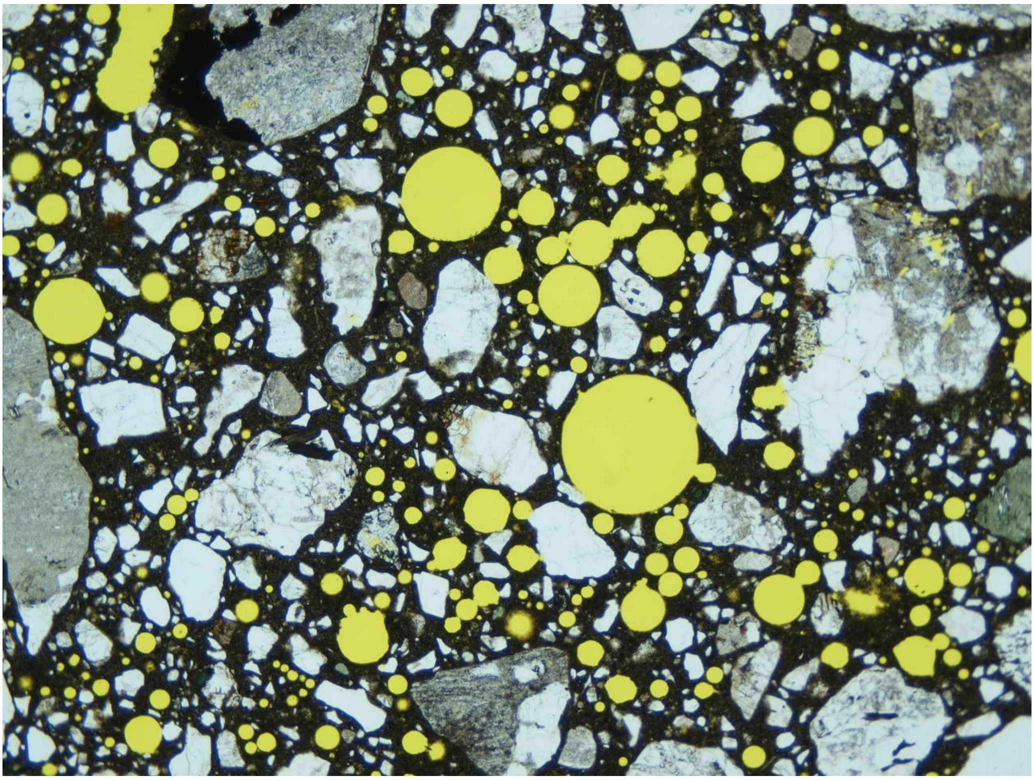
Civil Engineering Department

Securing the stable protective pore system of concrete

Report for
“Robust Air“ Research Project, 2017

Fahim Al-Neshawy
Jouni Punkki



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Abstract

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Abstract

Robust Air is a contract research project carried out at Aalto University, Department of Civil Engineering. The project was established due to evelated air content observed in some Finnish concrete structures. The aim of the Robust Air project was to secure the stability of the protective pore system in normal conditions. The stable protective pore system means that the air content or pore size distribution are not significantly changing after mixing of concrete.

The main part of the research was made in the laboratory tests which were divided into two parts. In the first part the concrete properties were altered and the same admixtures were used. In the admixture tests the concrete properties were kept constant and the admixtures were altered. The main interest of the laboratory tests was to analyze the air content of concrete as function of time. The measurements were carried out immediately after mixing, 30 min and 60 min and finally 75 min after mixing. In addition to the air content, also sensitivity for segregation was analyzed.

In addition to the laboratory tests, factory tests the Finnish concrete industry made tests in which the air content of concrete was measured after normal mixing time but also after 6 min mixing time.

Based on the experiments, it was observed that the mixing process of the air-entrained concrete is not necessarily effective enough. It is possible that only part of the entrained air is formed during the mixing process and there is a risk for elevated air content when the concrete is mixed in the concrete truck. The phenomenon was explained by *air content potential*. Each concrete has an air content potential (maximum air content) which depends on the admixture combination, concrete composition and the consistency of concrete. A relative effective mixing process is needed to achieve the Air content potential during the mixing process. And if the potential is not reached during the mixing process, there is a risk that the air content may increase later when the concrete is mixed in the truck.

Recommendations were given to minimize the risk for elevated air contents. The recommendations include development actions related to admixtures, concrete mixers, quality control systems and to requirements of frost resistance concrete. The concrete producers need to take the phenomenon better into account in the concrete manufacturing process.

Keywords Air content, Superplasticizer, Air-entraining, Admixtures, Cement, Mix Design, Testing.

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PREFACE

In Finland, elevated air contents have been reported in frost resistance concrete. The highest air contents determined from the samples drilled from structures have exceeded 15% and also significant deficiencies in compressive strength of concrete have been reported. Some indications of the elevated air contents have been seen during the latest years, but in summer 2016 couples of more severe cases came out.

The Finnish concrete sector agreed that the problem of high air content is needed to solve as soon as possible. The protective pore system needs to be such stable that the air content cannot change significantly after mixing. Therefore, a contract research project, *Robust Air*, was established at Aalto University, School of Engineering, Department of Civil Engineering.

The project was financed by the following organizations (the representative of each organization has also been given):

- Finnish Transportation Agency, Jani Meriläinen
- Confederation of Finnish Construction Industries RT, RM-concrete section, Ari Mantila
- SBK-Foundation, Jussi Mattila
- BASF Oy, Marko Kaisanlahti
- Oy Sika Finland Ab, Jani Kaasalainen / Kai Salo
- Finnsementti Oy, Satu Kosomaa
- Semtu Oy, Pirjo Tepponen
- GCP Applied Technologies, Per Devaust / Per Bogren
- Mapei Oy, Tarja Salmimies
- Ha-Be, Juhani Ukkonen
- Rudus Oy, Vesa Anttila
- Ruskon Betoni Oy, Mikko Vasama / Markus Nieminen
- Lujabetoni Oy, Markus Haatainen / Miro Harjumäki / Perttu Ruuska

The above-mentioned persons formed the steering group of the project. In addition, Risto Mannonen, Finnish Concrete Association and Matti Järvi, Inspecta Sertifiointi Oy participated in the project as expert members. The chairman of the steering group was Jussi Mattila.

From Aalto University Jouni Punkki, Professor of Practice and Fahim Al-Neshawy, Staff Scientist were responsible for the project.

The authors want to emphasize the role of the research team: Jukka Piironen, Laboratory Manager and research assistants Ammad Tauqir, Teemu Ojala, Farid Ullah and Abebe Zemenu.

The project was carried out during the period 1.1.-30.8.2017.

PROJECT SUMMARY

The aim of the *Robust Air* project was to secure the stability of the protective pore system in normal conditions. The stable protective pore system means that the air content or pore size distribution are not significantly changing after mixing of concrete.

The project consisted of the following parts:

A. Literature survey
B. Laboratory tests
C. Factory tests

In the literature survey the stability of air entrainment in fresh concrete was analyzed based on the literature available.

The laboratory tests were the main part of the project and they were divided into two parts. In the first part the concrete properties were altered and the same admixtures were used. In the admixture tests the concrete properties were kept constant and the admixtures were altered. The main interest of the laboratory tests was to analyze the air content of concrete as function of time. The measurements were carried out immediately after mixing, 30 min and 60 min and finally 75 min after mixing. In addition to the air content, also concrete's segregation sensitivity was analyzed.

In the factory tests the Finnish concrete industry made tests in which the air content of concrete was measured after normal mixing time but also after 6 min mixing time.

