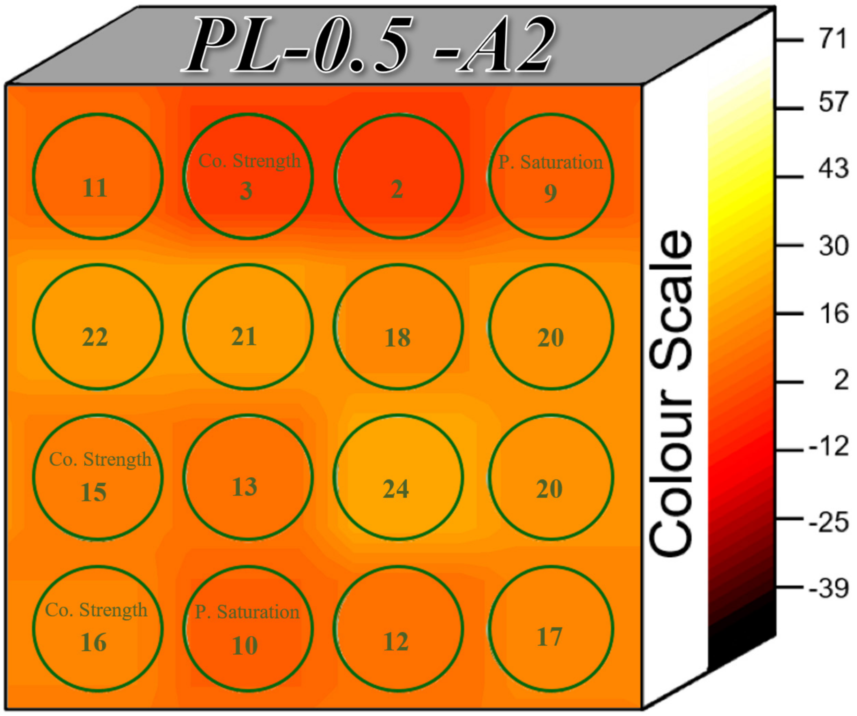

Figure 4-10 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

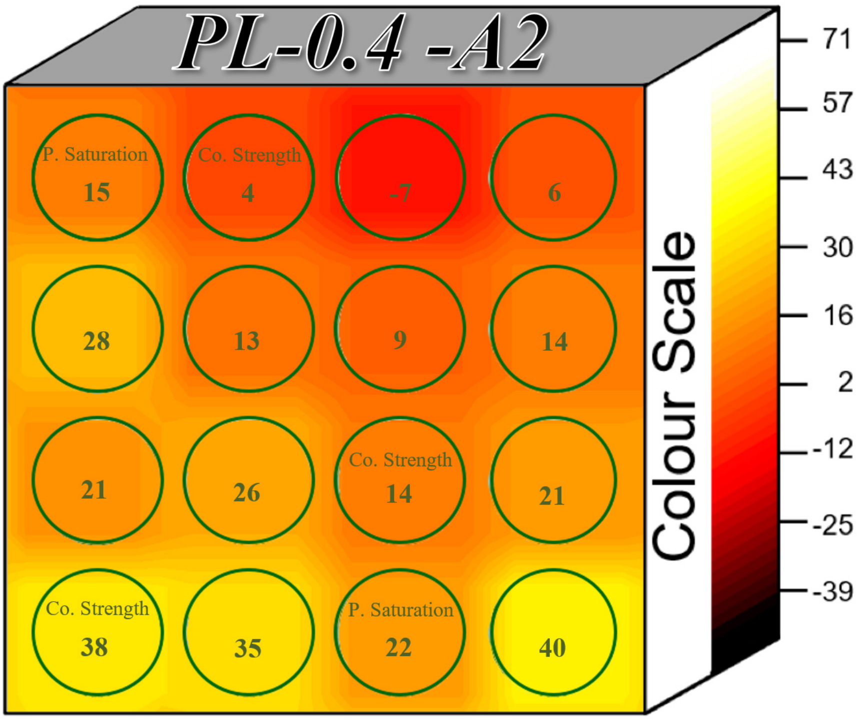

Figure 4-11 Density differences between hardened and fresh concrete are shown numerically and with color variation in units of kg/m^3. The cores are named according to the test methods selected for them (Co: Compressive, P: Pressure).

4.2.2 Air content in hardened concrete

Air content in hardened concrete is measured according to the non-standardized experimental methods. The figures hereafter show the visualisation of air content results in concrete blocks. Each bar with a distinctive colour in each core represents the result of a measuring method by percentage. The colours green, blue and red represents the Calculated method by water saturated density, Pressure Saturation method and Thin Section method correspondingly. The Thin Section Method is represented by light red on the top half core, and dark red in the bottom half of the core.
The cores that were tested for Pressure Saturation (shown in blue) were each cut into four discs, and the results are from the average of these four discs. For the cores that were tested with the Calculated method (shown in green), if also the Pressure Saturation is tested on the cores then the calculation was made from an average of the discs and at the same time if the core was not cut (i.e. there was no Pressure Saturation test), the calculation was made on the entire core.

For more information on each disk see the Appendix D. The cores on which Compressive Strength tests were performed, only the Calculated method tests were completed.