Based on the experiments, it was observed that the mixing process of the air-entrained concrete is not necessarily effective enough. It is possible that only part of the entrained air is formed during the normal mixing process and there is a risk for elevated air content when the concrete is mixing in the concrete truck. The phenomenon is explained by *Air content potential.* Each concrete has an Air content potential (maximum air content) which depends on the admixture combination, concrete composition and the consistency of concrete. A relative effective mixing process is needed to achieve the Air content potential during the mixing process. And if the potential is not reached during the mixing process, there is a risk that the air content may increase later when the concrete is mixed in the truck.

Recommendations are given to minimize the risk for elevated air contents. The recommendations include development actions related to admixtures, concrete mixers, quality control systems and to requirements of frost resistance concrete. The concrete producers need to take the phenomenon better into account in the concrete manufacturing process.

1 INTRODUCTION

Air content is an extremely important aspect of today's concrete performance and durability characteristics. Entrained air is needed in case of frost exposure. For the concrete exposed for freeze-thaw exposure (Exposure classes XF), the target value for total air content is typically 4...6% (8%).

Lately, elevated air contents have been observed in fresh air-entrained concrete measurements at construction site and from the samples drilled from structures. The highest air content measured from the samples drilled from the structures have exceeded 15%. The high air content has caused deficiencies in the compressive strength and other mechanical properties of concrete structures.

1.1 Problem statement (Research needs)

At the moment, the protective pore system achieved with help of air-entraining is not always stable enough. The air content may increase after mixing and may cause problems in strength and deformation properties of concrete.

There are several factors in the concrete production that can influence the stability of air entraining in concrete. Concrete composition and consistency have been noticed to affect the air entrainment. In addition, one critical factor could be the use of combination of air entraining agent (AEA) and polycarboxylate ether (PCE) –superplasticizers admixtures. Before the new type of PCE-superplasticizer the main challenge was the decreasing air content after mixing, not the increasing. It is well known that PCE-superplasticizer tends increase air content of concrete and therefore some foam killer is added into the PCE-superplasticizers.

1.2 Research objectives and approach

The objectives of the Robust Air - project were:

1. to investigate the stability of air-entrainment in concrete using different types of PCE superplasticizers, air-entraining agents and concrete mix design.
2. to set requirements of the air entraining concrete mixtures so that a stable protective pore system can be achieved

In order to reach these objectives, we have:

1. employed a state-of-the-art literature review about the air-entraining functioning of PCE-based superplasticizers
2. investigate the effects of the concrete composition and admixture combination on the stability of the air entrainment in fresh and hardened concrete in the laboratory
3. studied the following parameters that affect the stability of air content in concrete
   a. cement types
   b. different maximum aggregate sizes
   c. combinations of polycarboxylate ethers based superplasticizers and air entraining agent from seven different admixture producers

d. the effect of different mixing periods.
e. consistency of concrete

1.3 Report outline

Chapter 1 introduces the research background, problem, objectives and approach.

Chapter 2 is a review of the literature discussing important topics in the area of air entraining of concrete and the parameters affecting the stability of air in concrete. Current state of the art of using and polycarboxylate ether (PCE) –superplasticizers admixtures and air entraining agents are also reviewed.

Chapter 3 summarizes the experimental program (test procedures used to run the experimental investigation) for the research project, which includes the concrete materials, mixing procedure and testing of fresh and hardened concrete properties.

Chapter 4 summarizes and discusses the experimental results of different fresh and hardened concrete testing.

Chapter 5 presents the results of a test series carried out in the Finnish concrete industry in Summer 2017. Ready-mix concrete producers were asked to make tests related to the air content of fresh concrete

Chapter 6 presents the key findings of this research, the recommendations for implementation for the concrete industry, and the recommendations for future research.

2 LITERATURE REVIEW - STABILITY OF PROTECTIVE AIR VOIDS IN FRESH CONCRETE

2.1 Air content in concrete

Air content is an extremely important aspect of today’s concrete mix design criteria and subsequent concrete performance and durability characteristics. For example, the frost resistance of concrete is determined by the air-void system's ability to prevent the development of destructive pressures due to freezing and associated movement of moisture in the concrete pores. The specific requirements of the air-void system depend on the amount and movability of the water in the concrete pores.

Air-entraining admixtures are one part of the solution to preventing damage from freeze-thaw forces. Air entraining agents (AEAs), which are based on natural resins or synthetic surfactants, are added to the concrete mix to increase the controlled quantity of air in the form of microscopic bubble in cement paste. The intention of using AEAs is to get more stable and uniform air bubbles with small sizes homogeneously distributed in the cement paste. The fine air bubbles (the diameter smaller than 300 μm) in concrete can improve not only concrete freeze-thaw resistance but also the workability of fresh concrete.

In practice, the air bubbles in the concrete are very sensitive. There are many factors that can influence air content and the air void system in the concrete such as: paste composition, temperature of concrete mix, other chemical admixtures, mixer type and mixing time, and even the quality of mixing water. All of these factors make the process of entraining air more complicated. In addition, the air is also influenced by processes such as transportation, pumping, and compaction (Yang, 2012).

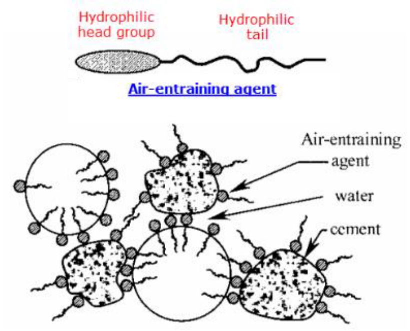
The objectives of this report are to investigate (i) the stability of air bubbles in fresh concrete and (ii) which factors influence the air stability in concrete.

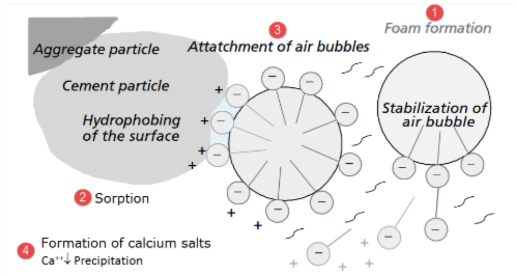
2.1.1 Air void system in concrete

One of the greatest advances in concrete technology was the development of air-entrained concrete in the mid-1930s. Nowadays, air entrainment is recommended for nearly all concretes, primarily to improve freeze-thaw resistance of concrete that is exposed to water and deicing chemicals (Kosmatka et al., 2002).

Air is entrained in fresh concrete by the mixing process. The addition of air entraining admixture to concrete helps to facilitate this process and to stabilize the air bubbles in the mix by reducing surface energy of water. Most air entraining admixtures are surface-active agents which are composed of long organic molecules with a hydrophilic end (negatively charged) and a hydrophobic end.

These molecules concentrate at the interface between paste and air bubbles, forming an elastic film around the air bubbles (schematically shown in Figure 1). The natural tendency of air bubbles in concrete is to accumulate to form larger air bubbles because of the decrease of surface energy. This film reduces the risk of air void coalescence when collisions occur during mixing process and anchors the air bubbles to the paste, thus effectively stabilizing the air bubbles. (Xiao, 2010).





Operating mechanism of the formation of air voids:

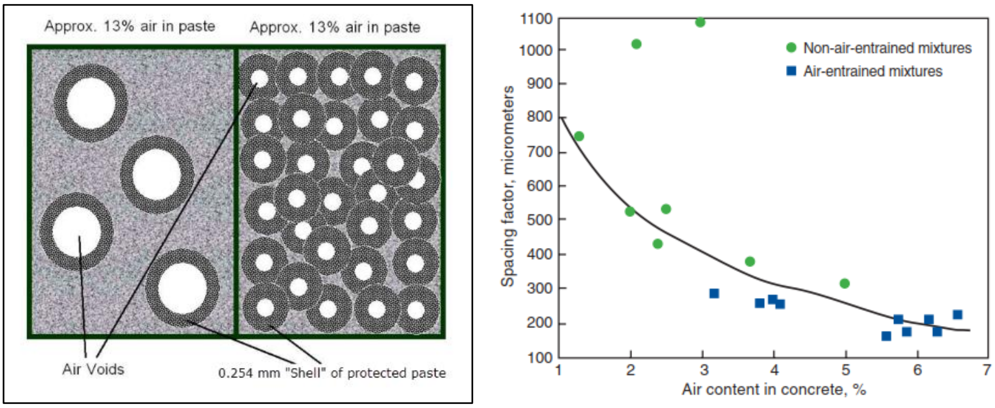
1) *Foam formation (stabilization of air bubbles),*
2) *Sorption of the air-entraining agent molecules and hydrophobing of the cement particles as a precondition for step 3,*
3) *Attachment of air bubbles to solid particles (improving the stability of the air void structure) and*
4) *Precipitation in the pore solution through the formation of insoluble calcium salts. (Eickschen, 2012).*

Figure 1. Illustration of the Air-Entraining Agent mechanism in cement paste.

The concrete air void system is characterized by three parameters: (i) air void content, (ii) specific surface and (iii) spacing factor. Generally concrete with good freeze-thaw resistance has a moderately high air content, a low enough spacing factor and relatively high specific surface.

- Air void content is the total volume fraction of air voids in concrete. In some literature, the air void content is sometimes defined in reference to the cement paste instead of the total air void content because the air void system only occurs in cement paste.
- Specific surface is defined as the surface area of air voids divided by the volume of air voids. It indicates the void frequency and the mean size of the voids. Smaller bubbles have a higher specific surface.
- Spacing factor is defined as “the average distance from any point in the paste to the edge of the nearest void”. The spacing factor is considered the most important factor with regard to freeze-thaw resistance since it is “the spacing of the air voids which determines the maximum distance that freezable water must travel through the cement paste to reach an escape boundary where ice crystals can grow freely without generating disruptive pressures”

Figure 2a shows the representation of two cement paste samples with the same air content of 13%. Assuming that the thickness of "shells" of protected paste by air voids is 0.254 mm (Hover, 2002), the protected area covered by "shells" in the paste to the right is much larger than that in the paste to the left. The paste to the right has a lower spacing factor than the left one even though they have the same air content.



(a) (b)

Figure 2. a) Comparison between two pastes, which have the same air content and different spacing factor and b) spacing factor as a function of total air content in concrete (Xiao, 2010 and Hover, 2002).

2.1.2 Air-content and durability of concrete

Entrained air greatly improves the resistance of concrete to damage resulting from freezing and thawing cycles. Microscopic air bubbles produced by admixtures called air-entraining agents relieve pressures caused by water freezing in the small voids present in hardened cement paste. Without these air bubbles, expansion of the freezing water would exert destructive pressures that can cause scaling and disintegration (Whiting and Nagi, 1998).

While the size and spacing of these air voids is important, total air content, which is more easily measured, is a good indicator of durability. The air void spacing needed for durability generally occurs when the air content of the mortar fraction is 9 ±1 %. Current specifications on air content also make little distinction among various service life of structures and the maximum aggregate size used. Some modification of this practice is desirable. Structures directly exposed to deicing salts and freezing temperatures (XF2 and XF4) require more entrained air than structures that are not exposed to de-icing salts (XF1 and XF2) (BY 65, 2016).

Table 1. Air-content recommendation for the frost resistance of concrete with a service life of 50 or 100 years (BY 65, 2016).

Max. Aggregate size, (D_{max})	**Service life of 50 years**				**Service life of 100 years**			
	XF1	**XF2**	**XF3**	**XF4**	**XF1**	**XF2**	**XF3**	**XF4**
16 mm	4.0	5.0	4.0	5.5	5.5	P50*	5.5	P70*
12 mm	4.5	5.0	4.5	5.5	6.0		6.0	
8 mm	5.0	5.0	5.0	5.5	6.5		6.5	

*) P-factor is used to evaluate the frost resistance of concrete in Finnish codes and standards. Requirements as per InfraRYL 2006 Section 42020.1.2 (P-value)

A well designed concrete mix design with adequate air content and placed by a knowledgeable professional will result in a quality durable finished concrete product that will last many years based on its intended design use. Inadequate air content can also have a negative effect on concrete quality; therefore regular routine concrete quality testing including air content should be an integral part of your quality control program as this is an item that can be controlled with knowledge of what is affecting the results. High or low air contents can be caused by a variety of material, in-house, and external factors; some of which are listed below (Whiting and Nagi, 1998).

Entrained air provides concrete with freeze-thaw durability and also improves concrete workability because the air voids act like fine aggregates in the cement paste, thus reducing the friction between solid aggregates. Entrained air also reduces the chances of bleeding and segregation during handling and transportation of concrete mixes. However, too much entrained air in concrete could lower the strength of the concrete as the mixture loses its integrity in the presence of air voids. A good "rule of thumb" is that each 1% of entrained air will lower strength by 5%.

2.2 Factors affecting the air content in concrete

Specifications for air-entrained concrete frequently require that air content be held within a percent or so of a target value. However, how easy is it to keep air content within this target values?

Variables that influence air content can be grouped into four categories:

i. Concrete materials and mix design
ii. Production procedures
iii. Construction practices
iv. Environmental conditions.

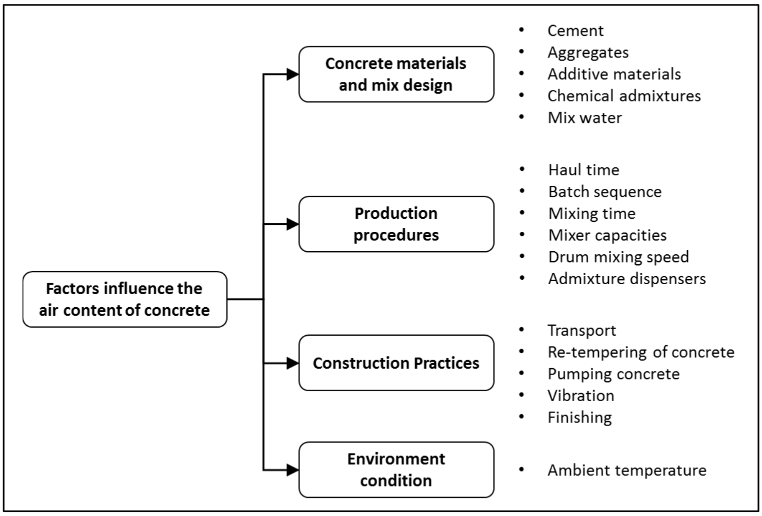


Figure 3. Factors influencing the air content of concrete (Whiting and Stark, 1983).

These categories are covered in this report. Each category describes the effects different variables have on air content. It should be noted that a part of the following information is based on the experiences with previous types of superplasticizer and therefore might not present the present situation.

2.2.1 Concrete materials and mix design

2.2.1.1 Cement

Air content can be affected by cement alkali content, cement fineness and cement content. The air content increases with increasing alkali level in the cement. This is because the alkali environment in cement paste allows the AEAs to create more air. However, high-alkali environment is not good for stabilizing the air bubbles and it also influence the air void system. Finer cement will normally decrease air content and require higher AEA dosages. There may be a decrease in air content as cement content is increased. Generally, air-entraining agents become less efficient with either an increase in cement content or an increase in cement fineness. Table 2 summarizes some of the effects cement has on the air-content of concrete (Whiting and Stark, 1983).