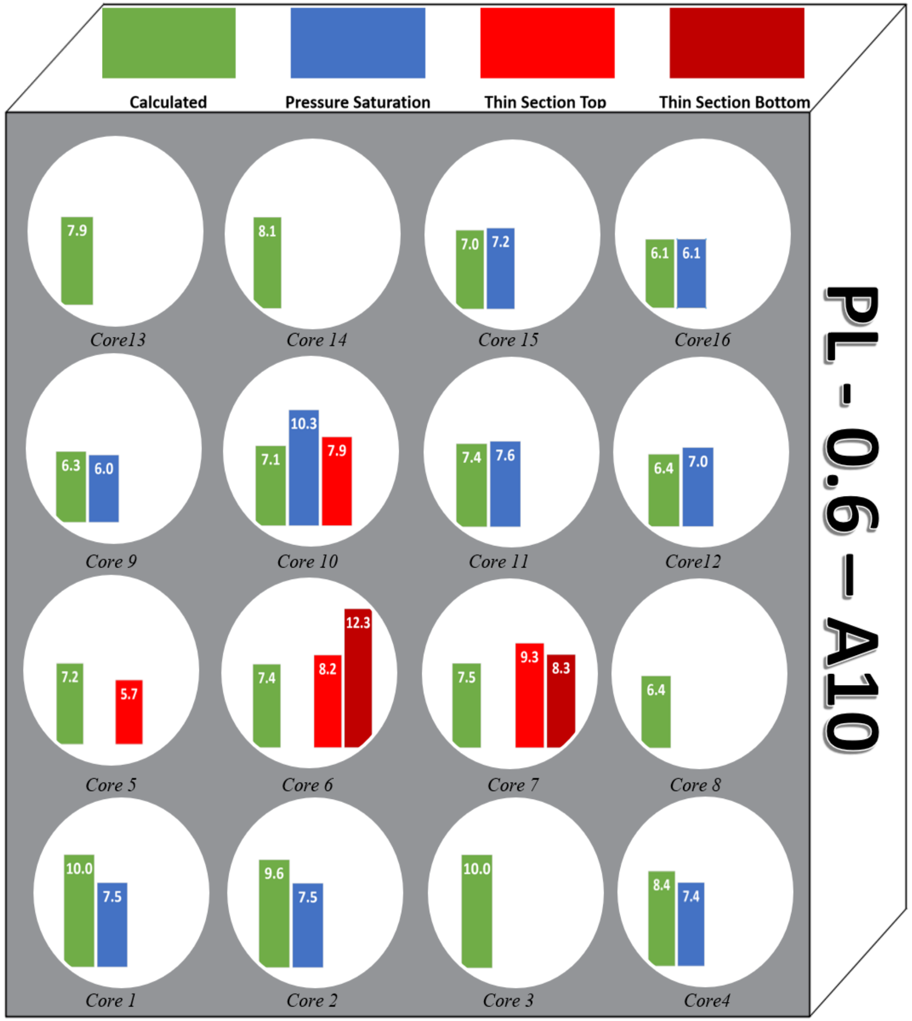

Figure 4-12 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

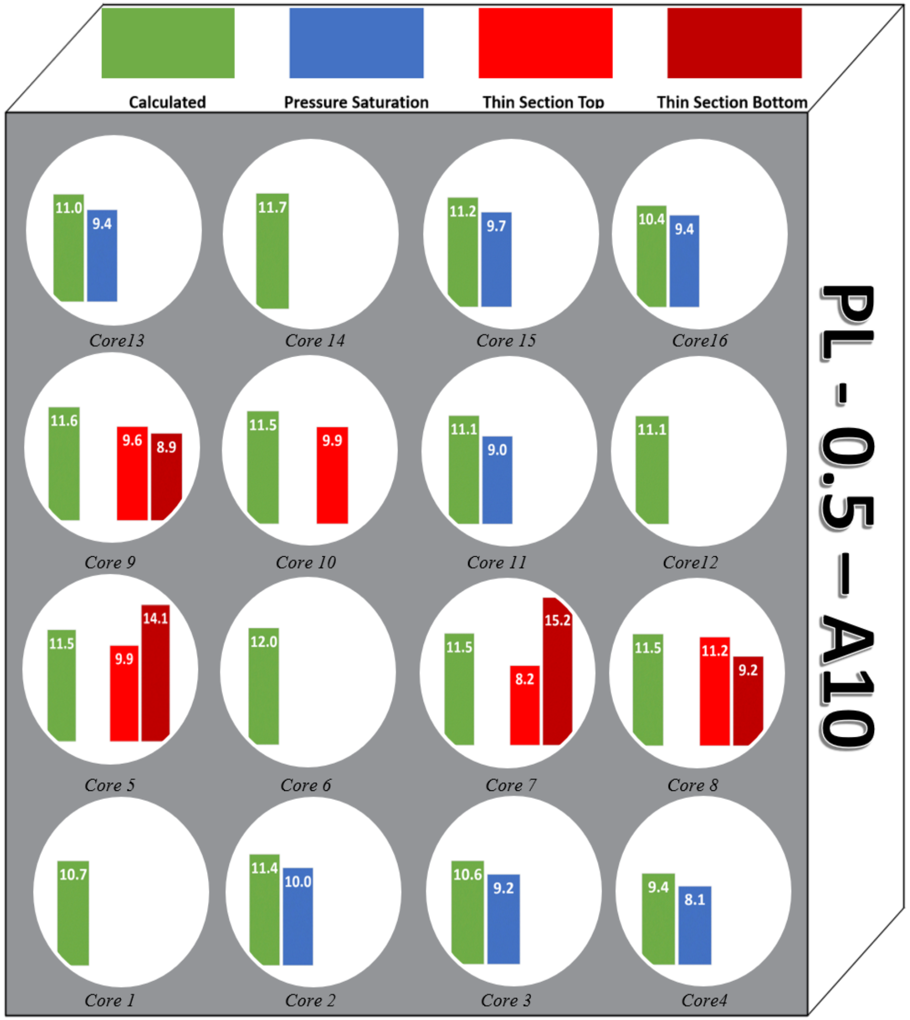

Figure 4-13 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

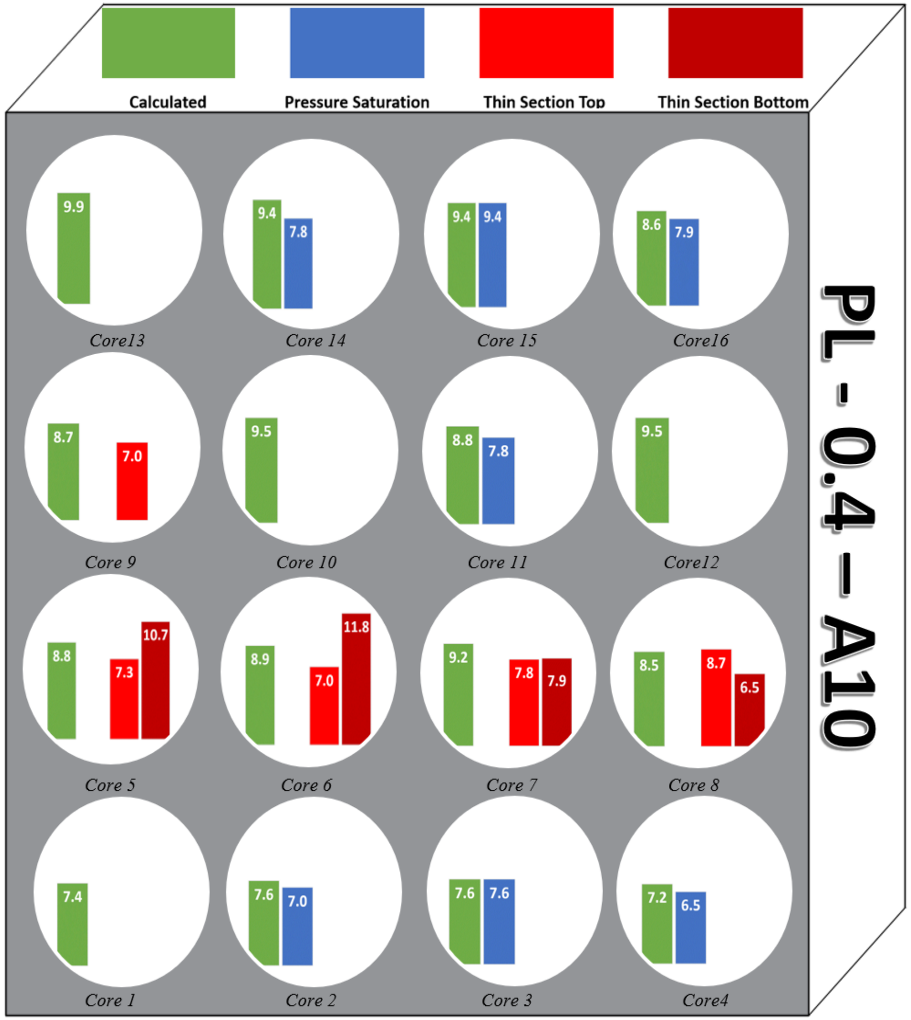

Figure 4-14 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

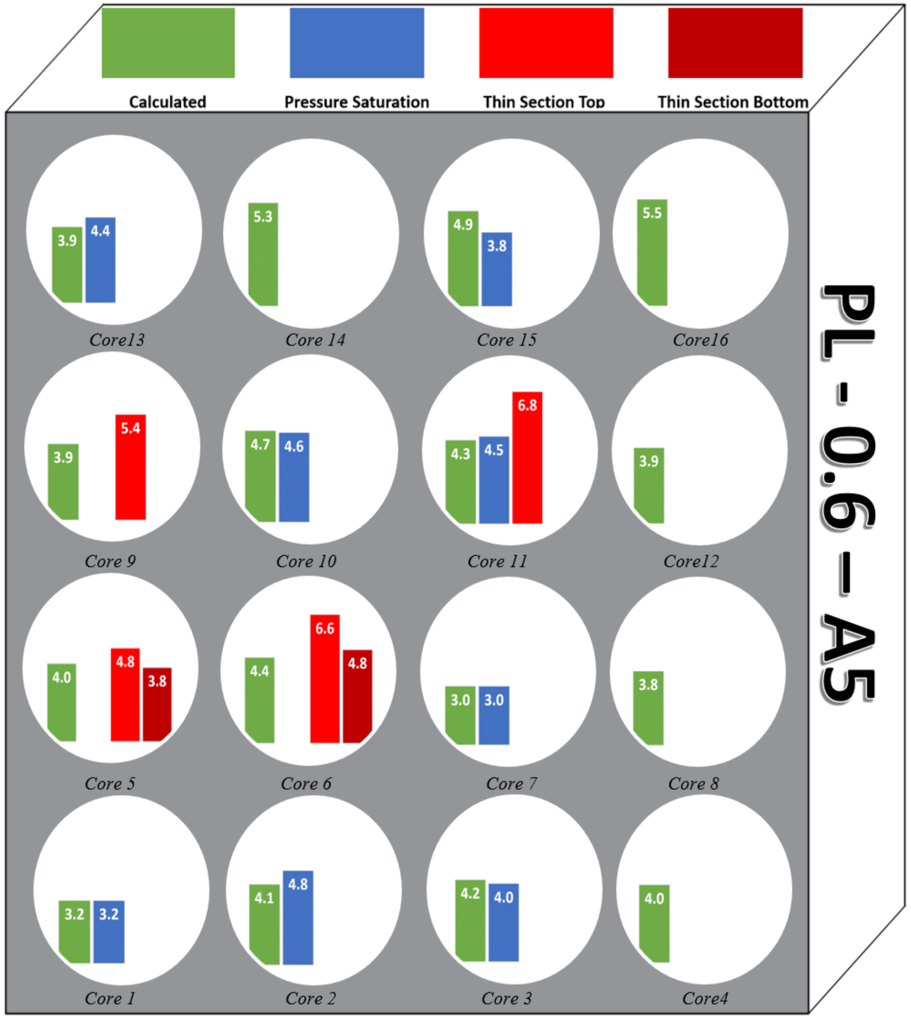

Figure 4-15 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

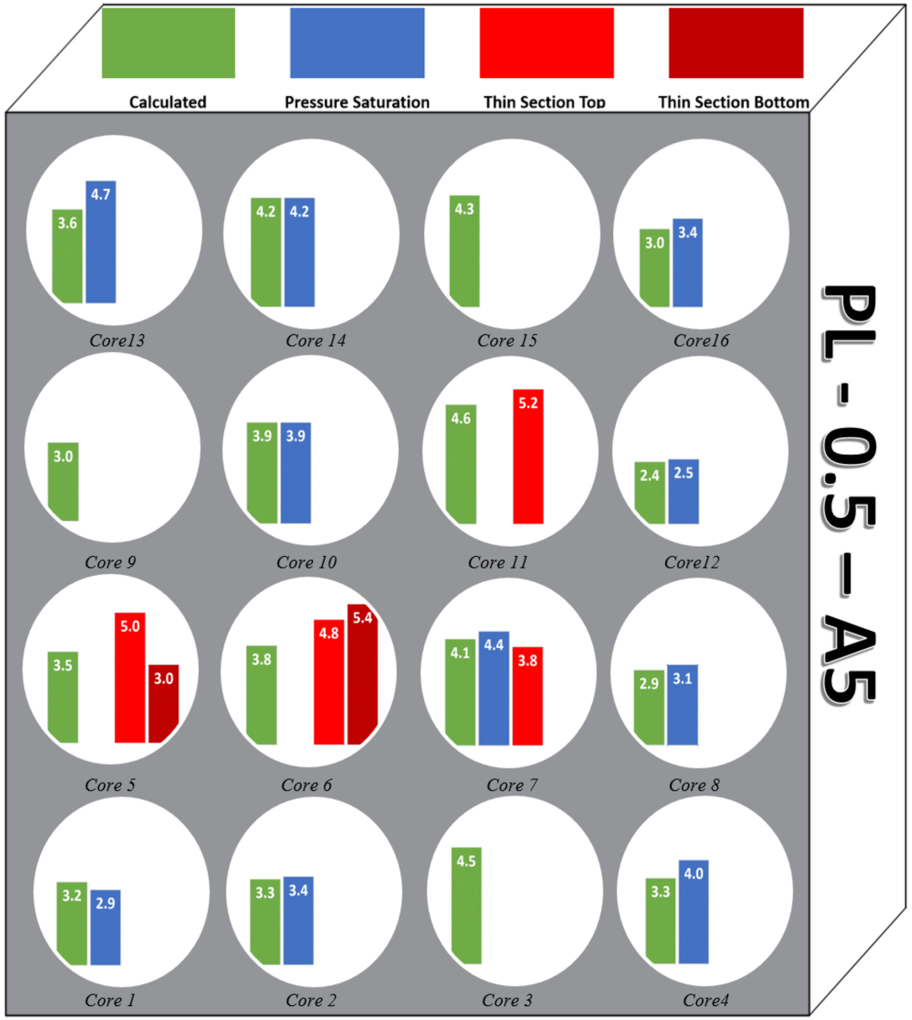

Figure 4-16 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

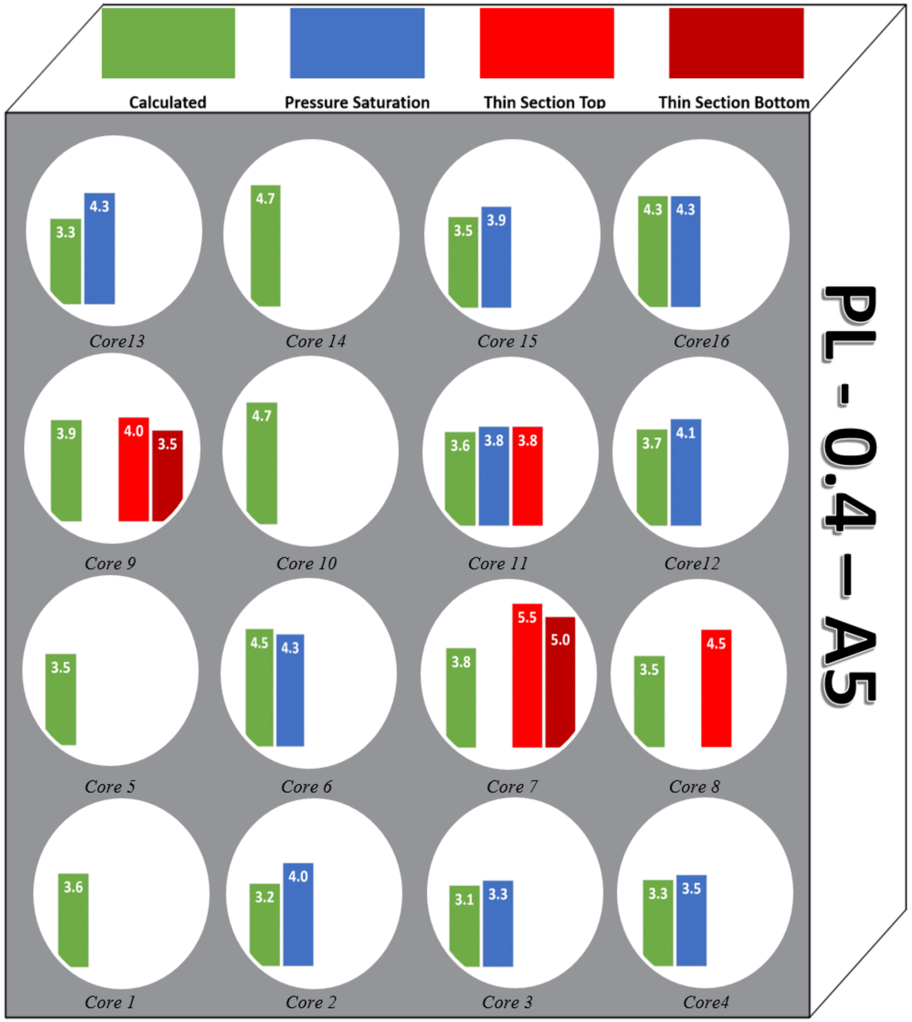

Figure 4-17 Test methods for measuring air content are shown in green, blue and light-dark red represents the Calculated method, Pressure Saturation, Thin Section on top and bottom of core correspondingly.

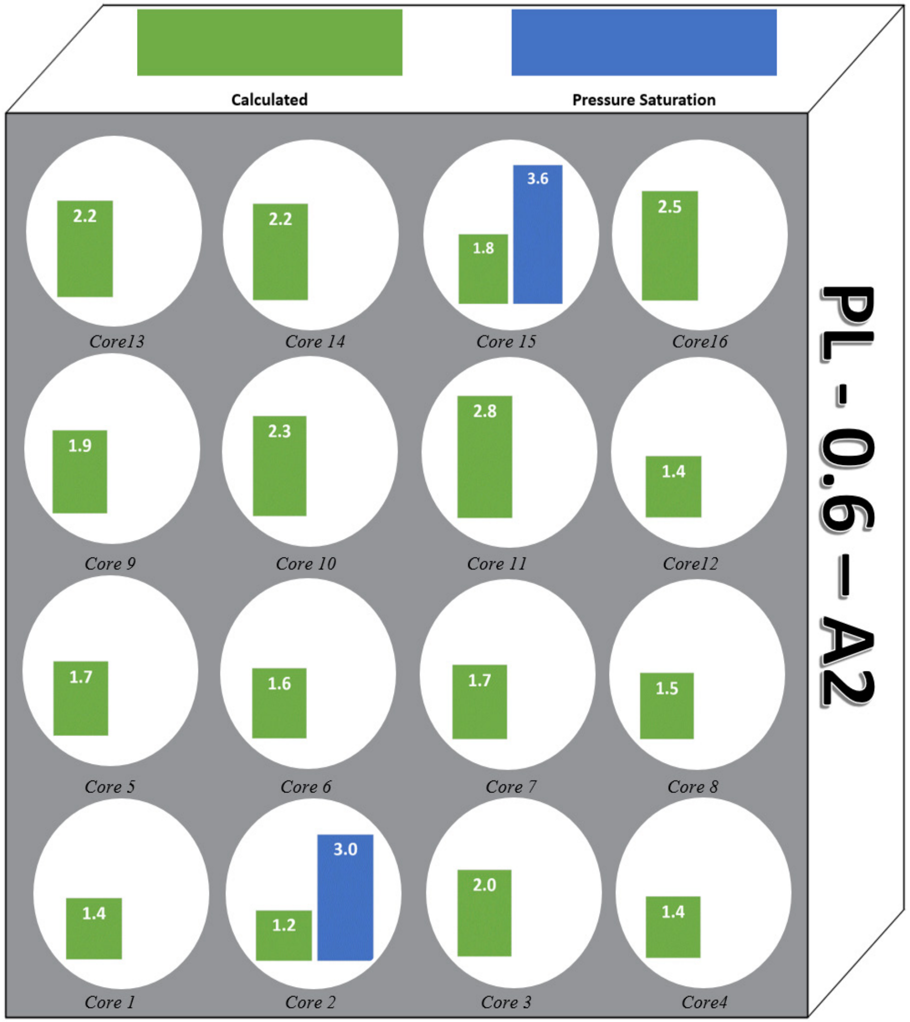

Figure 4-18 Test methods for measuring air content are shown in green, representing the Calculated method and Pressure Saturation method.

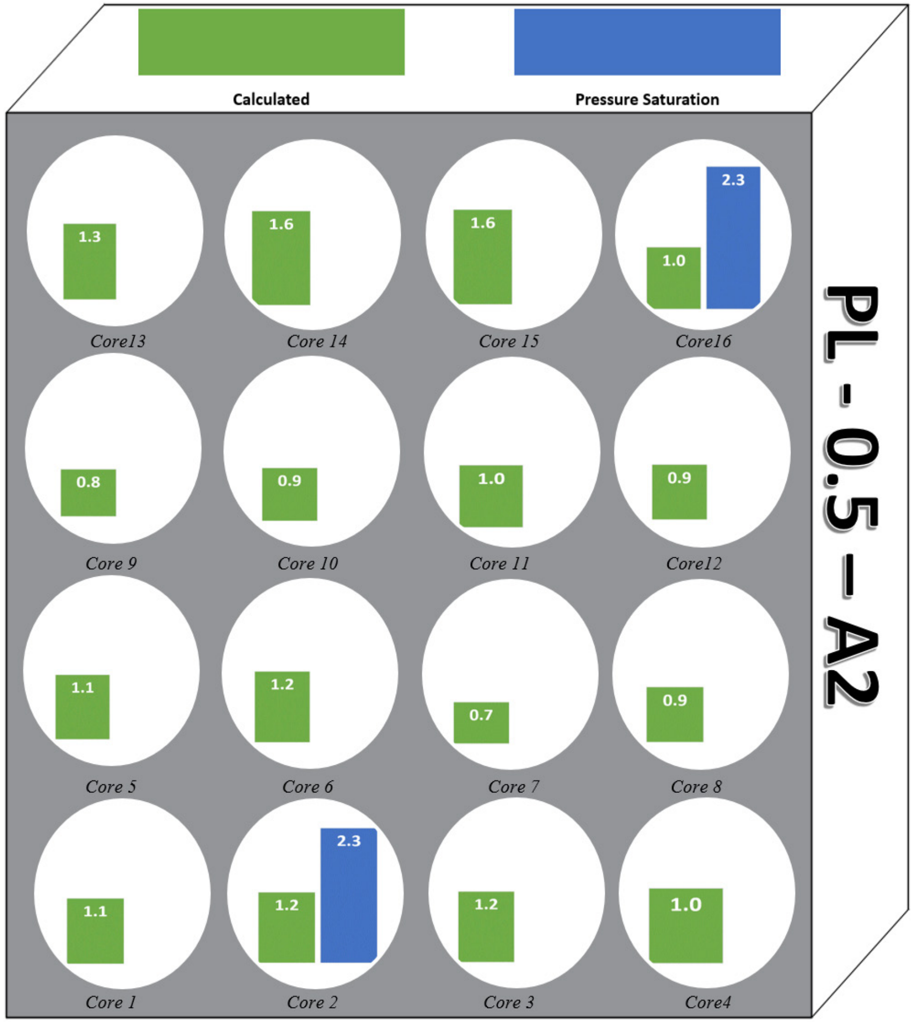

Figure 4-19 Test methods for measuring air content are shown in green, representing the Calculated method and Pressure Saturation method.

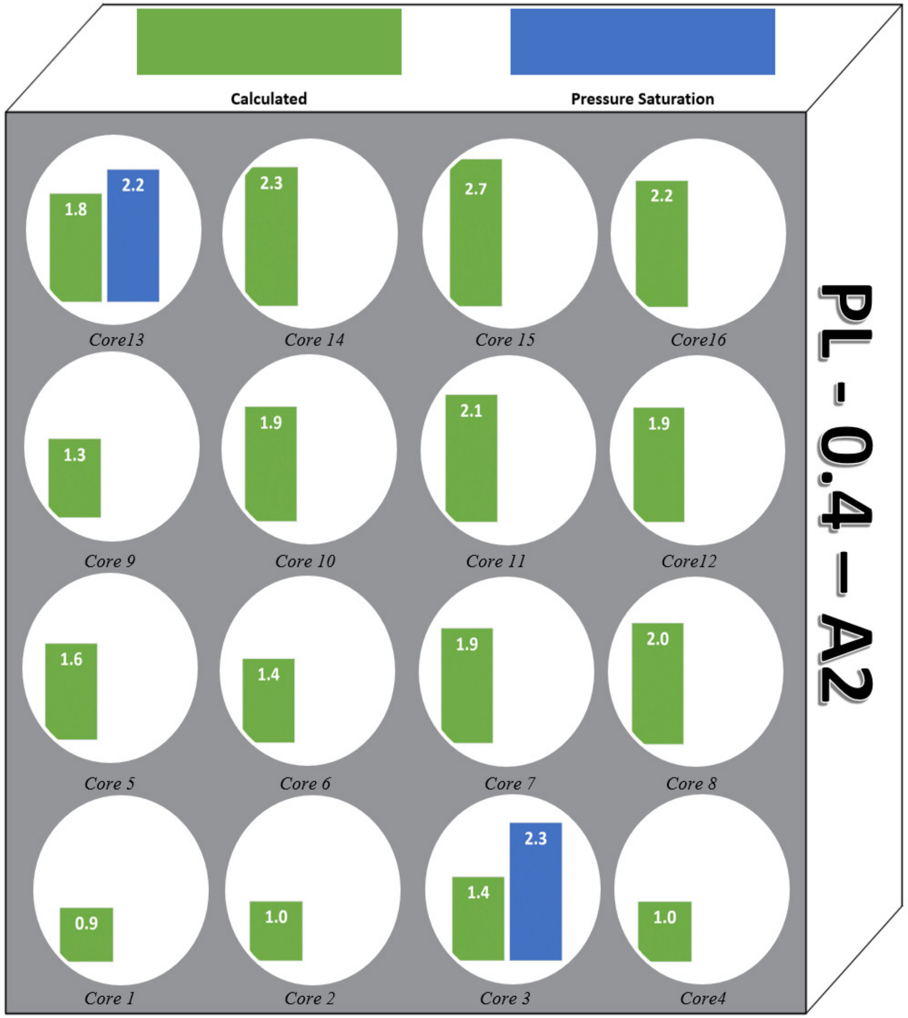

Figure 4-20 Test methods for measuring air content are shown in green, representing the Calculated method and Pressure Saturation method.

5 Analysis of fresh and hardened concrete properties

The following chapters analyze the results obtained from the experiments. The first section presents the analysis of the air contents in fresh concrete. The second section represents the analysis of the air content in hardened concrete.

5.1 Fresh concrete properties

Section 4.1 previously presented the results of the tests on fresh concrete. There are three classes of air content: low (2%), moderate (5%), and high (10%) air content concretes. The low air content class concrete was not air entrained. However, in the case of *PL-0.6-A2*, the air content is 3.9% measured by the Air Pressure Meter, Gravimetric method, and measured by CiDRA AIRtrac (static) as 5%. The reason for this elevated air content in this concrete could be because of the five-minute mixing procedure.

Figure 5-1 presents the comparison of different test methods used in this work for measuring the air content of fresh concrete. The X-axis represents the results of the Air Pressure Meter and the Y-axis the other methods used in the experiment. The Air Pressure Meter is the most commonly used instrument for measuring air content in fresh concrete. However, we do not know the absolute or true air content in concrete. Therefore, the results do not show the correctness of measurement but the correlation between them.

There is a good correlation between the Gravimetric method and Air Pressure Meter until 9 –10% of air content, and the results are less similar. Some of the results of AIRtrac have a good correlation between the Air Pressure Meter. However, the results of the AIRtrac measurement are influenced by the slump value of concrete. The slump value of the concretes used in these experiments differs from each other therefore providing bigger errors in certain measurements.

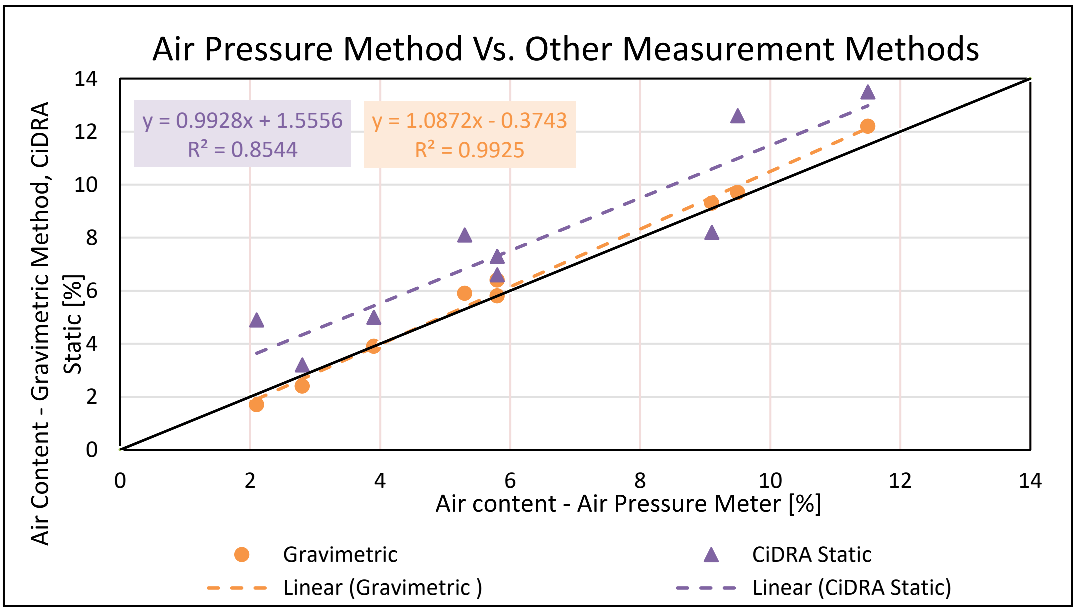

Figure 5-1 Comparison of different test methods used for air content measurements for nine fresh concrete.

5.2 Hardened concrete properties

The results that are obtained in the *result section* of hardened concrete shown in Figure 4-3 to Figure 4-11 can be analysed by the reader the density differences in the blocks. Some cores in concrete blocks have significantly different values compared to the rest. There are two possible reasons for such difference in density among the cores: (1)- differences in the air content, (2)- differences in the proportion of aggregate fraction between different parts of concrete.

For example, in Figure 4-3 *Pl-0.6-A10*, core numbers 1,2,3,4 and 8 are considered distinctive in comparison to all other cores in that block. Section 4.2.2 *Air content in hardened concrete* can be used to identify the probable cause of these deviations. The difference between the Calculated and Pressure Saturation methods, used to determine air content can reveal a solution for the questionable segregation or increased air content in the concrete. For these *(Pl-0.6-A10)* in Figure 4-12 distinctive cores lead us to think that the cause of different densities is mainly due to the differences in the proportion of aggregate fraction.