Table 2. Effects of cement on air content of concrete. (Whiting and Stark, 1983)

Cement	Effects on air content
Alkali content	• Air content increases with increase in cement alkali level
Fineness	• Decrease in air content with increased fineness of cement.
Cement content	• Decrease in air content with increase in cement content.

2.2.1.2 Aggregates

The characteristics and grading of aggregates have also significant influence on air entrainment. In paste, it is more difficult to entrain air because the entrained air is affected by buoyancy and there are no particles that can trap the air bubbles. In mortar and concrete, because of the addition of aggregates, the fine aggregates can form a space to hold the air bubbles and prevent them from escaping. Furthermore, aggregate with a sharp shape, like crushed stone, will entrain less air than gravel. The sharper the aggregate is the harder for the air bubbles to attach on it (Yang, 2012). Malisch (1996) defined the effect of fine and coarse aggregates on the air-content of concrete as follow:

2.2.1.3 Fine aggregate:

- Well-rounded particles entrain more air than angular particles.
- As fine fraction (less than 150 µm) increases, air content decreases.
- As middle fractions(300 to 500 µm) increase, air content increases
- Clays found in some sand deposits disperse slowly in water. When they disperse, air content decreases.

2.2.1.4 Coarse aggregate:

- Dust on the aggregate decreases air content.
- Crushed-stone concrete entrains less air than gravel concrete.

2.2.1.5 Mix water and water cement ratio

Changes in water content affect air content by changing both the water-cement ratio and the slump of the concrete.

Since the air bubbles must be formed in water, if the w/c ratio of the paste is too low, it is hard to entrain air in the paste. On the other hand, if the w/c ratio is too high, the small air voids can easily become large ones and then escape from the paste. It has been reported that with the increased w/c ratio, the spacing factor in hardened concrete will increase and the air void system become worse (Yang, 2012). As the water-cement ratio increases, more free water is available for the generation of air bubbles, so air content increases. Increase the water-cement ratio from 0.40 to 1.0, and air content can increase by over 4 percentage points.

An increase in slump also increases air content, even if the water-cement ratio is kept constant. In the slump classes S1 to S3, a 2 cm increase in slump will usually increase air content by 0.5 to 0.75 percentage point. For slump classes S4 and S5, concrete is often too fluid to retain entrained air and air content decreases (Whiting and Nagi, 1998).

2.2.1.6 Chemical admixtures

It is complex to conclude what and how the chemical admixtures affect the air entrainment. Most organic chemical admixtures like superplasticizer can increase the air entrainment since it can partly reduce the absorbed AEA molecules on the solid surface by competing with them. Other admixtures like retards, accelerators, etc., have minor effect on the air entrainment. However, today there are many kinds of AEAs like wood-derived acid salts AEA, vegetable oil acids AEA and synthetic detergents AEA, which may react with the chemical admixtures. This adds the difficulty on the study of the influence of chemical admixtures on the air entrainment (Yang, 2012).

Whiting (1984) indicated that water reducers, retarders, accelerators and superplasticizers all increase air content of concrete, but superplasticizers are of most concern. Mixes made with naphthalene-based superplasticizers require half the usual dosage of air- entraining agent, while mixes made with melamine-based products require about the same dosage, maybe higher. Exactly how much air-entraining agent is needed depends on the particular cement and admixtures being used. In some cases where superplasticizers have been used to produce flowing concrete, air losses of up to 2.5% points have been reported. Larger voids and greater space between voids have been reported for concrete containing superplasticizers, but most studies of the durability of superplasticized concretes have indicated good performance. This may be due in part to the lower water-cement ratio, which reduces both the amount of freezable water and the permeability of the concrete.

2.2.1.7 Mineral additives

Kqlaots (2004) and Nagi et al. (2007), cited in Yang (2012) explained that the use of supplementary cementitious materials as fly ash, ground granulated blast furnace slag, silica fume affects the air content of concrete. Fly ash, which contains carbon, can attract and absorb the surfactants in AEAs. Slag, which is normally used at high dosage and usually finer than cement, so under the same condition using slag may decrease the entrained air but improve the air void system. Silica fume does not have significant influence on the air content and the stability of air bubbles; however, because of its fineness, greater amounts of AEA are needed.

Table 3. Effects of aggregates, water chemical and mineral admixtures on air content of concrete (Whiting and Stark, 1983).

Variable	Effects on air content
Sand	• Air content increases with increase in sand content. • Organic impurities may increase or decrease air content. • Surface texture of sands may affect specific surface of voids.
Coarse aggregates	• Air content decreases as maximum size of aggregate increases. • Crusher fines on coarse aggregate decrease air content
Mix water	• Because of its high alkalinity, wash water from ready-mix trucks decreases air content. • Algae increase air.
Water reducers and retarders admixtures	• Lignosulfonates increase air. • Organic acid- based materials have less effect. • Spacing actors of voids increase at higher dosage
Accelerators	• Calcium chloride increases air. • Other types have little effect.
Superplasricizers	• Naphthalene-based materials increase air content. • Highly fluid mixtures may lose air. • Coarser air void systems are produced, and spacing factors of voids are increased.
Fly ash	• High carbon content or high loss on ignition decreases air content. • Fineness of ash may also have effect, especially for ashes with relatively low carbon content.
Pigments	• Carbon-black based pigments may absorb AEA and decrease air content.

2.2.2 Production procedures

Air bubbles in concrete are firstly entrained by mixing process. Hence, the mixing is important factor that together with the aggregates can affect air entrainment in concrete, since the large air bubbles can be split into smaller ones by the movement of aggregates in the mixer. From the viewpoint of work and energy, the formation of air bubbles in fresh concrete can be explained as follows:

- The mixing action gives the energy to the fresh concrete to create the interface between air and water and form the large air voids, and then split them into small voids. However, there is a tendency that the small air voids accumulate into larger voids.
- From the energy viewpoint it is clear that for the same volume of air, the one contains small air voids has a larger specific surface area and therefore higher energy than the one with large air voids, the latter can always more easily escape from the paste due to its larger buoyant force.

So the mixing action (mixer, mixing time, revolution rate, etc.), can affect how much energy can be turned into free surface energy of the air bubbles which balance the surface tension of the air bubbles. For example, mixing with longer time can of course entrain more air in fresh concrete by applying more work on the paste.

Air-entraining admixtures should be batched separately from other admixtures. A summary of the production procedures effects of air-content of concrete and corrective actions to be taken is shown in Table 4.

Table 4. Production procedures effects of air-content of concrete (Whiting, 1984).

Variable	**Effects on air content**
Batching sequence	• Simultaneous batching lowers air. • Late addition of AEA raises air.
Mixer capacity	• Air content increases as mixer capacity is approached.
Mixing time	• Central mixers: air increases up to 90 seconds, then decreases. • Truck mixers: increases up to 10 minutes, then decreases.
Mixing speed	• Air content increases up to about 20 rpms, then decreases.
Admixture metering	• Accuracy and reliability of metering system will effect uniformity of air content.
Haul time	• Long hauls reduce air content, especially in hot weather.

2.2.3 Construction practices

The way concrete is handled can have a significant effect on its air content and entrained air-void system. Construction-related variables and field conditions such as transport and delivery, retempering, placement, consolidation and finishing can affect the air content of concrete.

Yang (2012) and Whiting (1984) discussed the effect of construction-related variables on the air content of concrete as follow:

- **Transport and Delivery** – Air content is normally reasonably stable from the completion of adequate mixing through most delivery times. Typically, 1% – 2% of air content is usually lost during normal transport (more in hot weather, less in cold weather).
- **Re-tempering** - with water will generally increase air content. If necessary, re-temper with air entraining admixture at the job-site or increase the air dosage rate at the plant to compensate for air loss during transport.
- **Compaction** - If the time of high-frequency vibration is too long, the spacing factor of the air void system will increase. This is because the long-time vibration may make the small air voids merged together to form large ones.
- **Pumping** - Pumping Concrete may result in air content reductions of 2%-3% at the discharge end of the pump boom. Higher air losses usually are the result of boom configuration causing free fall of the concrete and will sometimes actually create a vacuum in the pump boom.
- **Finishing** - Finishing can affect the air content, but this is mainly at the surface and near surface of the concrete. However, normally only coarser voids can be affected.

Table 5. Summary of the effect of some of construction variables on air content of concrete (Whiting, 1984).

Variable	Effects on air content
Transport	• Some air (1 to 2%) normally lost during transport. • Air lost in pumping and on belt conveyors, especially at higher air contents.
Re-tempering	• Air contents increases after re-tempering, but this is ineffective after 4 hours.
Compaction	• Air content decreases under prolonged vibration or at high frequencies.
Finishing	• Excess finishing reduces air content in surface layer.

2.2.4 Environmental condition - Ambient temperature

Air contents normally decrease when concrete or ambient temperature increase as shown in Figure 4. In turn, air contents normally increase when concrete or ambient temperature decrease; both of which may require a dosage rate adjustment of the AEA.

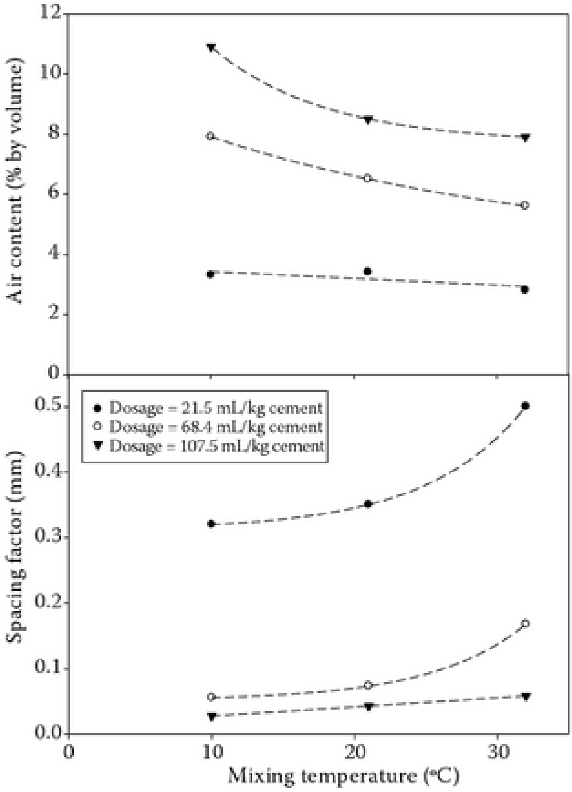


Figure 4. Change of air-content with time after mixing at various temperatures (Dyer, 2014).

Compared to the amount of air- entraining agent required when the temperature is 20 to 25°C:

- approximately 30% less air- entraining agent is required when the temperature is 5 to 10°C
- 30% more is required when the temperature is 38 to 43°C.
- The exact amount depends on the particular materials and practices used. *(Whiting and Stark, 1983).*

2.3 Stability of air-content in concrete

2.3.1 Mixing time, type and the amount of AEA (Reactivation potential of AEA)

Eickschen and Müller (2015) investigated the air void formation in relation to mixing time. They examined and optimized the test procedure in preliminary trials. A constant air content was obtained after a mixing time of 90 seconds. Longer mixing times did not produce any substantial change in the target air content of 5%. The quantity of air-entraining agent was therefore chosen so that an air content of 5.0 ± 0.5% was achieved after a mixing time of 90 seconds, then the dosage of AEA was doubled and tripled, as shown in Figure 5. Concretes was allocated to a mixing time of 30, 60 or 90 seconds or 2, 4, 7 or 10 minutes.

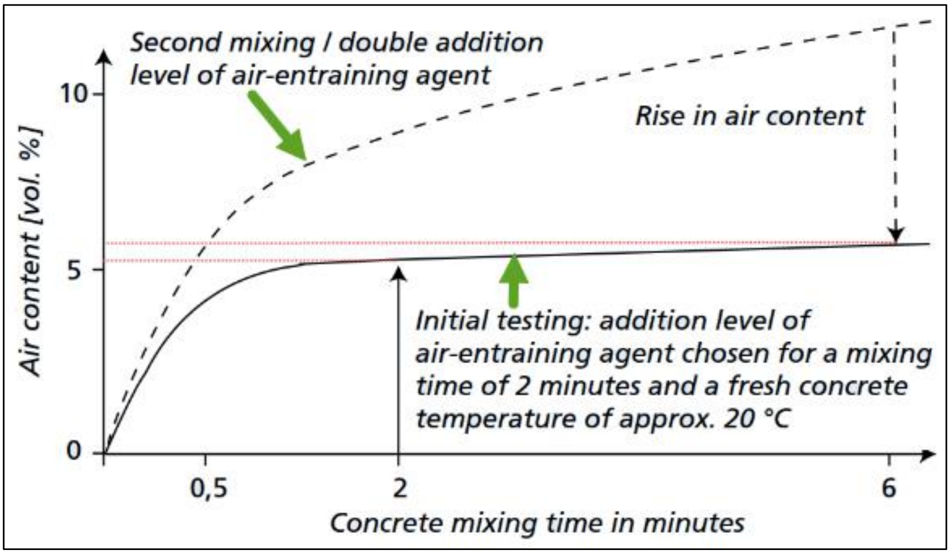


Figure 5. Testing the re-mixing of a concrete composition during initial testing in the laboratory (Eickschen and Müller, 2015).

The results show that with the air-entraining agent based on natural active substances, there was a disproportionately low increase in air content to only about 9%. With the air-entraining agent based on the alkyl sulfate active substance the air content rose to 16% after 15 minutes' mixing time and with the air-entraining agent based on the alkyl polyglycol ether sulfate active substance it rose to 18 %.