In the following sections results of density and air content hardened concrete going to be analysed in more detail.

5.2.1 Analysis of the Water Saturated Density

There were a total of 440 samples tested with the water Saturated Density method including full cores, half cores, and disks. The results of them are going to be analyzed in this section.

Segregation of the block is an influential factor and can provide false results for the air content of concrete. This is because segregation produces a difference in concrete density and properties. This density is then used to calculate the air content of concrete compared to the theoretical density. As it is shown in the results section 4.2.1 the density map shows no relation between the variation of density in the different core in the block. Overall, the density maps show the concrete blocks are well compacted, and segregation did not happen except in some smaller areas. Segregation was then investigated more thoroughly as shown in Table 5-1. Nevertheless, the effect of vibration poker displacement is clear in some blocks *PL-0.6-A5, Pl-0.5-A5, PL-0.4-A5* (see Figure 4-6 to Figure 4-8). The density seems to be lower in the path of the vibration rod shown in Figure 4-8 and higher in Figure 4-7.
Table 5-1 the *differences* row is calculated by the subtraction of Top and Bottom values. In Figure 5-2 differences from the top and bottom are compared with corresponding slump values.

Table 5-1 The results of the sensitivity of concrete for segregation test.

Segregation Sensitivity check [kg/m³]									
ID	**Pl-0.4-A2**	**Pl-0.4-A5**	**Pl-0.4-A10**	**Pl-0.5-A2**	**Pl-0.5-A5**	**Pl-0.5-A10**	**Pl-0.6-A2**	**Pl-0.6-A5**	**Pl-0.6-A10**
Top of Block	2402	2344	2203	2414	2343	2146	2354	2286	2208
Bottom of Block	2419	2354	2233	2417	2343	2154	2368	2302	2181
Differences	-17	-10	-30	-3	0	-8	-14	-16	27

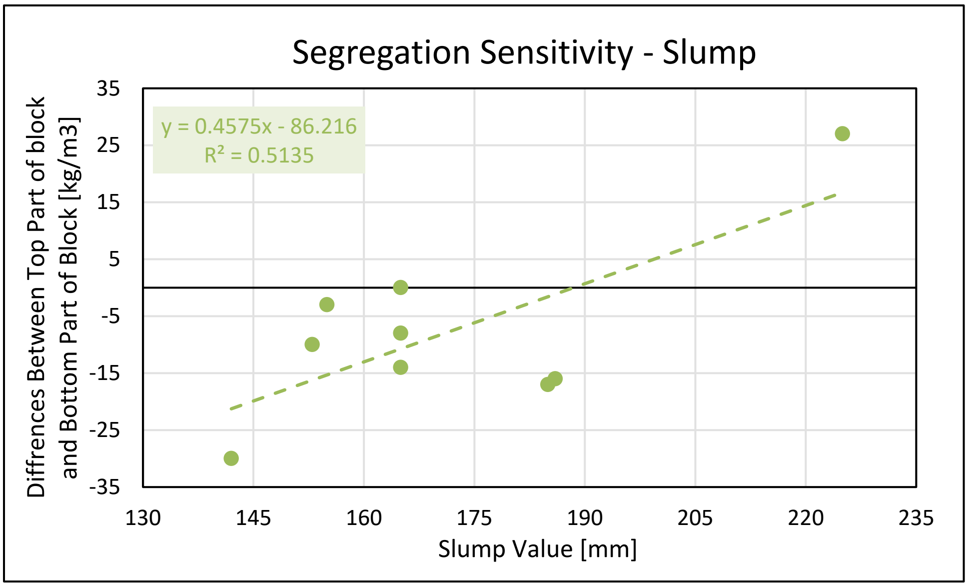

Figure 5-2 Comparison of segregation for nine concrete with corresponding slump values.

As Figure 5-2 shows, there is no clear correlation between the density differences with the slump value. However, it is clearly shown that density differences are in one boundary when the slump value is between 153-186 mm except for the highest and lowest slump value *(PL-0.6-A10, PL-0.4-A10).*

Figure 5-3 analyses the correlation between the Water Saturated Density measurements in hardened concrete and fresh density with error bars that represent the boundary minimum and maximum values. There is a good correlation between the fresh concrete density and average hardened concrete density. All the average densities in hardened concrete are more than in fresh concrete. In some concrete blocks, the variation of density between the cores is high. The variation is detailed in Figure 5-4. The average variation density among the blocks is about 50 kg/m^3, however, in some concrete it is more. For example, in *PL-0.6-A10* the density variation is about 100 kg/m^3 and has a slump value of 225 mm. Saturated density was analysed in Table 5-2 in more detail.

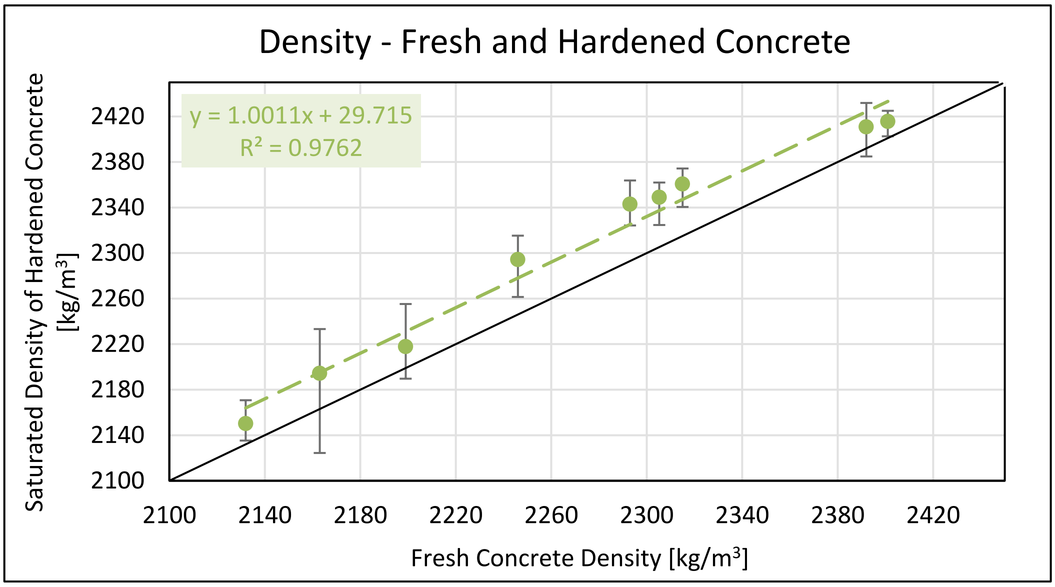

Figure 5-3 Comparison of density of fresh and hardened concrete with Min-Max error bar.

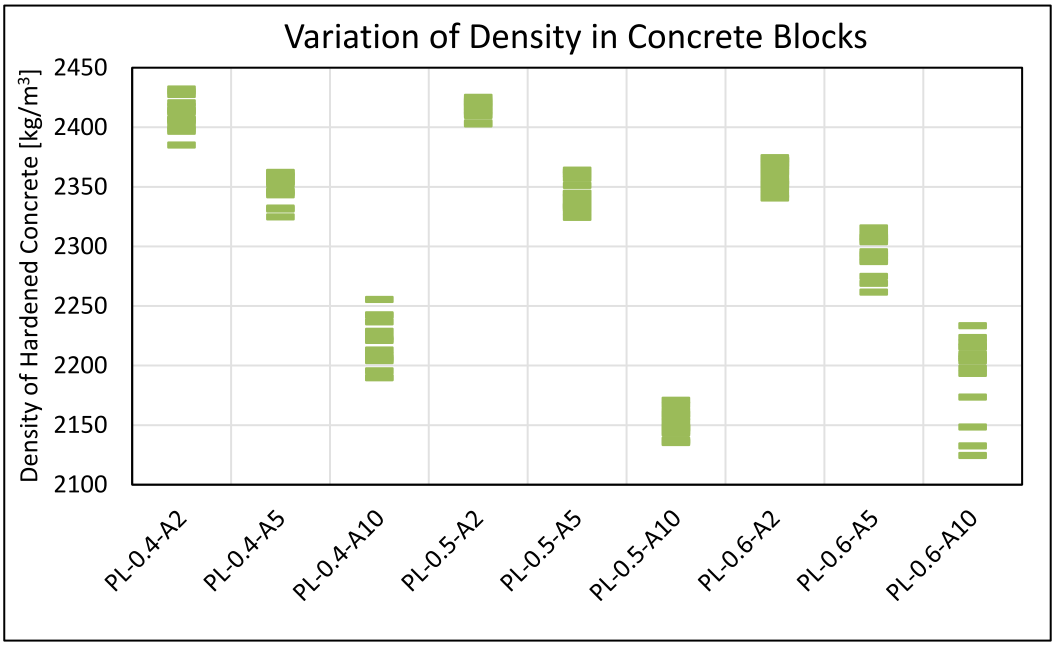

Figure 5-4 Variation of core density in nine concrete blocks.

Table 5-2 Results of Saturated density for sixteen cores in nine mixtures.

Saturated Density [%]									
	PI-0.4-A2	**PI-0.4-A5**	**PI-0.4-A10**	**PI-0.5-A2**	**PI-0.5-A5**	**PI-0.5-A10**	**PI-0.6-A2**	**PI-0.6-A5**	**PI-0.6-A10**
Maximum	2432	2362	2255	2425	2364	2171	2374	2315	2233
Minimum	2385	2325	2190	2403	2324	2135	2341	2261	2124
Average	2411	2349	2218	2416	2343	2150	2361	2294	2194
Standard Deviation	12.8	11.5	19.7	6.6	12.5	10.5	11.0	15.6	32.6

5.2.2 Analysis of Calculated method

The air content of hardened concrete by the Calculated method is measured from the Water Saturated Density measurement and the theoretical density according to section 3.4.1. This method can only be used if the theoretical density is known.

Figure 5-5 shows the correlation of the Calculated method results compared to the Air Pressure Meter results. There is a good correlation between the Air Pressure Meter and Calculated method; however, as the air content increases, the correlation is better. All the average results of the Calculated method are less than the fresh concrete results.

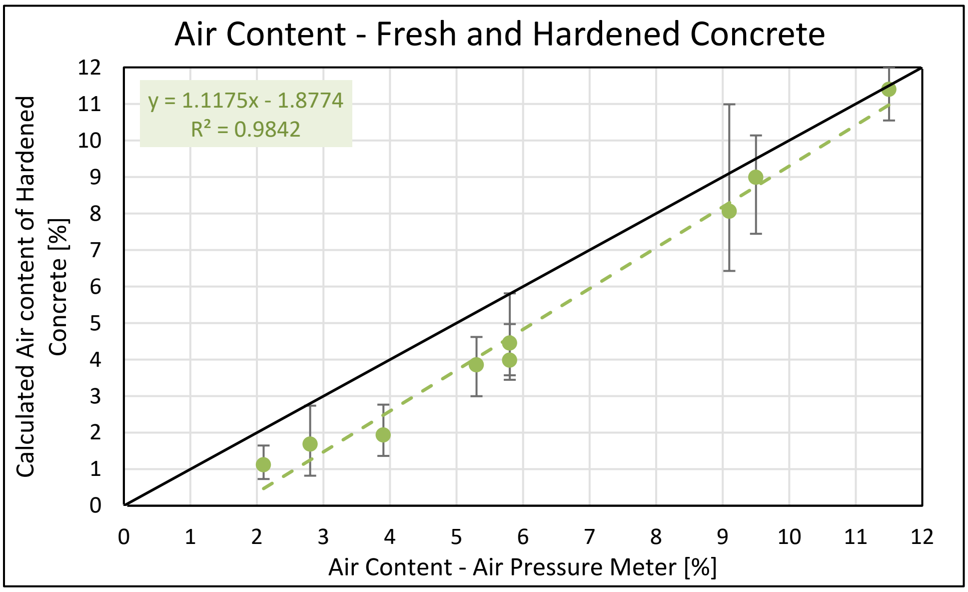

Figure 5-5 Correlation between Air Pressure Meter and Calculated method.

Air content calculated was analysed in Table 5-3 in more detail. The coefficient variation of non-entrained mixtures *(A2)* is highest among the concrete blocks.

Table 5-3 Air content determined by the Calculated method for sixteen cores in nine mixtures.

Calculated Method [%]									
	Pl-0.4-A2	Pl-0.4-A5	Pl-0.4-A10	Pl-0.5-A2	Pl-0.5-A5	Pl-0.5-A10	Pl-0.6-A2	Pl-0.6-A5	Pl-0.6-A10
Maximum	2.7	5.0	10.1	1.6	4.6	12.0	2.8	5.8	11.0
Minimum	0.8	3.4	7.4	0.7	3.0	10.5	1.4	3.6	6.4
Average	1.7	4.0	9.0	1.1	3.9	11.4	1.9	4.4	8.1
Standard Deviation	0.5	0.5	0.8	0.3	0.5	0.4	0.5	0.6	1.4
Coefficient of Variation	31%	12%	9%	24%	13%	4%	24%	15%	17%

5.2.3 Pressure Saturation method

5.2.3.1 Analysis of Pressure Saturation test

A total of 65 cores were examined with the Pressure Saturation method for nine concrete blocks. The experimental findings of this method are shown in the figures below. Figure 5-6 shows the air content correlation between fresh (Air Pressure Meter) and hardened concrete (Pressure Saturation). The error bars represent the air content variation among the average result of each concrete block.

As the result shows, there is a good correlation between the test methods. However, the trendline is slightly tilted from the reference line as air content increases. All the average results in hardened concrete are less than fresh concrete except for the concrete *PL-0.5-A2*.

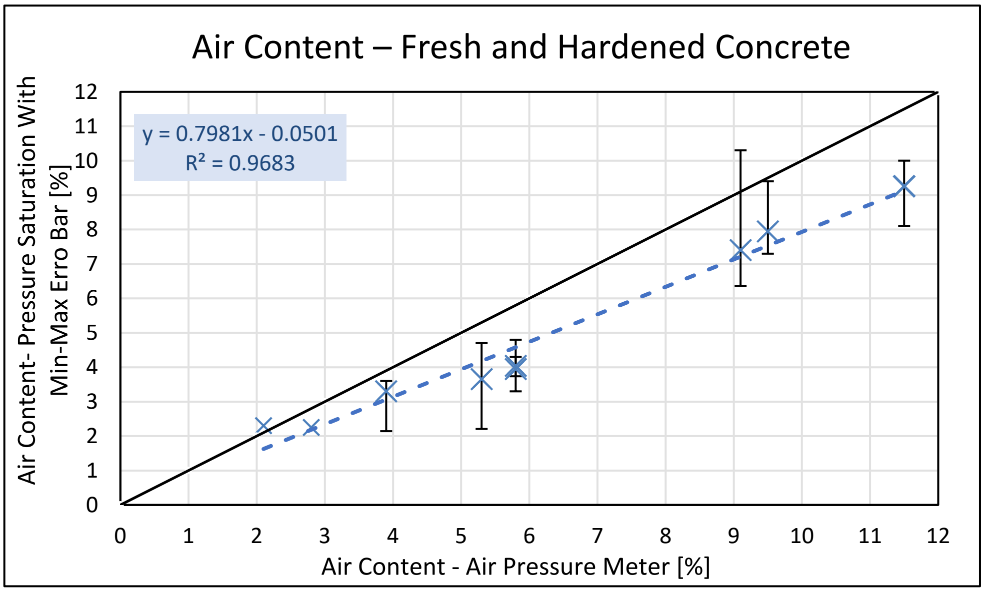

Figure 5-6 Compression of Pressure saturation method with Min-Max error bar of each block with the Air pressure meter.

Table 5-4 analysis the air content by Pressure saturation within six mixture and Figure 5-7 shows the variability of air content in nine mixtures. The coefficient of variation between the mixtures is between 7% to 19%. The variation of air content of entrained air mixtures is approximately about 1- 2.5% among all the blocks. However, the air content of a few cores is high. For example, the highest variation, which can be found among the concrete mix-design *Pl-0.6-A10* with 4.3% air content, differs in that block. In the non-entrained concretes, the variation of air content is approximately 1%. One reason for this could be that a smaller number of cores were examined (see Figure 5-7). The detailed results can be seen in Appendix B and D.

Table 5-4 Air content determined by Pressure Saturation method for six mixtures.

Air content of Pressure Saturation [%]						
	Pl-0.4-A5	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Maximum	4.3	4.7	4.8	9.4	10.0	10.3
Minimum	3.3	2.5	3.0	6.5	8.1	6.0
Average	3.9	3.7	4.0	7.9	9.3	7.4
Standard Deviation	0.4	0.7	0.7	1.1	0.6	1.2
Number of samples	9	10	8	7	7	9
Coefficient of Variation	9%	19%	16%	14%	7%	17%

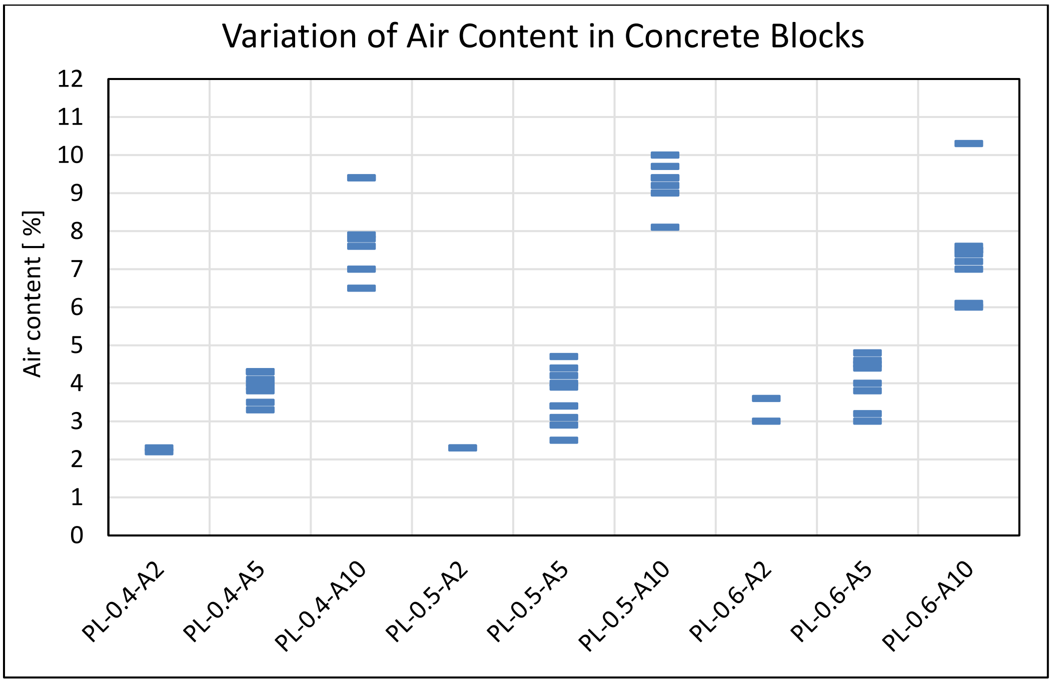

Figure 5-7 Variation of air content in nine concrete mix design.