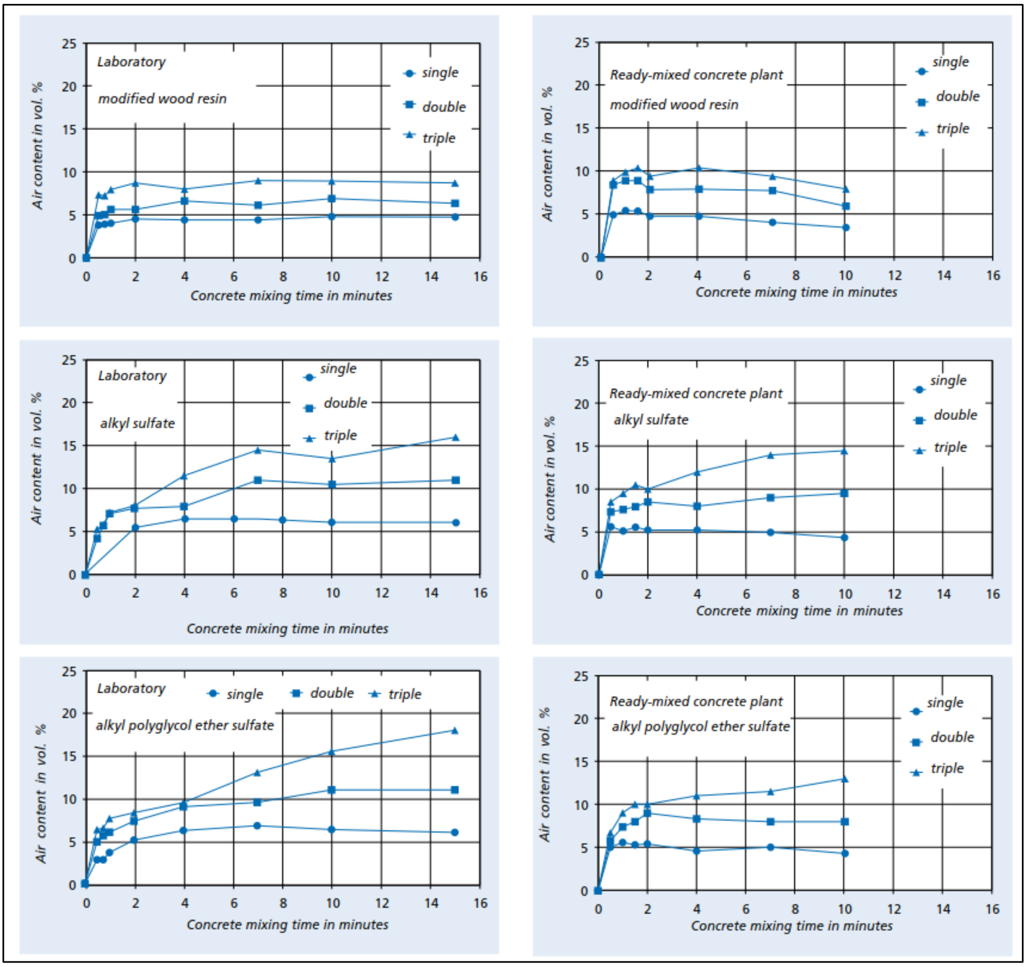


Figure 6. Air content of the fresh concrete in relation to the mixing time, the active substance and the amount of AEA added, left: laboratory and right: ready-mixed concrete plant (Eickschen and Müller, 2015).

2.3.2 Interactions of air-entraining agents and plasticizers in concrete

The mechanism of superplasticizer (SP) and air-entraining agent (AE) working in the same mix is shown in Figure 6. With the present of SP, the air content tends to be reduced. The negative charged on cement particles, given by the adsorption of SP molecules, prevent or lower the adsorption of AE molecules. As a result, there is less space for air bubbles to be entrained. Also, the negative charge keeps cement particles and air bubbles dispersing from each other and then reduces the friction of the mix. Besides the chemical property of SP and AE, the mixing procedure may also influence on its mechanism. In fact, when SP and AE are poured and mixed at the same, the mechanism of these two admixtures may become more complicated. To some level, the admixtures may disturb the effectiveness of each other resulting in both poor workability of the fresh mixture and poor stability of air entrainment. (Rath and Ouchi, 2015).

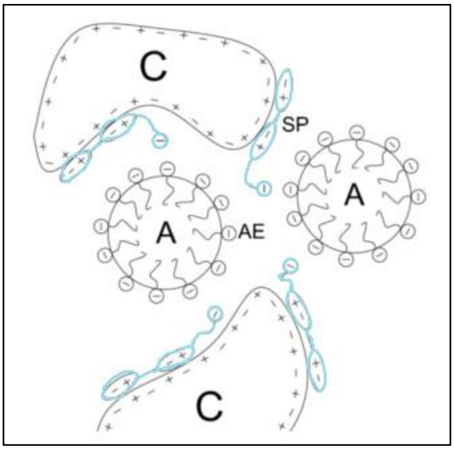


Figure 7. The mechanism of superplasticizer (SP) and air-entraining agent (AE). (Rath and Ouchi, 2015).

Lazniewska et. al. (2015) stated that most of the available superplasticizers cause a significant increase of the air content of concrete mixtures. The problem of compatibility of superplasticizer and air-entraining admixture increases in case of multicomponent Portland cement, due to different effects of these additives. The research results conducted by Lazniewska et. al. (2015) proved that in case of previously air-entrained concrete, i.e. performed with the use of that is made with innovative air-entraining multicomponent Portland cement, after the addition of new generation superplasticizer occurs very large increase in air entrainment. The problem of compatibility of superplasticizers with innovative air-entraining multicomponent Portland cement is very important and new. Compatibility testing of superplasticizers with the air-entraining cement with were not conducted.

Eickschen and Müller (2015) also observed that there have been reports of problems that have arisen in practice during the production of air-entrained concrete when using plasticizers, especially those based on polycarboxylate ether (PCE). The total air content fluctuated and in individual cases, the requirements for the air void parameters measured on the hardened concrete were not met in spite of the fact that the total air content of the fresh concrete complied with the requirements.

With plasticizers a distinction is made between classical plasticizers (based on melamine, naphthalene and lignin sulfonates) and polycarboxylate ethers (PCEs). The plasticizing action is dependent on sorption of the negatively charged plasticizer molecules on positively charged areas of the cement surface or initial hydration products, as shown in Figure 8. The action of the classical plasticizers is based on electrostatic repulsion, but PCEs also cause a spatial (steric) separation of the cement particles. Both of them reduce the formation of agglomerates of cement particles and other fine solid particles. The active substances in the classical plasticizers have a high charge density and are strongly sorbed onto the solid particles in a short time. In contrast to classical plasticizers, PCEs have specific number of side chains that are distributed along a main chain. The sorption of the PCEs can be selectively altered by varying the charge density and the lengths of the main and side chains, so that a strong initial plasticizing effect or a longer workability of the concrete can be achieved. PCEs can therefore be adapted to particular conditions of use (e.g. cement, fresh concrete temperature). However, changed marginal conditions can influence the effectiveness of the PCE and the workability time of the concrete. (Eickschen and Müller, 2015)

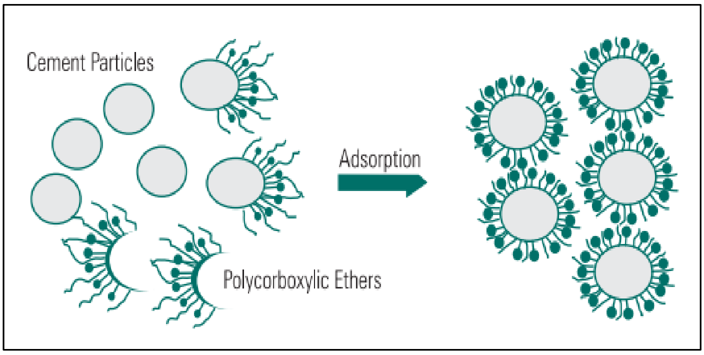


Figure 8. Mechanism of polycarboxylate ethers (PCEs).

Eickschen and Müller (2015) investigated the action mechanisms occurring during the production of air-entrained concrete with plasticizers to reduce the risk of incorrect applications. They tested fine concretes (maximum grain size 4 mm) with a specific air content and plasticizers were then added in several stages in order to show any possible de-foaming action in relation to the combination of starting materials. The air content and consistency of the content were determined after each partial addition. The air void formation in the fresh and hardened concrete (air void parameters) in relation to the combination of starting materials and the concrete age was also determined in concretes with a maximum grain size of 16 mm. The test results were used to develop a model to explain the air void formation during combined addition of air-entraining agents and plasticizers. Ten concretes (cement content 320 kg/m³, w/c ratio 0.50, shown in Table 6) were produced in order to investigate the action mechanisms of air void formation in fresh and hardened concrete in relation to the combination of the air-entraining agent/plasticizer/cement starting materials. The quantities of admixtures added were laid down so that the concrete had an air content of 5.5 ± 0.5% and a flow table spread of 49 cm to 55 cm (consistency class F4) 30 minutes after production (precast element PCE) or 45 minutes after production (ready-mixed concrete PCE or conventional plasticizer based in naphthalene sulfonate). The concretes were produced with CEM I and CEM III/A cements in combination with the following admixtures (plasticizers and air-entraining agents):

- Air-entraining agent: modified wood resin, synthetic tenside 1
- Plasticizer: precast element PCE and ready-mixed concrete PCE as well as plasticizer based on naphthalene sulfonate (only in combination with CEM III cement).

Table 6. Cement/admixture combinations (cement content 320 kg/m3, w/c ratio 0.50) (Eickschen and Müller, 2015)

Cement–42.5N	**Plasticizer**			**Air-entraining agent**		
	Type	Quantity added %-weight w.r.t cement		Type	Quantity added %-weight w.r.t cement	
		Plasticizer	Active substance		AEA	Active substance
CEM I	PCE precast element 30 minutes (1)	0.29	0.084	Mod. wood resin	0.075	0.0146
		0.25	0.073	Syn. tenside 1	0.020	0.0016
	PCE ready-mixed concrete 45 minutes (1)	0.50	0.100	Mod. wood resin		
				Syn. tenside 1	0.020	0.0016
CEM III/A	PCE precast element 30 minutes (1)	0.30	0.087	Mod. wood resin	0.165	0.0320
		0.29	0.084	Syn. tenside 1	0.040	0.0032
	PCE ready-mixed concrete 45 minutes (1)	0.55	0.110	Mod. wood resin	0.180	0.0350
		0.50	0.100	Syn. tenside 1	0.040	0.0032
	Naphthalene sulfate 45 minutes (1)	0.80	0.320	Mod. wood resin	0.200	0.0388
		0.80	0.320	Syn. tenside 1	0.080	0.0155

(1) Period from 30 or 45 minutes after end of mixing: air content 5.5 ± 0.5 vol. % and flow table spread 490 mm to 550 mm (F¤ class)

Examples of the influence of the plasticizer on air void formation are shown in Figure 9 and Figure 10 for combinations of the three plasticizers with the CEM I and CEM III cements and two air entraining agents (modified wood resin, synthetic tenside 1). Comparable results were obtained with the three plasticizers and the PCE. The quantity of plasticizer added was increased in small stages of 0.20 %-weight (PCE) or 0.30 %-weight (melamine and naphthalene sulfonate) w.r.t. cement (mixing time of 30 seconds in each case). The air content and the flow table spread (Hägermann table) were determined after each partial addition. The air content and flow table spread are shown in Figure 9a and Figure 9d in relation to the total active substance in the plasticizer for better comparability of the plasticizers.

After the first and second partial additions of plasticizer a slight drop in air content or a constant air content were recorded with the air-entraining agent based on natural active substance (Figure 9a and Figure 10c). After the third partial addition of plasticizer there was a universal increase in air content. With synthetic air-entraining agent 1 the air content always increased even after the first partial addition (Figure 9b and Figure 10d). The rise was substantially greater than with the natural air-entraining agent. The rise in air content was more strongly marked when using the PCE-based plasticizers than with the conventional plasticizers (e.g. melamine sulfonate).

No appreciable differences were found between the PCEs (ready-mixed concrete and precast elements) or between CEM I and CEM II cements. With CEM III cement the rise was somewhat more strongly marked than with CEM I cement. No substantial drop in air content due to defoaming action of the plasticizers was detected.

Combinations with the synthetic air-entraining agent and a PCE-based plasticizer exhibited a greater range of fluctuation in air content than combinations with natural air-entraining agents and conventional plasticizers.

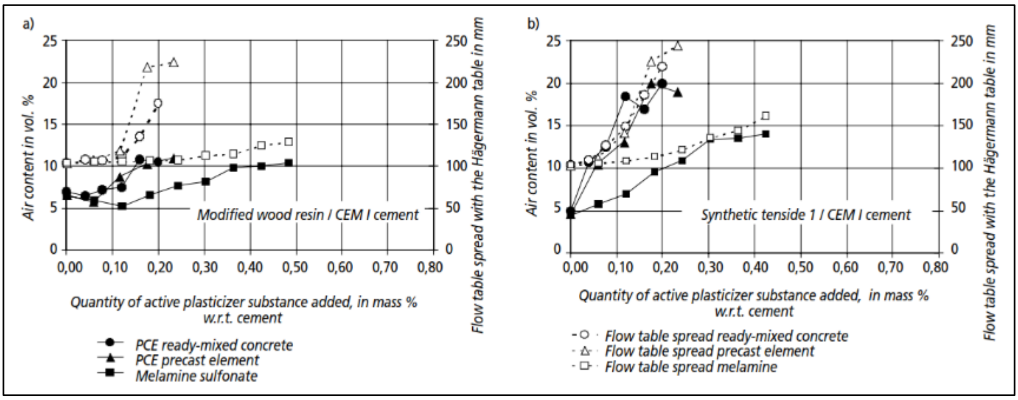


Figure 9. a and b: Air void formation and consistency relative to the type and addition level of the when using CEM I cement: left – air-entraining agent based on wood resin, and right – synthetic tenside 1.

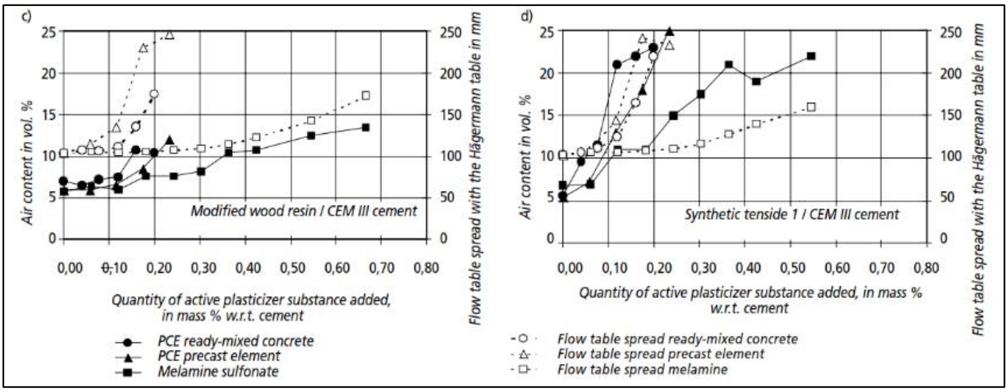


Figure 10. c and d: Air void formation and consistency relative to the type and addition level of the when using CEM III cement: left – air-entraining agent based on wood resin, and right – synthetic tenside 1.

Eickschen and Müller (2015) concluded that no instance of a de-foaming action of the plasticizer was found in the investigations on fine concretes. The air content increased with rising addition level of plasticizer. The extent of the increase was low when using air-entraining agents based on natural active substances, while a greater increase was recorded with the synthetic tenside. The reason for the different air void formation is that air-entraining agents are passed back into the pore solution after the addition of the plasticizer. Air bubbles are stabilized while the plasticizer is being mixed in. With a sparingly soluble natural air-entraining agent most of the air-entraining agent that has been “released” is precipitated and there is only a slight increase in air content. The air content can increase more sharply with a readily soluble synthetic tenside.

2.3.3 Type of superplasticizer

Lazniewska and Szwabowskia (2015) studied the effect of different types of superplasticizer on the stability of air content on concrete, shown in Table 7. The study was divided into three stages:

1) The first stage of the study is to match the type and the quantity of plasticizers and superplasticizers to the air content of mortar, which was approximately similar to that of the reference mortar, i.e. without plasticizing and superplasticizing admixtures. The liquid plasticizing and superplasticizing admixture dosed with the mixing water, in accordance with the recommendation of EN 480-1 “Admixtures for concrete, mortar and grout. Test methods. Reference concrete and reference mortar for testing”.
2) In the second stage of the research, compatibility with cement plasticizers and plasticizing admixtures in the highest degree among the analyzed SPs in the first stage the research was evaluated in terms of stability of the air entrainment and maintenance of the consistency of mortar for one hour.
3) In the third stage of the study the influence of w/c (0.45 and 0.55) and temperature (12.0 ± 1 °C and 29.0 ± 1 °C) on the stability of the air entrainment and consistency of mortar with of most compatible SP was tested.