The porosity calculation of concrete disks was done according to section 3.4.2. The results are represented in Figure 5-8. As the graph shows, the capillary and gel pores are increasing as the water-cement ratio increases. These pores should be constant in each water to cement ratio because of the same amount of cement and water in the mix. However, for the *A10* concretes, these values are much larger. In the 0.4 and 0.5 water-cement ratios the results show that the porosity is similar. It can be due to the cement paste which is higher in 0.4 than 0.5 w/c ratio concrete. Therefore, the porosity of 0.4 is similar to 0.5.

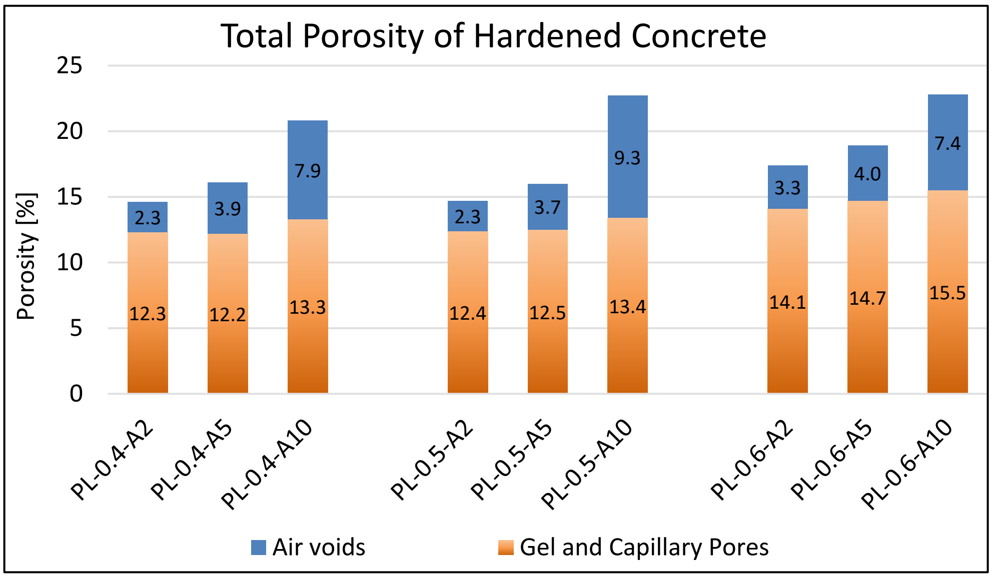

Figure 5-8 Porosity and Air contents calculation of nine blocks by Pressure Saturation Method.

5.2.3.2 Detail analysis of Pressure Saturation test

In order to analyse the Pressure Saturation results of the concrete in more detail, the following investigation was carried out (see Figure 5-9, Figure 5-10 and Figure 5-11). The idea of this investigation is to see if any of the parameters such as water-cement ratio, air content changes, or Slump value have an influence on the air content in hardened concrete. In this Figures, the error is designated in the Y-axis of the graph which is the difference of Air Pressure Meter and Pressure Saturation Method. The X-axis represents the parameters of concrete properties.

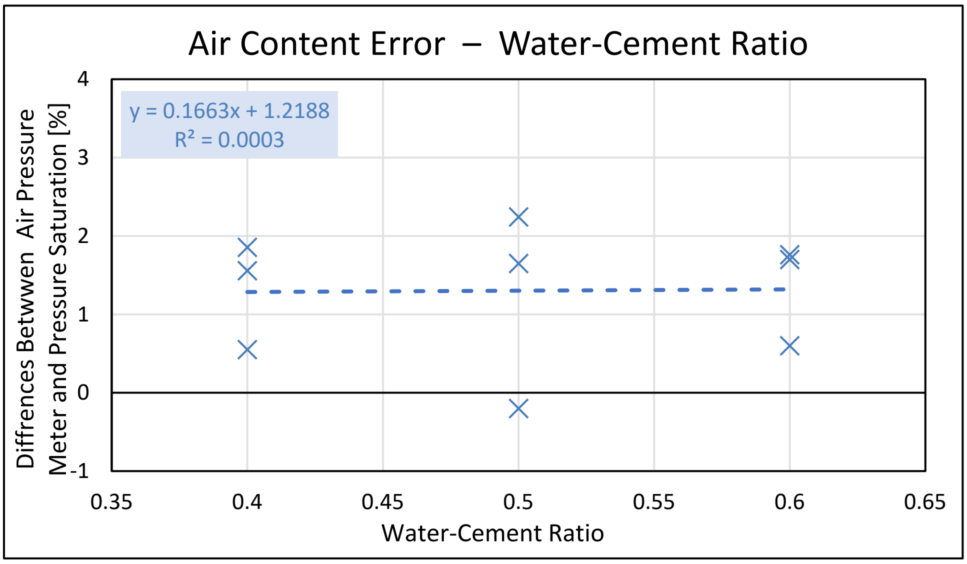

Figure 5-9 Analysis of error (Differences between of Pressure saturation method and Air pressure meter) with water-cement ratios for nine concrete.

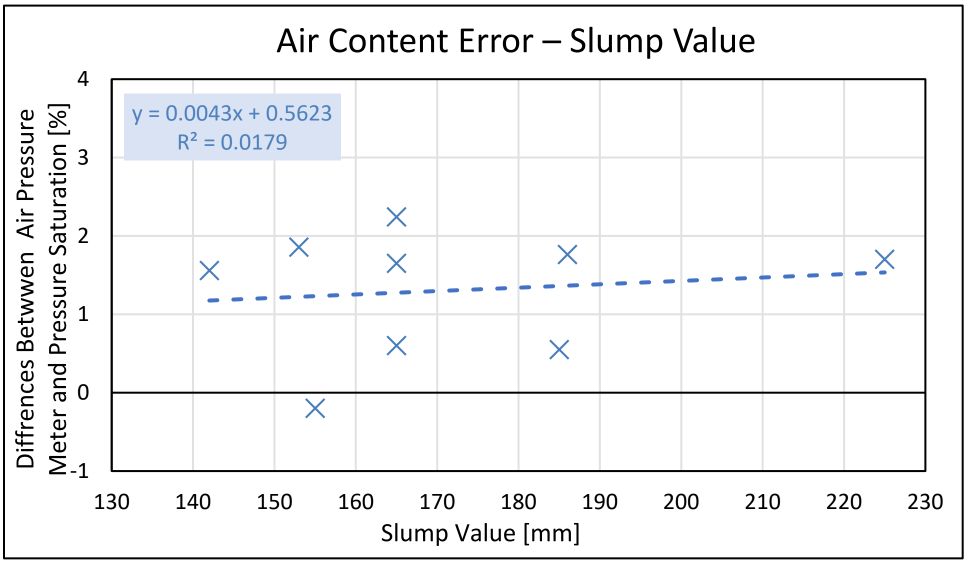

Figure 5-10 Analysis of error (Differences between of Pressure saturation method and Air pressure meter) with Slump value for nine concrete.

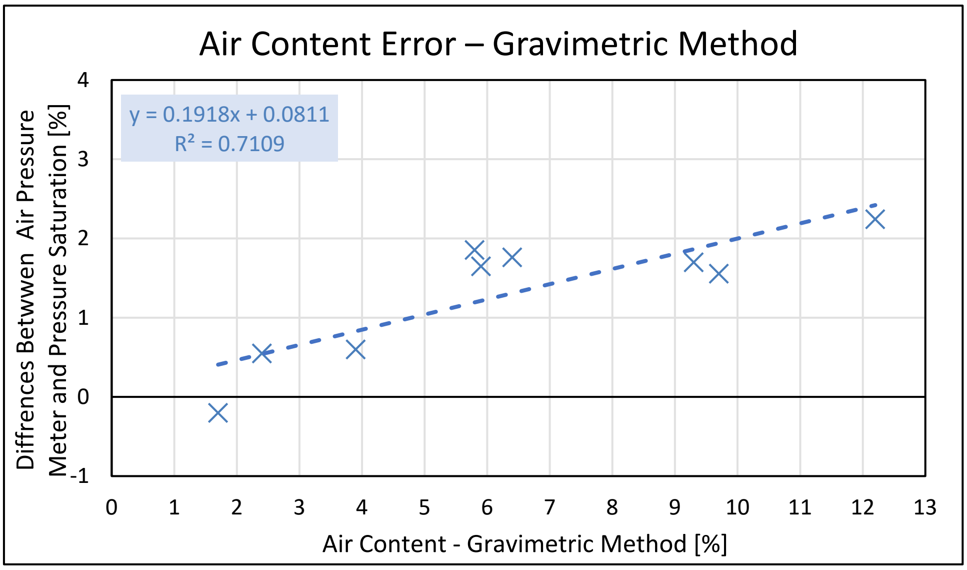

Figure 5-11 Analysis of error (Differences between of Pressure saturation method and Air pressure meter) with air content changes by Gravimetric method for nine concrete.

According to Figure 5-9 and Figure 5-10, the water-cement ratio and slump value did not have any influence in the results of air content in hardened concrete in this method. As results represented in Figure 5-11 show, there is a slightly good correlation of error with air content changes measured by the Gravimetric method. However, in some cases the with approximate 9-10% of air content, there is a similar error as for 5-6% air content concretes. The range of this error is 1.6-2.2% in entrained concretes and -0.2-0.6% in the non-entrained concrete.

The rest of the specimens was done with 24 hours pressure saturation, and then data were measured. Then the specimen was placed again under pressure saturation for 96 hours (see Table 5-5).

Table 5-5 Different times of Pressure Saturation with the same sample were examined.

Pressure Saturation Test with Different Time [%]			
ID	**Pl-0.4-A5-C3-3**	**Pl-0.4-A10-C2-2**	**Pl-0.5-A10-C4-1**
24 Hours	3.1	6.8	8.8
96 Hours	3.3	6.5	9.0

As Table 5-5 shows, the time of pressure saturation for more than 24 hours does not have an influence on the results. However, there is a difference between the two measurements, but it can be caused by repeatability error.

5.2.4 Analysis of Thin section

In Finland, Thin Section analysis is normally carried out in accordance with test guidelines of VTT TEST R003-002010. The results obtained from them are directly comparable. VTT TEST R003-002010 has been developed for Thin Section analysis, and surface finish is done slightly differently from the introduction.

A total of nine laboratories were invited to test the air entrained concrete mixtures cast in this master's thesis work. Six of these laboratories tested all the air entrained concretes and three laboratories tested two air entrained concretes. Overall 54 samples were tested by the nine laboratories. In addition, two laboratories have done Polished Slab Analysis, one with VTT TEST R003-002010 and the other one with SFS-EN 480-11. The numbers of the results are limited and it cannot be analysed or compared to any method. The result of these tests can be seen in Appendix C.

5.2.4.1 Air Content

The VTT TEST method is not intended to estimate the air content rather than for the quality of the air void system. However, the method is commonly used for measuring the air content. The total air content was analyzed in Table 5-6, and Figure 5-12 shows the result variations compared to Air Pressure Meter results.

Table 5-6 Total of air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Air content of Thin Section [%]						
	Pl-0.4-A5	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Maximum	5.5	5.4	6.8	11.8	15.2	12.3
Minimum	3.5	3.0	3.8	6.5	8.2	5.7
Average	4.4	4.5	5.4	8.3	10.7	8.6
Standard Deviation	0.76	0.94	1.16	1.81	2.41	2.16
Number of Samples	6	6	6	9	9	6
Coefficient of Variation	17%	21%	22%	22%	23%	25%

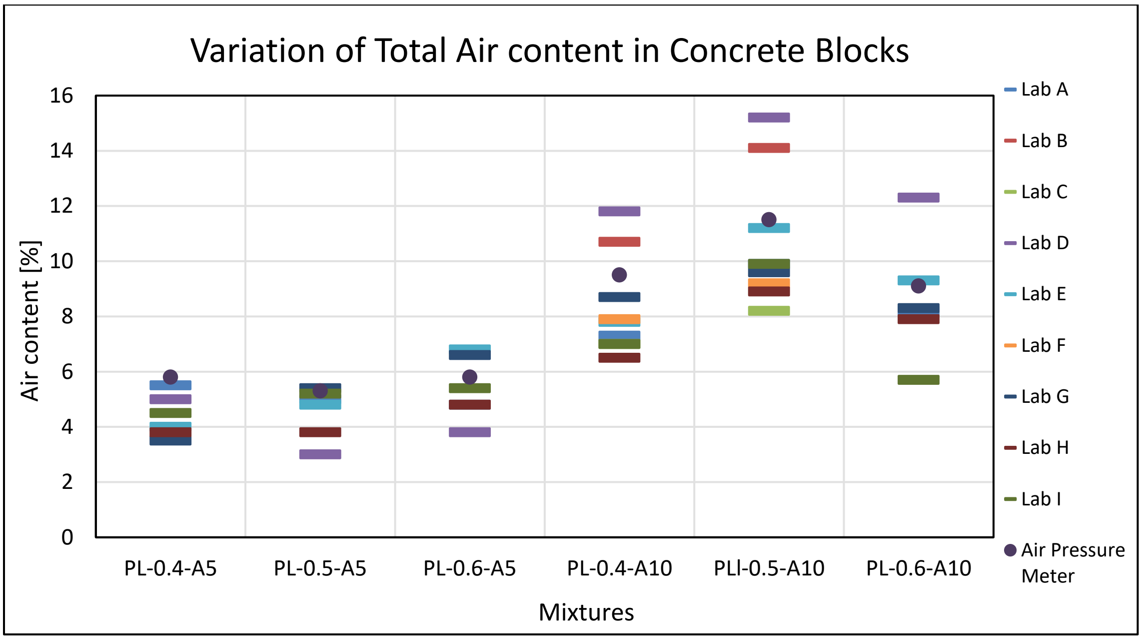

Figure 5-12 Variation of total air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Figure 5-13 shows the average air content determined by Thin Section analysis (VTT TEST) compared to fresh concrete. On average, the Thin Section analysis gives a very similar level of value compared to fresh concrete (Air Pressure Meter). There is high variation in high levels of air content. This high variation is due to the entrapped air.

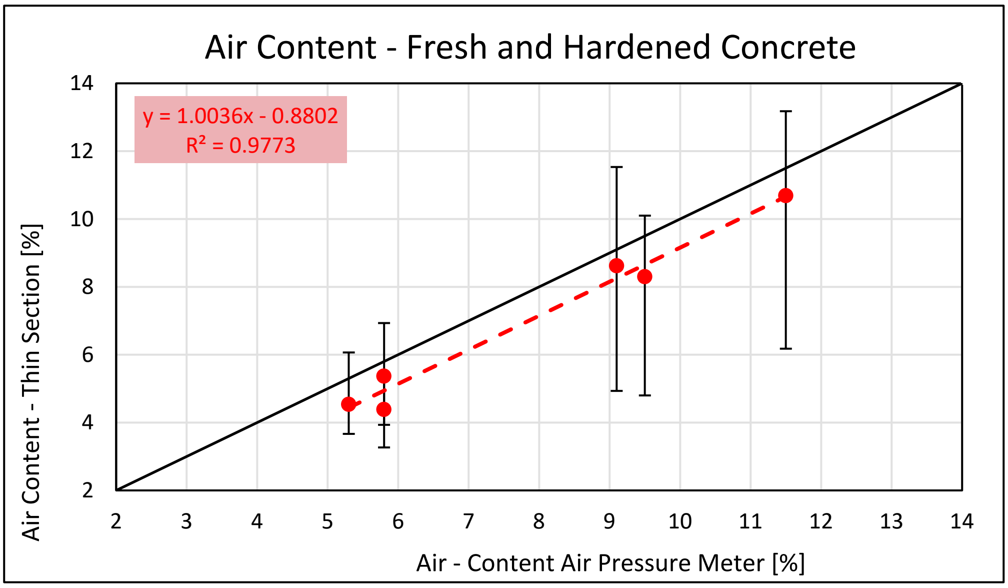

Figure 5-13 Compression of Thin Section method with Min-Max error bar of each block with the Air pressure meter.

The analysis in VTT TEST-R003-00-2010 method separate the protective and compaction air voids. Air voids with a diameter < 0.8 mm are counted as protective voids. The protective air voids analysis is shown in Table 5-7, and entrapped air voids analysis is shown in Table 5-8.

Table 5-7 Entrained air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Entrained Air [%]						
	Pl-0.4-A5	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Maximum	2.7	2.6	3.2	10.9	12.3	9.8
Minimum	1.3	1.3	1.7	5.6	8.0	4.6
Average	1.8	2.0	2.3	7.4	9.2	7.2
Standard Deviation	0.50	0.50	0.54	1.68	1.28	1.92
Number of samples	6	6	6	9	9	6
Coefficient of Variation	29%	26%	23%	23%	14%	27%

Table 5-8 Entrapped air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Entrapped Air [%]						
	Pl-0.4-A5	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Maximum	3.9	3.5	4.9	2.2	4.6	4.7
Minimum	1.8	1.4	1.2	0.2	0.1	0.1
Average	2.6	2.8	2.8	0.9	1.5	1.4
Standard Deviation	0.70	0.77	1.43	0.78	1.57	1.83
Number of samples	6	6	6	9	9	6
Coefficient of Variation	27%	28%	51%	84%	103%	129%

Table 5-8 shows considerable variation in the volume proportion of entrapped air between the laboratories. The entrapped air in *PL-0.4-A5, PL-0.5-A5* and *PL-0.6-A5* is high, more than 50% of the total air content.

5.2.5 Analysis of the Comparison of Methods to Each other

Figure 5-14 compares the Calculated method and Pressure Saturation for individual specimens. These specimens represent the drilled core value, which is the average result of the core's four disks. In Figure 5-14, a couple of cores have higher or lower calculated air content values compared to the air content determined using Pressure Saturation. In those cases, it is probable that some aggregate segregation has taken place and therefore the calculated air content is erroneous.

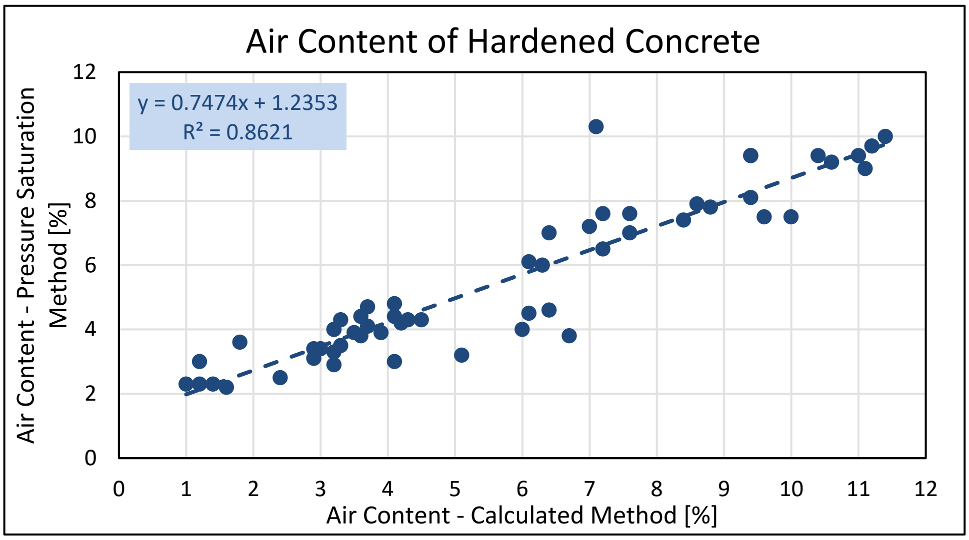

Figure 5-14 Comparison of different test methods used for measurements of air content in hardened concrete in nine mixtures.

Figure 5-15 compares the result of an individual specimen tested by Thin Section to the air content determined by the Calculated method. Figure 5-15 shows that some of the samples have very high air content by Thin Section method compared to the Calculated method. It could be the error by the laboratories or error in the method itself.

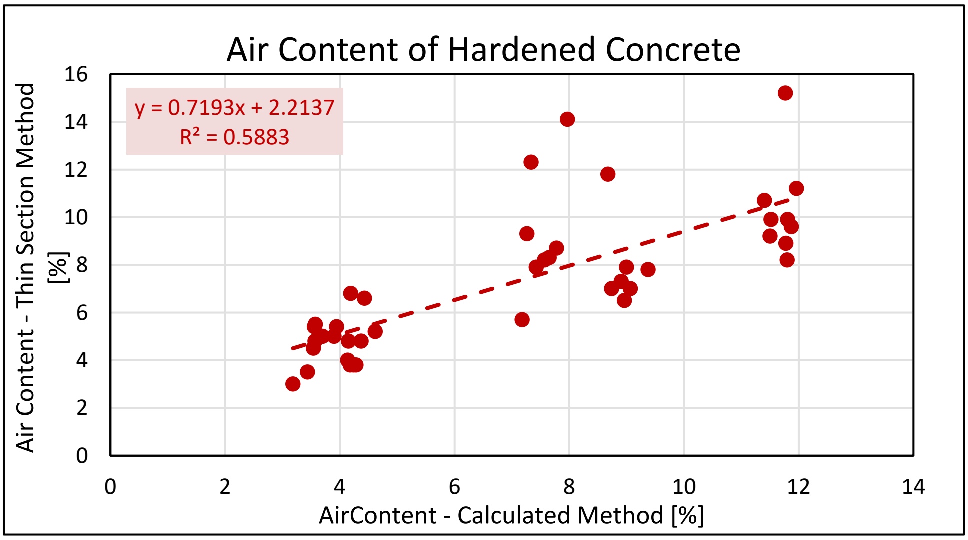

Figure 5-15 Comparison of different test methods used for measurements of air content in hardened concrete in six mixtures.

Considering the average of air content results of each block the correlation *(coefficient of determination (R^2))* is higher. This does not mean it has a better correlation, but one reason could be less point is considered in the determination of the R^2 value. In Figure 5-16, the Calculated methods in the X-axis are compared to the Thin Section or Pressure Saturation in the Y-axis.

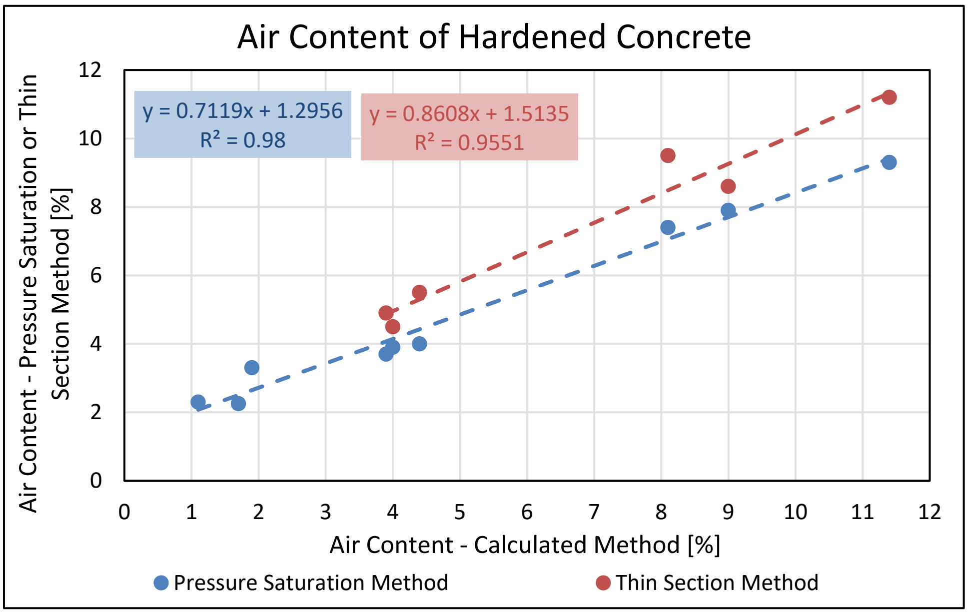

Figure 5-16 Comparison of different test methods used for measuring the average air content of blocks.

Figure 5-17 shows the comparison of the methods for measuring air content in hardened concrete with respect to the fresh concrete.

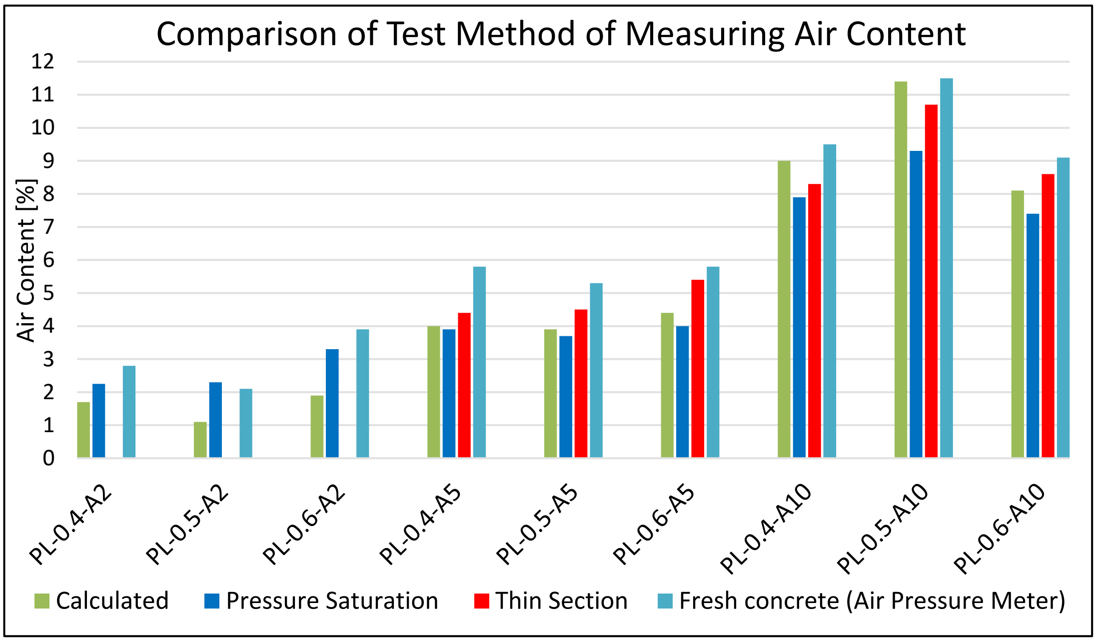

Figure 5-17 Comparison of different test methods of measuring the average air content of nine mixture in hardened concrete and reference to the fresh concrete (Air Pressure Meter).

5.2.6 Compressive Strength Test analysis

The comparison of drilled specimens with lab specimens is shown in Figure 5-18. There was inconsistency in the Compressive Strength test with high air content *(target air content: A10),* especially for concrete *PL-0.5-A10*. The effect of high air content on the compressive strength has a higher influence as compared to the water-cement ratio which remains somewhat secondary in this case. The *A5* concretes have clearly higher density (about 50 kg/m^3) compared to the fresh concrete. The compressive strength of lab specimens *PL-0.6-A2 and PL-0.6-A5* have almost the same strength value; however, for the drilled specimens, it is different.

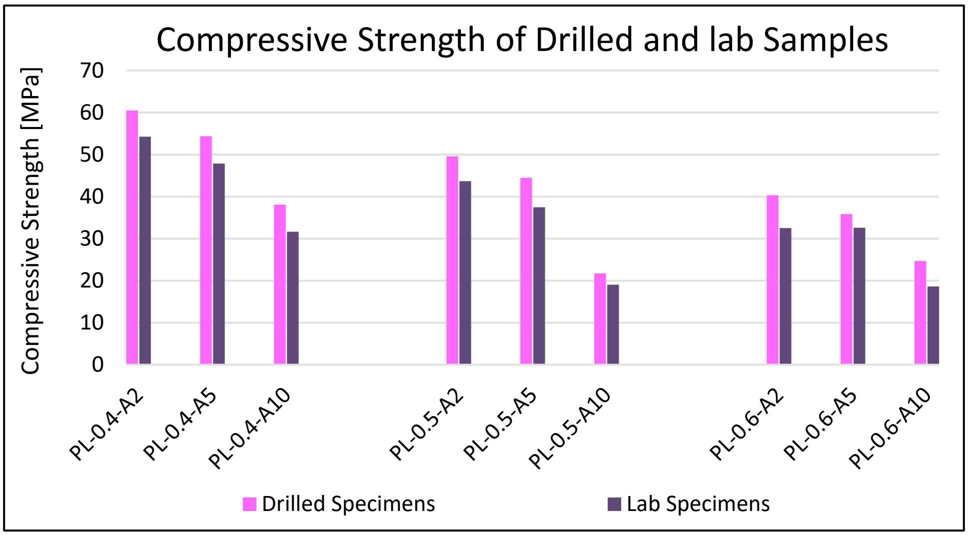

Figure 5-18 Compression of drilled and lab specimens for nine mixtures within three water-cement ratios.

Figure 5-19 and Figure 5-20 show the relationship of compressive strength with drilled specimens compared with air content of hardened (Pressure Saturation) and fresh (Air Pressure Meter) concrete correspondingly.

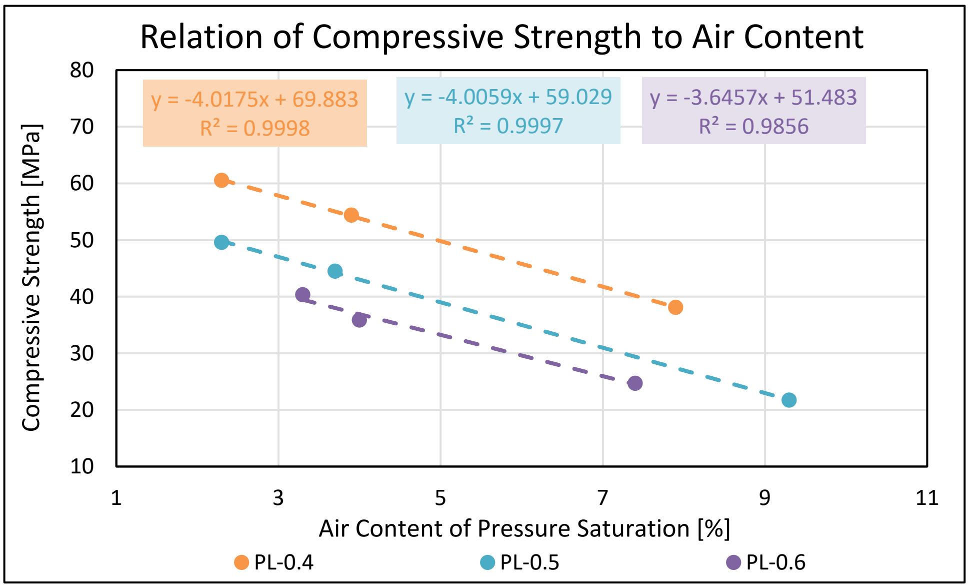

Figure 5-19 Correlation of drilled Compressive Strength samples at the age of 28 days and air content in hardened concrete for nine mixtures.

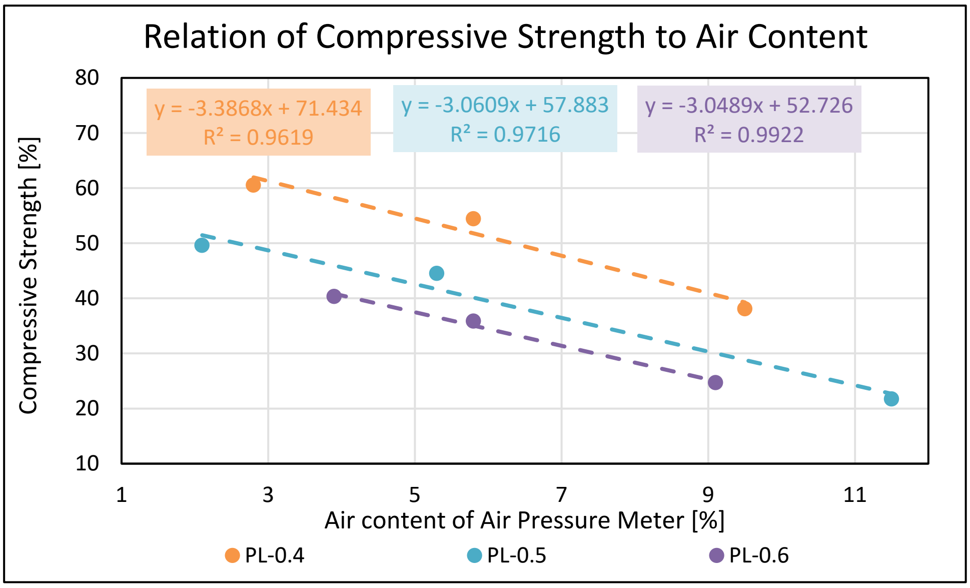

Figure 5-20 Correlation of drilled Compressive Strength samples at the age of 28 days and air content in fresh concrete for nine mixtures.

Figure 5-19 and Figure 5-20 present the compressive strength test results for the nine concrete mixtures categorized into water-cement ratios. The concrete with w/c ratio 0.4 shows a larger shift than the concretes 0.5 and 0.6. The concrete with water-cement ratio 0.4 has 400 kg cement content which is quite different compared to the 0.5 and 0.6 with 320 and 300 kg cement. Therefore, there has been a bigger shift compared to the 0.5 and 0.6 water-cement ratios.

The correlation of compressive strength with the air content of hardened concrete is better than fresh concrete. The compressive strength changes 3.9 MPa per one percent of air content according to Figure 5-19 and 3.1 MPa according to Figure 5-20.

6 Discussion, Conclusion and Future Work

6.1 Discussion of results and Analysis

In this chapter, the thesis discusses the results and analysis of the research which was conducted previously. The objective of this thesis is to determine the air content of hardened content and to draw a correlation to fresh concrete air content. Furthermore, to investigate the possible factors affecting the results.

The air content of hardened concrete depends on the air content of fresh concrete. Fresh concrete is influenced by many factors, detailed in the literature review of this thesis, as follows:

- Concrete materials and mix design
- Production procedures
- Construction practices
- Environmental conditions.

During the production of the optimal mix design, it was observed that the air content of fresh concrete was influenced by the amount of aggregate gradation, admixtures such as air entrained agents and superplasticizer, the mixer, and compaction. However, keeping all the above constant, it was observed in the laboratory work that the air content in the bottom and top parts of the batch were not exactly the same. The resulting outcome of this is a difference of air content in hardened concrete.

Massive amounts of samples were tested in this research investigation to measure the air content of hardened concrete by different methods. These methods included the Calculated method based on the saturated density, Pressure Saturation test and Thin Section round-robin test.

Through the density of hardened concrete, it was observed that the densities of nine mixtures were higher from fresh concrete densities in general. The possible reasons for this can be slightly higher vibration time then for the fresh concrete in the Air Pressure Meter container or can be due to the natural self-compaction of the concrete in the formwork which allowed for the escaping of the air from the concrete.

The thesis investigated the correlation between the results of fresh concrete air content (Air Pressure Meter) and hardened concrete air content measured by the Calculated method. The correlation is good with a coefficient of determination (R^2) of 0.984 between them. According to the standard deviation of concrete mixtures in this thesis. The maximum error can be achieved from this method was ± 1.4% from the mean value. This method can be used only if concrete is not segregated and the theoretical density of concrete is known.

Keeping in mind that the true air content of hardened concrete cannot be determined by any method, the Calculated method could provide a baseline for the determination of the air content of hardened concrete in the same way as the Air Pressure Meter is used for fresh concrete. This could be possible because the trendline of the data points shifts, meaning that the densities in all cases are higher with similar amounts. These experiments also revealed that the variation of air content in the non-air-entrained concrete is higher than air-entrained concrete. The Calculated method did not show any factors that influence the results including water-cement ratio or changes in air content. It was observed that false results on the cores occurred where segregation was found within the concrete with the highest slump.

The Pressure Saturation test was performed for the nine concrete mixtures. The average values of the Pressure Saturation results were compared with the Air Pressure Meter in which the coefficient of determination (R^2) was 0.968. In general, only in the air entrained mixtures less amount of air contents was measured by the Pressure Saturation method for the concretes than for the other methods. The coefficient determination (R^2) of average values for the nine blocks with the Calculated method was 0.98 and the sample to sample R^2 was 0.86. However, if we do not consider the segregated samples the correlation rises to 0.92. The coefficient of variation of Pressure Saturation results is similar to the Calculated method results within air entrained concrete. According to the standard deviation of Pressure Saturation among concrete mixtures in this thesis. The maximum error was ± 1.2% from the mean value.

The results of porosity measurement by the Pressure Saturation show that the capillary and gel pores increase as water-cement ratio increases. These pores should be constant in each water to cement ratio due to the same amount of cement paste. However, for the *A10* concretes, these values are much larger.

More detailed investigation was performed for the Pressure Saturation method to determine if any of the following parameters have influence on the results: water-cement ratios, slump values, air content changes, and different time of pressure under water. The results show only one of these parameters had influence on the results:

The difference of air content between fresh and hardened concrete increases when investigating concretes with higher air content. This could be due to the air which exists in the samples and cannot escape under pressure in the Pressure Saturation apparatus. The values of Pressure Saturation are expected to be more than what the results present based on the results of the Calculated method and Thin Section analysis. Entrained air results of Thin Section for *A10* concretes have similar values to the Pressure Saturation results.

Six out of the nine concretes were examined by Thin Section analysis through a round-robin test. Thin Section analysis was performed according to the standard VTT TEST R003-002010. The correlation of average total air content of Thin Section to air content of fresh concrete and Pressure Saturation results was 0.977 and 0.959 respectively. The coefficient determination (R^2) of individual samples to the Calculated method is 0.588. Among the concrete mixture, the standard deviation maximum error was ± 2.4% from the mean value.

The variation of the results between the laboratories was large at high levels of air content. This makes the results unreliable. This is due to the large variation when observing only entrapped air in the samples. The coefficient of variation of entrained air is between 14% to 29% but the coefficient variation of entrapped air is between 27% to 129%. Therefore, the entrapped air analysis has the most significant influence on the dispersion of results of total air content. The entrapped air in *PL-0.4-A5, PL-0.5-A5* and *PL-0.6-A5* was more than 50% of the total air content which provides that the concrete has poor protection and high porosity. These influence the quality of the concrete.

The quality assessment of the Thin Section tests was reliable because of the less variation in the qualification of the air void system. The results showed that the spacing factor of two concretes, *PL-0.4-A5 and PL-0.5-A5,* partially exceeds 0.4 mm. This value was over the limit specified by the standard VTT TEST – R003-00-2010 suggesting that the protection of the concrete failed. The results are presented in Appendix C.

6.2 Conclusion

A large number of concrete tests were carried out in order to analyse and evaluate the methods to measure the air content of hardened concrete by different methods and the correlation between fresh to hardened concrete air content. In addition, the thesis investigated the affecting factors that can influence the results. The research work consisted of a literature review, laboratory work, analysis of the results and the drawing of conclusions.

The laboratory work comprised of the preparation of nine different concretes in three groups of water-cement ratios and different air contents ranging from 2% to 10% by volume. A total of sixteen cores were drilled from each block. Their densities were measured. For the analysis of Thin Section, a round-robin test was organized in Finland. Five out of eight cores were selected based on the similar densities from two middle drilled cores in each block. The selected cores were sawn into half and sent to nine laboratories. A total of 54 samples were tested by Thin Section analysis.

The rest of the cores were selected for the Pressure Saturation test and Compressive strength test. The cores for Pressure Saturation were cut into 20 mm disks. In addition to the cores for the compressive strength test, 100 mm laboratory cubes were cast for the Compressive Strength test as well.

The following paragraphs conclude the investigation work:

1. The Calculated method, that is based on the water saturated density of hardened concrete, proved to have a good air content correlation to fresh concrete with an R^2 value of 0.98 unless the concrete was segregated or inhomogeneous. However, if the mix design is not known this method cannot be used. This method is a good reference for the determination of the air content of hardened concrete only in the laboratory environment.

2. Pressure Saturation proved that this method can be the most practical of all. The correlation of this method to the fresh concrete was R^2 0.968. However, this method provided smaller air content values than the other methods for air entrained mixtures. The coefficient of variation in each block is the same as the Calculated method.

3. Thin Section within a round-robin test analysis proved that the results are unreliable due to problems with relatively large variation of results regarding total air content. This is due to the high coefficient of variation of entrapped air (27% to 129%) in certain concretes. However, the average total air content results of Thin Section have a good correlation between the fresh concrete air content and Pressure Saturation.

6.3 Future Work

The present project was rather compact and the main target was measuring the air content of hardened concrete by existing tools and methods. However, future research could study the modification of these methods.

The Pressure Saturation method seems to be promising to measure the air content in hardened concrete. It could be improved by modifying the apparatus in a way that it allows the air from inside of the concrete to escape and then apply pressure to it.

It would be useful to find out the precision in measurement by different laboratories on a single sample. In the experiment conducted in this thesis, both the laboratories participating in the round-robin test and the concrete samples were varying. The laboratories could be evaluated better by performing the test on similar samples.

The number of the Polished Slab was too low in order to analyse the air voids for this thesis with respect to the Thin Section. Polished Slab could be studied more and compared with existing methods.

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Appendix A – Combined Aggregate for Concrete

Table A-1 Concrete of PL-0.4- A2 to A10.

Aggregate type	Aggregate size D/d	Aggregate portion (%)	Percentage by mass passing – Sieve size (mm)										Grading Factor
			0,125	0,25	0,5	1	2	4	8	16	32	64	H
Filler	Filler 96	7	29	66	88	94	97	99	100	100	100	100	61
Fine Aggregates (FA)	0.1/0.6	9	9	31	70	100	100	100	100	100	100	100	73
	0.5/1.2	12	1	2	4	73	100	100	100	100	100	100	82
	1/2	14	2	6	11	15	81	100	100	100	100	100	86
	2/5	16	0	0	0	0	1	56	100	100	100	100	73
Coarse Aggregates (CA)	5/10	20	0	0	0	0	0	3	78	99	100	100	76
	8/16	22	0	0	0	0	0	0	1	97	100	100	66

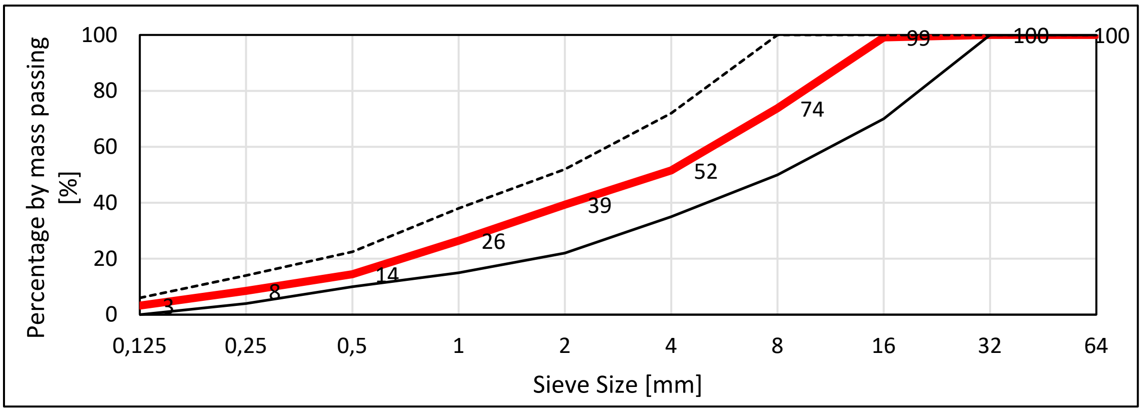


Figure A-1 Combination of aggregate used for PL-0.4- A2 to A10.

Table A-2 Concrete of PL-0.5- A2 to A10.

Aggregate type	Aggregate size D/d	Aggregate portion (%)	Percentage by mass passing										Grading Factor
			Sieve size (mm)										
			0,125	0,25	0,5	1	2	4	8	16	32	64	H
Filler	Filler 96	6	29	66	88	94	97	99	100	100	100	100	52
Fine Aggregates (FA)	0.1/0.6	9	9	31	70	100	100	100	100	100	100	100	73
	0.5/1.2	11	1	2	4	73	100	100	100	100	100	100	75
	1/2	14	2	6	11	15	81	100	100	100	100	100	86
	2/5	17	0	0	0	0	1	56	100	100	100	100	78
Coarse Aggregates (CA)	5/10	20	0	0	0	0	0	3	78	99	100	100	76
	8/16	23	0	0	0	0	0	0	1	97	100	100	69

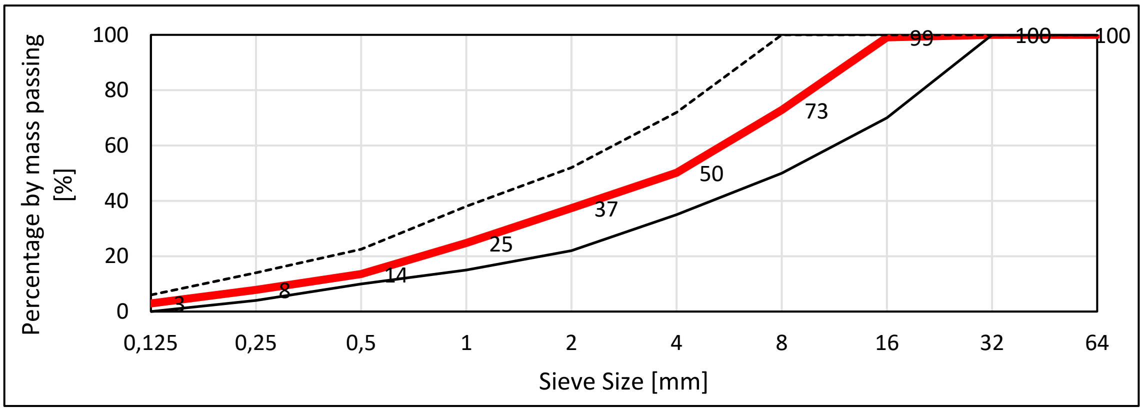


Figure A-2 Combination of aggregate used for PL-0.5- A2 to A10.

Table A-3 Concrete of PL-0.6- A2 to A10.

Aggregate type	Aggregate size D/d	Aggregate portion (%)	Percentage by mass passing										Grading Factor
			Sieve size (mm)										
			0,125	0,25	0,5	1	2	4	8	16	32	64	H
Filler	Filler 96	8	29	66	88	94	97	99	100	100	100	100	70
Fine Aggregates (FA)	0.1/0.6	14	9	31	70	100	100	100	100	100	100	100	113
	0.5/1.2	14	1	2	4	73	100	100	100	100	100	100	95
	1/2	15	2	6	11	15	81	100	100	100	100	100	92
	2/5	16	0	0	0	0	1	56	100	100	100	100	73
Coarse Aggregates (CA)	5/10	16	0	0	0	0	0	3	78	99	100	100	61
	8/16	17	0	0	0	0	0	0	1	97	100	100	51

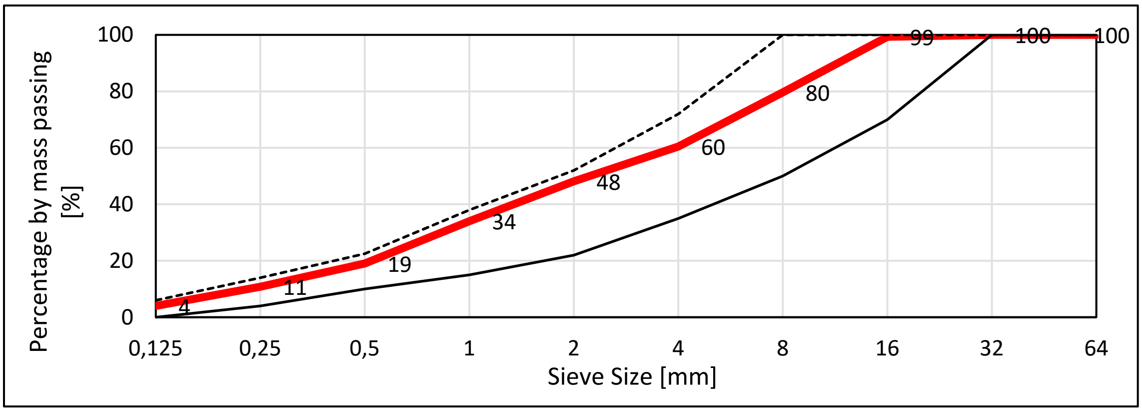


Figure A-3 Combination of aggregate used for PL-0.6- A2 to A10.

Table A- 4 Admixtures used in the concrete mixtures.

	Admixtures [dm³/m³]								
	Pl-0.4-A2	**Pl-0.4-A5**	**Pl-0.4-A10**	**Pl-0.5-A2**	**Pl-0.5-A5**	**Pl-0.5-A10**	**Pl-0.6-A2**	**Pl-0.6-A5**	**Pl-0.6-A10**
AEA	0.000	0.0016	0.000	0.000	0.011	0.155	0.000	0.009	0.157
S-Plasticizer	4.697	3.600	4.697	2.818	1.879	0.157	1.761	0.367	0.000

Appendix B – Properties of Concrete

Block 1 PL-0.4 -A2

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2407	15	2413	21	1.8	1.8	2.2	-	-
Core 14	2396	4	-	-	2.3	-	-	-	-
Core 15	2385	-7	-	-	2.7	-	-	-	-
Core 16	2398	6	-	-	2.2	-	-	-	-
Core 9	2420	28	-	-	1.3	-	-	-	-
Core 10	2405	13	-	-	1.9	-	-	-	-
Core 11	2401	9	-	-	2.1	-	-	-	-
Core 12	2406	14	-	-	1.9	-	-	-	-
Core 5	2413	21	-	-	1.6	-	-	-	-
Core 6	2418	26	-	-	1.4	-	-	-	-
Core 7	2406	14	-	-	1.9	-	-	-	
Core 8	2413	21	-	-	1.6	-	-	-	
Core 1	2430	38	-	-	0.9	-	-	-	-
Core 2	2427	35	-	-	1.0	-	-	-	-
Core 3	2414	22	2418	26	1.5	1.4	2.3	-	-
Core 4	2432	40	-	-	0.8	-	-	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
1.7	1.6	2.3	-	2411	-

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2392	2403	2.4	2.8	3.2	185

Figure B- 1 Density and air content of fresh and hardened concrete is detailed for each core.

Block 2 PL-0.4 -A5

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2354	49	2365	60	3.8	3.3	4.3	-	-
Core 14	2331	26	-	-	4.7	-	-	-	-
Core 15	2346	41	2356	51	4.1	3.5	3.9	-	-
Core 16	2346	41	2340	35	4.1	4.3	4.3	-	-
Core 9	2352	47	-	-	3.9	-	-	4.0	3.5
Core 10	2332	27	-	-	4.7	-	-	-	-
Core 11	2343	38	2359	54	4.2	3.6	3.8	3.8	-
Core 12	2344	39	2356	51	4.2	3.7	4.1	-	-
Core 5	2362	57	-	-	3.5	-	-	-	-
Core 6	2325	20	2336	31	5.0	4.5	4.3	-	-
Core 7	2354	49	-	-	3.8	-	-	5.5	5.0
Core 8	2360	55	-	-	3.5	-	-	4.5	
Core 1	2358	53	-	-	3.6	-	-	-	-
Core 2	2355	50	2363	58	3.7	3.2	4.0	-	-
Core 3	2362	57	2370	65	3.4	3.1	3.3	-	-
Core 4	2359	54	2366	61	3.6	3.3	3.5	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
4.0	3.6	3.9	4.4	2349	2328

Fresh Concrete Results

Measured Density	Theoretical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2305	2324	5.8	5.8	7.3	153

Figure B- 2 Density and air content of fresh and hardened concrete is detailed for each core.

Block 3 PL-0.4 -A10

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2195	-4	2253	-	9.9	-	-	-	-
Core 14	2190	-9	2208	9	10.1	9.4	7.8	-	-
Core 15	2190	-9	2208	9	10.1	9.4	9.4	-	-
Core 16	2209	10	2226	27	9.4	8.6	7.9	-	-
Core 9	2224	25	-	-	8.7	-	-	7.0	
Core 10	2206	7	-	-	9.5		-	-	-
Core 11	2205	6	2221	22	9.5	8.8	7.8	-	-
Core 12	2204	5	-	-	9.5	-	-	-	-
Core 5	2222	23	-	-	8.8	-	-	7.3	10.7
Core 6	2221	22	-	-	8.9	-	-	7.0	11.8
Core 7	2213	14	-	-	9.2	-	-	7.8	7.9
Core 8	2229	30	-	-	8.5	-	-	8.7	6.5
Core 1	2255	56	-	-	7.4	-	-	-	-
Core 2	2242	43	2253	54	8.0	7.6	7.0	-	-
Core 3	2236	37	2250	51	8.2	7.6	7.6	-	-
Core 4	2242	43	2261	62	8.0	7.2	6.5	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
9.0	8.4	7.7	8.3	2218	2203

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2199	2193	9.7	9.5	12.6	142

Figure B- 3 Density and air content of fresh and hardened concrete is detailed for each core.

Block 4 PL-0.5 -A2

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2412	11	-	-	1.3	-	-	-	-
Core 14	2404	3	-	-	1.6	-	-	-	-
Core 15	2403	2	-	-	1.6	-	-	-	-
Core 16	2410	9	2412	11	1.3	1.0	2.3	-	-
Core 9	2423	22	-	-	0.8	-	-	-	-
Core 10	2422	21	-	-	0.9	-	-	-	-
Core 11	2419	18	-	-	1.0	-	-	-	-
Core 12	2421	20	-	-	0.9	-	-	-	-
Core 5	2416	15	-	-	1.1	-	-	-	-
Core 6	2414	13	-	-	1.2	-	-	-	-
Core 7	2425	24	-	-	0.7		-	-	-
Core 8	2421	20	-	-	0.9	-	-	-	-
Core 1	2417	16	-	-	1.1	-	-	-	-
Core 2	2411	10	2417	16	1.3	1.2	2.3	-	-
Core 3	2413	12	-	-	1.2	-	-	-	-
Core 4	2418	17	-	-	1.0	-	-	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
1.1	1.1	2.3	-	2416	-

Fresh Concrete Results

Measured Density	Theoritica l Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2401	2394	1.7	2.1	4.9	155

Figure B- 4 Density and air content of fresh and hardened concrete is detailed for each core.

Block 5 PL-0.5 -A5

Hardened Concrete Results

Core	Density of Core [kg/m3]	(Density of Core) - (Density of Fresh Concrete) [kg/m3]	Average Density of Disks [kg/m3]	(Average Density of Disk) - (Density of Fresh Concrete) [kg/m3]	Air Content [%]: Calculated by Core / Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half / Thin Section 1st Half
Core 13	2335	42	2345	52	4.2 / 3.6	4.7	- / -
Core 14	2332	39	2342	49	4.3 / 4.2	4.2	- / -
Core 15	2333	40	-	-	4.3 / -	-	- / -
Core 16	2357	64	2379	86	3.3 / 3.0	3.4	- / -
Core 9	2364	71	-	-	3.0 / -	-	- / -
Core 10	2340	47	2350	57	4.0 / 3.9	3.9	- / -
Core 11	2324	31	-	-	4.6 / -	-	5.2
Core 12	2360	67	2387	94	3.1 / 2.4	2.5	- / -
Core 5	2351	58	-	-	3.5 / -	-	5.0 / 3.0
Core 6	2344	51	-	-	3.8 / -	-	4.8 / 5.4
Core 7	2333	40	2346	53	4.3 / 4.1	4.4	3.8 / -
Core 8	2362	69	2375	82	3.1 / 2.9	3.1	- / -
Core 1	2341	48	2368	75	3.9 / 3.2	2.9	- / -
Core 2	2345	52	2366	73	3.8 / 3.3	3.4	- / -
Core 3	2328	35	-	-	4.5 / -	-	- / -
Core 4	2337	44	2356	63	4.1 / 3.3	4.0	- / -

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
3.9	3.4	3.7	4.5	2343	2332

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2293	2315	5.9	5.3	8.1	165

Figure B- 5 Density and air content of fresh and hardened concrete is detailed for each core.

Block 6 PL-0.5 -A10

Hardened Concrete Results

Core	Density of Core [kg/m3]	(Density of Core) - (Density of Fresh Concrete) [kg/m3]	Average Density of Disks [kg/m3]	(Average Density of Disk) - (Density of Fresh Concrete) [kg/m3]	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2159	27	2159	27	11.0	11.0	9.4	-	-
Core 14	2143	11	-	-	11.7	-	-	-	-
Core 15	2137	5	2156	24	11.9	11.2	9.7	-	-
Core 16	2147	15	2155	23	11.5	10.4	9.4	-	-
Core 9	2144	12	-	-	11.6	-	-	9.6	8.9
Core 10	2147	15	-	-	11.5	-	-	9.9	
Core 11	2136	4	2156	24	12.0	11.1	9	-	-
Core 12	2157	25	-	-	11.1		-	-	-
Core 5	2148	16	-	-	11.5	-	-	9.9	14.1
Core 6	2135	3	-	-	12.0	-	-	-	-
Core 7	2147	15	-	-	11.5	-	-	8.2	15.2
Core 8	2148	16	-	-	11.5	-	-	11.2	9.2
Core 1	2167	35	-	-	10.7	-	-	-	-
Core 2	2153	21	2156	24	11.3	11.4	10.0	-	-
Core 3	2162	30	2170	38	10.9	10.6	9.2	-	-
Core 4	2171	39	2197	65	10.5	9.4	8.1	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
11.4	10.7	9.3	10.7	2150	2106

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2132	2184	12.2	11.5	13.5	165

Figure B- 6 Density and air content of fresh and hardened concrete is detailed for each core.

Block 7 PL-0.6 -A2

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2353	38	-	-	2.2	-	-	-	-
Core 14	2355	40	-	-	2.2	-	-	-	-
Core 15	2343	28	2356	41	2.7	1.8	3.6	-	-
Core 16	2348	33	-	-	2.5	-	-	-	-
Core 9	2362	47	-	-	1.9	-	-	-	-
Core 10	2352	37	-	-	2.3	-	-	-	-
Core 11	2341	26	-	-	2.8	-		-	-
Core 12	2374	59	-	-	1.4	-	-	-	-
Core 5	2367	52	-	-	1.7	-	-	-	-
Core 6	2369	54	-	-	1.6	-	-	-	-
Core 7	2367	52	-	-	1.7	-		-	-
Core 8	2372	57	-	-	1.5	-	-	-	-
Core 1	2373	58	-	-	1.4	-	-	-	-
Core 2	2363	48	2371	56	1.8	1.2	3.0	-	-
Core 3	2358	43	-	-	2.0	-		-	-
Core 4	2372	57	-	-	1.4	-	-	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
1.9	1.5	3.3	-	2361	-

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2315	2359	3.9	3.9	5.0	165

Figure B- 7 Density and air content of fresh and hardened concrete is detailed for each core.

Block 8 PL-0.6 -A5

Hardened Concrete Results

Core	Density [kg/m3]: Density of Core	Density [kg/m3]: (Density of Core) - (Density of Fresh Concrete)	Density [kg/m3]: Average Density of Disks	Density [kg/m3]: (Average Density of Disk) - (Density of Fresh Concrete)	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half / 1st Half
Core 13	2287	41	2307	61	4.7	3.9	4.4	- / -
Core 14	2275	29	-	-	5.3		-	- / -
Core 15	2261	15	2283	37	5.8	4.9	3.8	- / -
Core 16	2269	23	-	-	5.5	-	-	- / -
Core 9	2306	60	-	-	3.9	-	-	5.4
Core 10	2290	44	2289	43	4.6	4.7	4.6	- / -
Core 11	2294	48	2297	51	4.5	4.3	4.5	6.8 / -
Core 12	2308	62	-	-	3.9	-	-	- / -
Core 5	2305	59	-	-	4.0	-	-	4.8 / 3.8
Core 6	2295	49	-	-	4.4	-	-	6.6 / 4.8
Core 7	2308	62	2330	84	3.9	3.0	3.0	- / -
Core 8	2310	64	-	-	3.8	-	-	- / -
Core 1	2315	69	2323	77	3.6	3.2	3.2	- / -
Core 2	2292	46	2303	57	4.5	4.1	4.8	- / -
Core 3	2288	42	2300	54	4.7	4.2	4.0	- / -
Core 4	2304	58	-	-	4.0	-	-	- / -

Average Results of Methods [%]

Calculated by Cores	alculated by Disk	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
4.4	4.0	4.0	5.4	2294	2285

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2246	2281	6.4	5.8	6.6	186

Figure B- 8 Density and air content of fresh and hardened concrete is detailed for each core.

Block 9 PL-0.6 -A10

Hardened Concrete Results

Core	Density of Core [kg/m3]	(Density of Core) - (Density of Fresh Concrete) [kg/m3]	Average Density of Disks [kg/m3]	(Average Density of Disk) - (Density of Fresh Concrete) [kg/m3]	Air Content [%]: Calculated by Core	Air Content [%]: Calculated by Disks Average	Air Content [%]: Pressure Saturation	Air Content [%]: Thin Section 2nd Half	Air Content [%]: Thin Section 1st Half
Core 13	2198	35	-	-	7.9	-	-	-	-
Core 14	2193	30	-	-	8.1		-	-	-
Core 15	2206	43	2220	57	7.6	7.0	7.2	-	-
Core 16	2219	56	2240	77	7.0	6.1	6.1	-	-
Core 9	2223	60	2236	73	6.8	6.3	6.0	-	-
Core 10	2206	43	2216	53	7.6	7.1	10.3	7.9	-
Core 11	2204	41	2209	46	7.7	7.4	7.6	-	-
Core 12	2216	53	2234	71	7.2	6.4	7.0	-	-
Core 5	2215	52	-	-	7.2	-	-	5.7	
Core 6	2209	46	-	-	7.4	-	-	8.2	12.3
Core 7	2208	45	-	-	7.5	-	-	9.3	8.3
Core 8	2233	70	-	-	6.4	-	-	-	-
Core 1	2124	-39	2147	-16	11.0	10.0	7.5	-	-
Core 2	2132	-31	2158	-5	10.7	9.6	7.5	-	-
Core 3	2148	-15	-	-	10.0	-	-	-	-
Core 4	2173	10	2187	24	8.9	8.4	7.4	-	-

Average Results of Methods [%]

Calculated by Cores	Calculated by Disks	Pressure Saturation	Thin Section	Density of Cores	Density of Block Without Cores
8.1	7.6	7.4	8.6	2194	2285

Fresh Concrete Results

Measured Density	Theoritical Density	Gravimetric [%]	Air Pressure Meter [%]	CiDRA AirTrac Meter [%]	Slump [mm]
2163	2148	9.3	9.1	8.2	225

Figure B- 9 Density and air content of fresh and hardened concrete is detailed for each core.

Appendix C – Thin Section Properties

A total of nine labs were involved in Thin Section investigation. The labs are identified as lab A to I.

Figure C- 1 Entrained air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Entrained Air [%]						
Mix Design	**Pl-0.4-A5**	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Lab-A	1.6	2.6	2.4	7.0	9.3	7.8
Lab-B				8.5	9.5	
Lab-C				6.5	8.0	
Lab-D	2.7	1.6	2.6	10.9	12.3	9.8
Lab-E	1.3	1.3	1.9	5.6	8.2	4.6
Lab-F				7.7	8.4	
Lab-G	1.7	2.1	3.2	8.3	9.1	7.9
Lab-H	1.4	1.7	2.1	6.2	8.8	7.8
Lab-I	1.8	2.4	1.7	5.8	8.9	5.3

Figure C- 2 Entrapped air content within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Entrapped Air [%]						
Mix Design	**Pl-0.4-A5**	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Lab-A	3.9	2.4	2.4	0.3	0.6	0.4
Lab-B				2.2	4.6	
Lab-C				0.6	0.2	
Lab-D	2.3	1.4	1.2	0.9	2.9	2.5
Lab-E	2.7	3.5	4.9	2.2	3.0	4.7
Lab-F				0.2	0.8	
Lab-G	1.8	3.3	3.4	0.4	0.6	0.4
Lab-H	2.4	3.1	1.4	0.4	0.1	0.1
Lab-I	2.7	2.8	3.7	1.2	1.0	0.4

Figure C- 3 Specific surface within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Specific Surface [mm^2]						
Mix-Design	**Pl-0.4-A5**	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Lab-A	17	19	30	46	41	42
Lab-B				23	24	
Lab-C				35	38	
Lab-D	12	22	24	27	30	28
Lab-E	14	18	28	36	40	40
Lab-F				37	39	
Lab-G	16	19	22	37	43	39
Lab-H	19	15	27	43	43	31
Lab-I	13	13	29	26	28	29

In the case of two concretes (Pl-0.4-A5 and Pl-0.5-A5) lab A, lab B and lab C did not report the spacing factor value of them.

Figure C- 4 Spacing factor within the laboratories named Lab-A, Lab-B…. were determined by Thin Section method among six mixtures according to VTT TEST.

Spacing Factor [mm]						
Mix-Design	**Pl-0.4-A5**	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Lab-A		0.34	0.23	0.09	0.07	0.08
Lab-B				0.16	0.10	
Lab-C				0.13	0.11	
Lab-D		0.36	0.27	0.08	0.06	0.08
Lab-E			0.28	0.13	0.09	0.12
Lab-F				0.11	0.09	
Lab-G	0.51	0.38	0.28	0.10	0.07	0.09
Lab-H	0.47	0.46	0.27	0.10	0.07	0.10
Lab-I	0.56	0.47	0.27	0.17	0.11	0.17

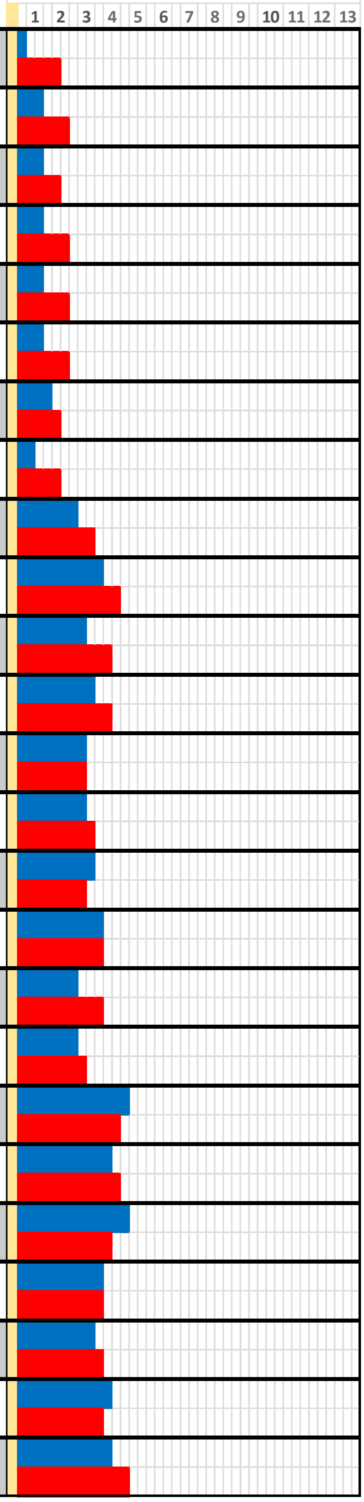
Figure C- 5 Total of air content within the laboratories named Lab-A, Lab-B were determined by Polished Slab method among six mixtures according to VTT TEST and SFSEN480-11.

Total Air Content by Polished Slab [%]						
ID	**Pl-0.4-A5**	**Pl-0.5-A5**	**Pl-0.6-A5**	**Pl-0.4-A10**	**Pl-0.5-A10**	**Pl-0.6-A10**
Lab-A	5.0	7.2	6.9	12.5	16.7	15.8
Lab-B	4.5	5.0	4.9	7.1	10.1	8.7

Appendix D – Pressure Saturation Detailed Properties

Table D- 1 Measurement results of Pressure Saturation of each disk in density, porosity and air content for 0.4 water-cement ratio.

Pressure Saturation							
0.4 Water-Cement Ratio-Air Content Design From A2 to A10-Core's Specimen-Disk number							*Calculated* / *Pressure Saturation*
Specimen	Dry Density	Saturated Density	Total Porosity	Suction Porosity	Air Content Pressure Saturation	Air Content Calculated	Air content
0.4-A2-C3-1	2315	2433	13.9%	11.8%	2.0%	1.0%	
0.4-A2-C3-2	2297	2419	14.6%	12.2%	2.4%	1.5%	
0.4-A2-C3-3	2297	2422	14.7%	12.4%	2.3%	1.4%	
0.4-A2-C3-4	2295	2417	14.6%	12.2%	2.4%	1.6%	
0.4-A2-C13-1	2294	2417	14.8%	12.4%	2.5%	1.6%	
0.4-A2-C13-2	2292	2416	14.8%	12.5%	2.3%	1.7%	
0.4-A2-C13-3	2281	2412	15.0%	13.1%	1.9%	1.8%	
0.4-A2-C13-4	2309	2428	14.1%	11.9%	2.2%	1.2%	
0.4-A5-C2-1	2263	2384	15.5%	12.0%	3.4%	2.7%	
0.4-A5-C2-2	2232	2354	16.6%	12.2%	4.3%	3.8%	
0.4-A5-C2-3	2251	2373	16.3%	12.2%	4.1%	3.0%	
0.4-A5-C2-4	2235	2360	16.7%	12.5%	4.2%	3.5%	
0.4-A5-C3-1	2257	2376	15.1%	11.9%	3.3%	3.1%	
0.4-A5-C3-2	2260	2377	15.3%	11.8%	3.5%	3.0%	
0.4-A5-C3-3	2247	2370	15.5%	12.3%	3.1%	3.3%	
0.4-A5-C4-1	2237	2357	15.8%	12.0%	3.8%	3.9%	
0.4-A5-C4-2	2267	2378	14.7%	11.1%	3.6%	3.0%	
0.4-A5-C4-3	2256	2379	15.3%	12.3%	3.0%	3.0%	
0.4-A5-C6-1	2213	2335	16.6%	12.2%	4.3%	4.7%	
0.4-A5-C6-2	2234	2351	16.0%	11.7%	4.3%	4.1%	
0.4-A5-C6-3	2215	2337	16.4%	12.2%	4.2%	4.7%	
0.4-A5-C11-1	2231	2359	16.6%	12.7%	3.8%	3.8%	
0.4-A5-C11-2	2245	2369	16.3%	12.4%	3.8%	3.3%	
0.4-A5-C12-1	2229	2354	16.3%	12.5%	3.8%	3.9%	
0.4-A5-C12-2	2225	2350	17.2%	12.5%	4.7%	4.1%	



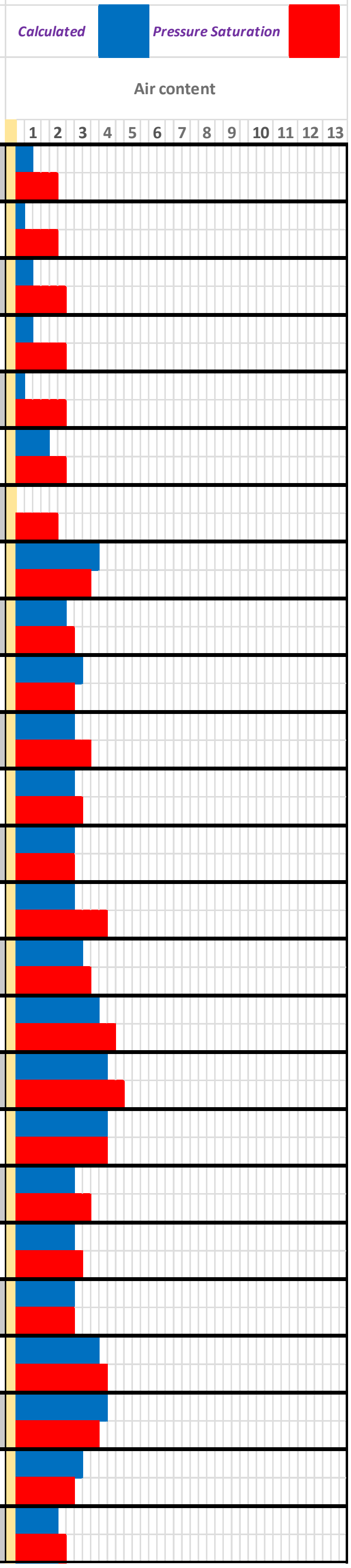
0.4-A5-C12-3	2252	2373	15.9%	12.0%	3.8%	3.2%
0.4-A5-C12-4	2243	2364	16.1%	12.1%	3.9%	3.6%
0.4-A5-C13-1	2283	2386	16.2%	10.3%	5.9%	2.7%
0.4-A5-C13-2	2260	2377	15.0%	11.7%	3.4%	3.0%
0.4-A5-C13-3	2223	2347	16.1%	12.4%	3.6%	4.2%
0.4-A5-C15-1	2240	2367	16.3%	12.6%	3.7%	3.2%
0.4-A5-C15-2	2243	2370	16.5%	12.7%	3.9%	3.2%
0.4-A5-C15-3	2230	2358	16.5%	12.8%	3.7%	3.7%
0.4-A5-C15-4	2226	2350	16.8%	12.4%	4.3%	3.7%
0.4-A5-C16-1	2191	2321	17.8%	13.0%	4.7%	5.3%
0.4-A5-C16-2	2245	2369	16.4%	12.5%	3.9%	3.3%
0.4-A10-C2-1	2125	2249	19.7%	12.5%	7.2%	7.9%
0.4-A10-C2-2	2156	2276	18.7%	12.0%	6.8%	6.8%
0.4-A10-C2-3	2119	2246	19.6%	12.7%	6.9%	8.0%
0.4-A10-C3-1	2145	2268	19.8%	12.3%	7.5%	7.0%
0.4-A10-C3-2	2123	2252	20.7%	13.0%	7.8%	7.8%
0.4-A10-C3-3	2126	2256	20.4%	12.9%	7.4%	7.6%
0.4-A10-C3-4	2112	2244	20.8%	13.2%	7.6%	8.1%
0.4-A10-C4-1	2147	2268	18.7%	12.0%	6.7%	7.1%
0.4-A10-C4-2	2143	2266	18.5%	12.2%	6.3%	7.2%
0.4-A10-C4-3	2137	2265	19.2%	12.8%	6.4%	7.2%
0.4-A10-C11-1	2071	2230	21.1%	15.9%	5.2%	8.7%
0.4-A10-C11-2	2059	2222	26.6%	16.3%	10.4%	9.0%
0.4-A10-C14-1	2056	2192	21.8%	13.6%	8.2%	10.2%
0.4-A10-C14-2	2099	2222	20.0%	12.4%	7.6%	9.0%
0.4-A10-C14-3	2090	2221	20.7%	13.2%	7.6%	9.0%
0.4-A10-C15-1	2080	2215	20.8%	13.5%	7.3%	9.3%
0.4-A10-C15-2	2078	2212	21.2%	13.4%	7.8%	9.4%
0.4-A10-C15-3	2074	2212	21.6%	13.8%	7.9%	9.4%
0.4-A10-C16-1	2093	2225	21.2%	13.2%	8.0%	8.9%
0.4-A10-C16-2	2111	2245	21.1%	13.4%	7.7%	8.1%
0.4-A10-C16-3	2096	2231	21.5%	13.6%	8.0%	8.6%
0.4-A10-C16-4	2084	2222	21.8%	13.8%	7.9%	9.0%

Table D- 2 Measurement results of Pressure Saturation of each disk in density, porosity and air content for 0.5 water-cement ratio.

Pressure Saturation

0.5 Water-to- Cement Ratio-Air content From A2 to A10-Core's Specimen-Disk number

Specimen	Dry Density	Saturated Density	Total Porosity	Suction Porosity	Air Content Pressure Saturation	Air Content Calculated
0.5-A2-C2-1	2287	2410	14.6%	12.4%	2.2%	1.2%
0.5-A2-C2-2	2311	2440	14.9%	12.9%	2.0%	0.9%
0.5-A2-C2-3	2289	2415	15.2%	12.7%	2.5%	1.3%
0.5-A2-C16-1	2291	2410	14.4%	11.9%	2.5%	1.3%
0.5-A2-C16-2	2299	2418	14.3%	11.9%	2.4%	1.0%
0.5-A2-C16-3	2268	2399	15.5%	13.2%	2.3%	1.7%
0.5-A2-C16-4	2322	2438	13.7%	11.7%	2.0%	0.2%
0.5-A5-C1-1	2231	2358	16.0%	12.6%	3.4%	3.8%
0.5-A5-C1-2	2267	2388	14.9%	12.1%	2.7%	2.6%
0.5-A5-C1-3	2238	2372	16.2%	13.4%	2.7%	3.2%
0.5-A5-C2-1	2256	2379	15.6%	12.2%	3.4%	3.0%
0.5-A5-C2-2	2263	2383	15.1%	12.0%	3.1%	2.8%
0.5-A5-C2-3	2253	2378	15.4%	12.5%	2.8%	3.0%
0.5-A5-C4-1	2242	2364	16.1%	12.2%	3.9%	3.0%
0.5-A5-C4-2	2223	2361	17.3%	13.8%	3.5%	3.0%
0.5-A5-C4-3	2223	2348	17.0%	12.5%	4.5%	3.6%
0.5-A5-C7-1	2225	2348	16.9%	12.3%	4.6%	4.2%
0.5-A5-C7-2	2224	2354	17.2%	12.9%	4.2%	4.0%
0.5-A5-C8-1	2256	2379	15.6%	12.2%	3.4%	3.0%
0.5-A5-C8-2	2263	2383	15.1%	12.0%	3.1%	2.8%
0.5-A5-C8-3	2253	2378	15.4%	12.5%	2.8%	3.0%
0.5-A5-C10-1	2238	2362	16.4%	12.4%	4.0%	3.6%
0.5-A5-C10-2	2220	2349	16.8%	12.9%	3.8%	4.2%
0.5-A5-C12-1	2247	2373	15.4%	12.5%	2.9%	3.2%
0.5-A5-C12-2	2276	2398	14.5%	12.2%	2.4%	2.2%



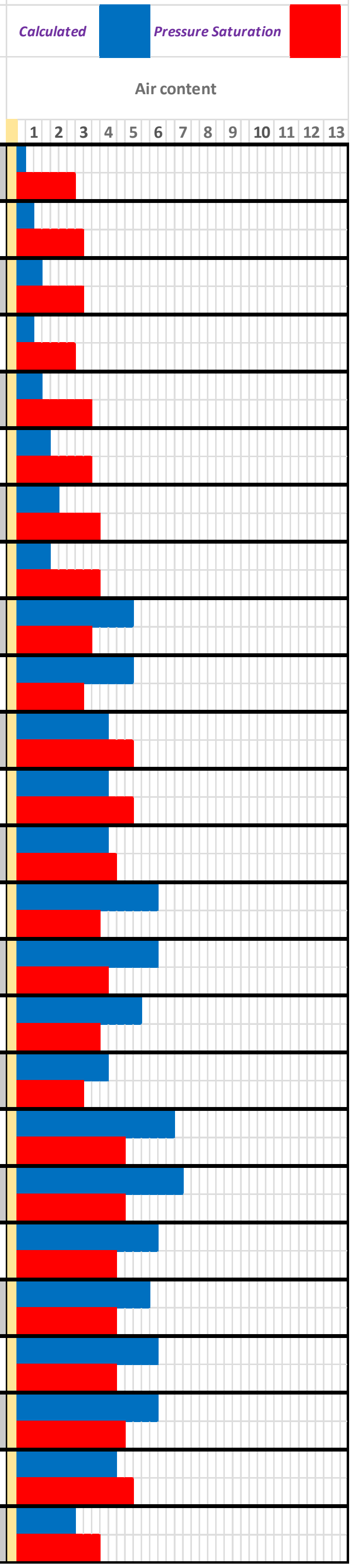
0.5-A5-C12-3	2271	2400	14.9%	12.9%	1.9%	2.1%
0.5-A5-C12-4	2271	2394	15.1%	12.3%	2.7%	2.3%
0.5-A5-C13-1	2216	2334	17.0%	11.7%	5.2%	4.1%
0.5-A5-C13-2	2223	2343	16.9%	12.1%	4.8%	3.7%
0.5-A5-C13-3	2223	2353	17.2%	13.0%	4.2%	3.3%
0.5-A5-C14-1	2207	2336	17.5%	13.0%	4.6%	4.7%
0.5-A5-C14-2	2239	2358	16.1%	11.9%	4.2%	3.8%
0.5-A5-C14-3	2221	2347	16.3%	12.6%	3.8%	4.2%
0.5-A5-C16-1	2244	2365	16.2%	12.1%	4.1%	3.5%
0.5-A5-C16-2	2249	2374	15.8%	12.5%	3.3%	3.1%
0.5-A5-C16-3	2268	2393	15.5%	12.5%	3.0%	2.4%
0.5-A10-C2-1	2020	2151	23.1%	13.1%	10.0%	11.7%
0.5-A10-C2-2	2028	2158	23.0%	13.0%	10.0%	11.4%
0.5-A10-C2-3	2047	2173	22.5%	12.6%	9.8%	10.8%
0.5-A10-C2-4	2030	2158	22.9%	12.9%	10.0%	11.5%
0.5-A10-C3-1	2050	2179	22.0%	13.0%	9.0%	10.4%
0.5-A10-C3-2	2038	2171	22.7%	13.3%	9.4%	10.7%
0.5-A10-C3-3	2039	2172	22.7%	13.4%	9.3%	10.7%
0.5-A10-C4-1	2045	2181	22.5%	13.7%	8.8%	10.3%
0.5-A10-C4-2	2068	2200	21.2%	13.2%	7.9%	9.5%
0.5-A10-C4-3	2093	2224	20.7%	13.2%	7.5%	8.5%
0.5-A10-C11-1	2024	2160	22.5%	13.6%	8.9%	11.2%
0.5-A10-C11-2	2017	2154	22.7%	13.7%	8.9%	11.4%
0.5-A10-C11-3	2030	2168	23.0%	13.8%	9.2%	10.8%
0.5-A10-C13-1	2011	2162	24.1%	15.1%	9.1%	11.1%
0.5-A10-C13-2	2030	2165	23.1%	13.4%	9.7%	11.0%
0.5-A10-C15-1	2046	2183	22.9%	13.6%	9.3%	10.2%
0.5-A10-C15-2	1995	2133	24.0%	13.8%	10.1%	12.3%
0.5-A10-C15-3	2025	2159	23.0%	13.4%	9.6%	11.2%
0.5-A10-C16-1	2063	2189	21.9%	12.6%	9.3%	10.1%
0.5-A10-C16-2	2026	2158	23.3%	13.2%	10.1%	11.4%
0.5-A10-C16-3	2028	2160	23.3%	13.3%	10.0%	11.3%
0.5-A10-C16-4	1982	2130	23.1%	14.9%	8.3%	8.7%

Table D- 3 Measurement results of Pressure Saturation of each disk in density, porosity and air content for 0.6 water-cement ratio.

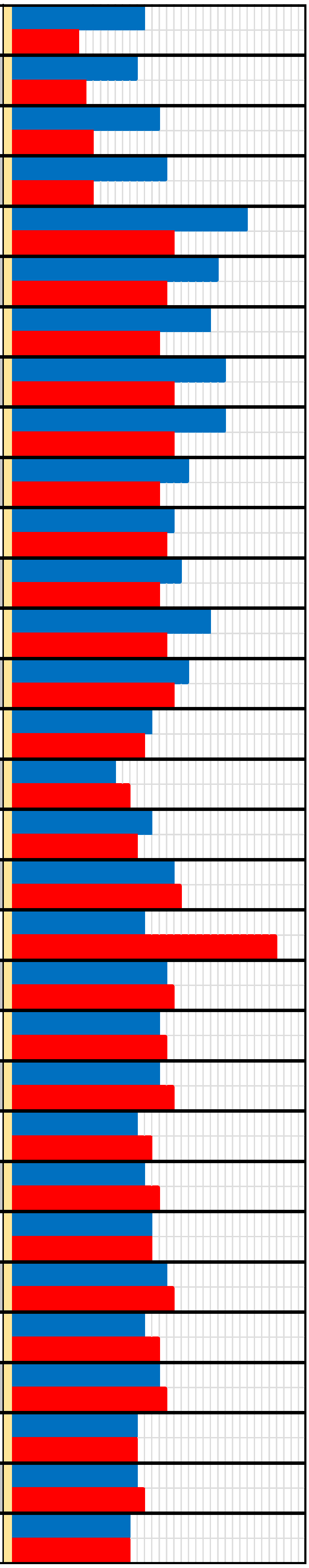
Pressure Saturation

0.6 Water-to- Cement Ratio-Air content From A2 to A10-Core's Specimen-Disk number

Specimen	Dry Density	Saturated Density	Total Porosity	Suction Porosity	Air Content Pressure Saturation	Air Content Calculated
0.6-A2-C2-1	2240	2380	16.8%	13.9%	2.9%	0.8%
0.6-A2-C2-2	2224	2366	17.2%	14.2%	3.1%	1.3%
0.6-A2-C2-3	2214	2360	17.6%	14.6%	3.0%	1.6%
0.6-A2-C2-4	2229	2372	17.2%	14.4%	2.9%	1.2%
0.6-A2-C15-1	2220	2361	17.5%	14.2%	3.4%	1.5%
0.6-A2-C15-2	2208	2350	17.8%	14.2%	3.6%	1.9%
0.6-A2-C15-3	2207	2347	17.9%	14.0%	3.9%	2.1%
0.6-A2-C15-4	2222	2360	17.5%	13.7%	3.7%	1.7%
0.6-A5-C1-1	2181	2324	17.8%	14.3%	3.5%	5.2%
0.6-A5-C1-2	2175	2326	18.1%	15.1%	3.0%	5.1%
0.6-A5-C2-1	2155	2296	19.1%	14.1%	5.0%	4.0%
0.6-A5-C2-2	2155	2298	19.4%	14.3%	5.1%	4.2%
0.6-A5-C2-3	2155	2302	19.1%	14.7%	4.4%	4.0%
0.6-A5-C3-1	2146	2298	19.0%	15.2%	3.8%	6.2%
0.6-A5-C3-2	2148	2299	19.4%	15.1%	4.3%	6.2%
0.6-A5-C3-3	2170	2316	18.6%	14.7%	3.9%	5.5%
0.6-A5-C7-1	2211	2350	16.9%	13.9%	3.0%	4.1%
0.6-A5-C10-1	2130	2284	20.1%	15.4%	4.7%	6.8%
0.6-A5-C10-2	2133	2281	19.6%	14.8%	4.7%	6.9%
0.6-A5-C10-3	2149	2298	19.2%	14.9%	4.3%	6.3%
0.6-A5-C10-4	2172	2312	18.6%	14.1%	4.5%	5.7%
0.6-A5-C11-1	2158	2302	18.9%	14.5%	4.4%	6.1%
0.6-A5-C11-2	2156	2300	19.0%	14.4%	4.6%	6.2%
0.6-A5-C13-1	2142	2289	19.7%	14.7%	5.0%	4.4%
0.6-A5-C13-2	2182	2329	18.6%	14.7%	3.9%	2.8%



0.6-A5-C15-1	2142	2297	18.9%	15.4%	3.4%	6.3%
0.6-A5-C15-2	2158	2301	18.1%	14.3%	3.9%	6.1%
0.6-A5-C15-3	2132	2281	18.8%	14.9%	3.9%	6.9%
0.6-A5-C15-4	2113	2272	19.9%	15.8%	4.0%	7.3%
0.6-A10-C1-1	1946	2129	26.1%	18.3%	7.7%	11.0%
0.6-A10-C1-2	1984	2157	24.8%	17.3%	7.5%	9.8%
0.6-A10-C1-3	1996	2169	24.5%	17.3%	7.2%	9.3%
0.6-A10-C2-1	1980	2148	24.4%	16.8%	7.6%	10.2%
0.6-A10-C2-2	1977	2149	25.0%	17.2%	7.8%	10.1%
0.6-A10-C2-3	2031	2190	23.0%	16.0%	7.1%	8.4%
0.6-A10-C4-1	2038	2204	23.9%	16.6%	7.3%	7.8%
0.6-A10-C4-2	2037	2201	23.6%	16.3%	7.3%	8.0%
0.6-A10-C4-3	2007	2168	23.6%	16.1%	7.5%	9.3%
0.6-A10-C4-4	2032	2192	23.7%	16.0%	7.7%	8.4%
0.6-A10-C9-1	2076	2229	21.6%	15.3%	6.3%	6.8%
0.6-A10-C9-2	2126	2265	19.7%	13.9%	5.8%	5.3%
0.6-A10-C9-3	2072	2228	21.7%	15.6%	6.1%	6.8%
0.6-A10-C10-1	2048	2205	23.8%	15.7%	8.1%	7.8%
0.6-A10-C10-2	2132	2236	22.8%	10.4%	12.4%	6.5%
0.6-A10-C11-1	2062	2211	22.5%	14.9%	7.7%	7.6%
0.6-A10-C11-2	2080	2225	21.9%	14.5%	7.4%	7.0%
0.6-A10-C11-3	2076	2221	22.2%	14.5%	7.7%	7.1%
0.6-A10-C12-1	2096	2241	21.3%	14.6%	6.8%	6.3%
0.6-A10-C12-2	2093	2236	21.4%	14.3%	7.1%	6.5%
0.6-A10-C15-1	2075	2229	22.2%	15.3%	6.8%	6.8%
0.6-A10-C15-2	2058	2213	23.2%	15.5%	7.6%	7.4%
0.6-A10-C15-3	2087	2236	21.8%	14.9%	7.0%	6.5%
0.6-A10-C15-4	2066	2220	22.8%	15.4%	7.4%	7.2%
0.6-A10-C16-1	2100	2246	20.8%	14.6%	6.1%	6.1%
0.6-A10-C16-2	2086	2236	21.2%	15.0%	6.5%	6.2%
0.6-A10-C16-3	2104	2253	20.8%	15.0%	5.8%	5.8%



Appendix E – Compressive Strength Test of Drilled and Laboratory Samples

Table E- 1 28 days of laboratory and 31 days of drilled compressive strength test result.

Average Compressive Strength Tests [Mpa]									
	Pl-0.4-A2	**Pl-0.4-A5**	**Pl-0.4-A10**	**Pl-0.5-A2**	**Pl-0.5-A5**	**Pl-0.5-A10**	**Pl-0.6-A2**	**Pl-0.6-A5**	**Pl-0.6-A10**
Lab	54.3	47.9	31.7	43.7	37.5	19.0	32.5	32.6	18.6
Drilled	60.5	54.4	38.1	49.6	44.5	21.7	40.3	35.9	24.7