Table 7.The type and amounts of admixtures used in the Lazniewska and Szwabowskia (2015) research

Symbol	**Main chemical base**	**% mass of CEM II/B-V cement**
PCE-1	Polycarboxylate ether	0.870
MN	Modified naphthalene, powder	0.620
AAP	Modified amino phosphonates	3.110
SNF-2	Sulfonated naphthalene-formaldehyde resins	1.900
SMF	Sulfonated melamine formaldehyde	3.450
MLG-1	Lignosulfonates	4.080

Figure 11 presents the test results of stability of the air-entrainment of mortar depending on the type plasticizers or superplasticizers. Research results show that:

- Admixtures based on sulfonated melamine formaldehyde (SMF) and lignosulfonates (MGL) stabilize the best the air-entrainment.
- Admixtures based on polycarboxylate ether (PCE-1) double the air-content of mortar comparing to the reference mortar and slightly increase the air content in mortar after 60 min.
- Admixtures based on modified powder naphthalene (MN) and admixtures based on amino phosphonates (AAP) decrease the air content of mortar after 5 minutes comparing to the reference mortar, but stabilize the air content after 60 minutes.
- Admixtures based on naphthalene (SNF-2) slightly increase the air-content of mortar after 60 min.

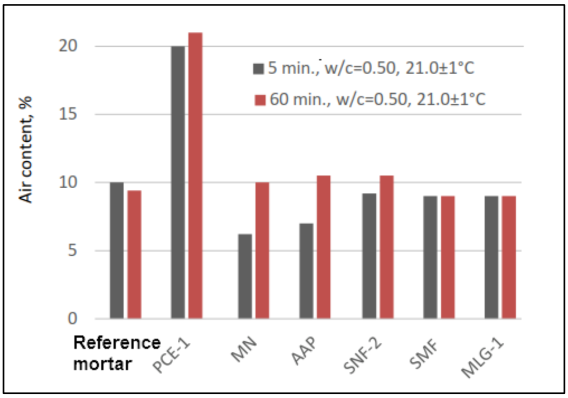


Figure 11.The comparison of air-content of the air-entrained mortar with different type of plasticizers and superplasticizers after 5 and 60 min (Lazniewska and Szwabowskia, 2015).

3 EXPERIMENTAL PROGRAM

An experimental research program was undertaken at Aalto University School of Engineering to evaluate the effects of aggregate size, type of cementitious materials, compressive strength and consistency of concrete on measuring the air content of fresh concrete. Different materials and mix proportions were adopted; they included the following parameters:

- Two compressive strength classes and P-factors of concrete: C30/37-P30 and C35/45-P50
- Maximum aggregate size. 16 mm and 8 mm
- Type of cement: three different types of cement
- Consistency classes: S3 and F5 consistency classes
- Type of chemical admixture: 7 different types of air-entraining agents and polycarboxylate ether based superplasticizers.

3.1 Materials, mix designs and mixing procedure

Mix designs with pre-determined cement contents and varying water-cement ratios (w/c) were used for this research. The cement content and superplasticizer dosage were selected to correspond the typical values in the concrete industry. Water contents were adjusted so that the required workability was achieved. The values of water-cement ratio, 0.33 to 0.38, are lower than the typical values used in the concrete industry. This is due to the lower water requirement of the laboratory aggregates.

Three types of cement were used in the tests. Two cements (Plus Cement and SR-Cement) were produced by Finnsementti's cement plant at Parainen. The third cement was Rapid-cement produced by CEMEX Ltd, Broceni, Latvia. The chemical analysis according to information received from the cement producers is shown in Table 8.

Table 8. Typical properties of cement and clinker of the used cements.

Chemical composition	**Plus Cement, Finnsementti CEM II/B-M (S-LL) 42,5 N**	**SR-Cement, Finnsementti CEM I 42,5 N - SR3**	**RAPID, Broceni CEM I 52,5 N**
1d strength	15 MPa	18 MPa	20 – 22 MPa
2d strength	28 MPa	31 MPa	
7d strength	39 MPa	48 MPa	47 – 52 MPa
28d strength	49 MPa	56 MPa	59 – 60 MPa
Initial setting time	150 – 210 min.	160 – 200 min.	154 – 182 min
Soundness	0 – 1,5 mm	0 – 3,5 mm	
Fineness (Blaine)	420 – 470 m²/kg	380 – 410 m²/kg	435 – 467 m²/kg
Chemical properties of clinker			
CaO	65 %	64 %	63%
SiO_2	21 %	21 %	20%
Al_2O_3	4.7 %	3.8 %	5,5%
Fe_2O_3	3.5 %	4.7 %	0,5%
MgO	3.1 %	3,0%	1,0%
Lime stone	6 – 15%	≤ 5%	
Blast furnace slag	15 – 25%	≤ 5%	

The aggregate used in these tests was granitic gravel, which was washed, dried and graded by sieving. Concrete mixes were made by using the same aggregate grading. The grading curve of the combined aggregate and the particle-size distribution is presented in Appendix 1.

Seven different types of air-entraining agents and polycarboxylate ether based superplasticizers were used in the research. The admixtures were stored (in a polyethylene bottle) at the room temperature (+ 20 °C). The properties of different admixtures according to information received from their manufacturers are presented in Table 9 and Table 10.

The water used was tap water from the water distribution system of Espoo city. The water's temperature was approximately + 20 °C.

Table 9. Properties of the air-entraining agents used in the tests.

Admixture code	**Manufacturer**	**Colour**	**Recommended dosage / binder**	**Density, kg/dm^3**
MasterAir 100	BASF Oy	amber - brown	0.02% - 0.08%	1.01
ILMA-PARMIX	Finnsementti Oy	amber	0.01% - 0.08%	1.02
PANTAPOR 2020 (LP)	Ha-Be Betonchemie GmbH	brown	0.01% - 0.40%	1.07
Mapeair 50	MAPEI	light-brown	0.06% - 0.3%	1.01
Master Air 102	Semtu Oy	brown	0.03 % - 0.1%	1.03
Sika Air-Pro V5	Oy Sika Finland Ab	bright yellowish	0.05% - 1.0%	1.04
Darex AEA T (LP)	GCP Applied Technologies	colorless	0.2% - 1.01%	1.01

Table 10. Properties of the polycarboxylate ether based superplasticizers used in the tests.

Admixture code	**Manufacturer**	**Colour**	**Recommended dosage / binder**	**Density, kg/dm^3**
MasterGlenium SKY 600	BASF Oy	yellow	0.2% - 2.0%	1.03
VB-PARMIX	Finnsementti Oy	brownish	0.3% - 3%	1.03
PANTAHIT TB100 (FM)	Ha-Be Betonchemie GmbH	amber	0.2 – 2.20%	1.07
Dynamon SX-23	MAPEI	yellow-brown	0.3% - 2.0%	1.05
Sem Flow MC	Semtu Oy	amber - brown	0.2% - 2.5%	1.05
Sikament -RSX (25%)	Oy Sika Finland Ab	green	0.2% - 2.5%	1.04
ADVA Flow 444-L	GCP Applied Technologies	amber	0.2% - 3.0%	1.05

The principle of coding the concrete mixes presented in Figure 12 bases on the type of chemical admixture, compressive strength, cement type, maximum aggregate size and consistency class.

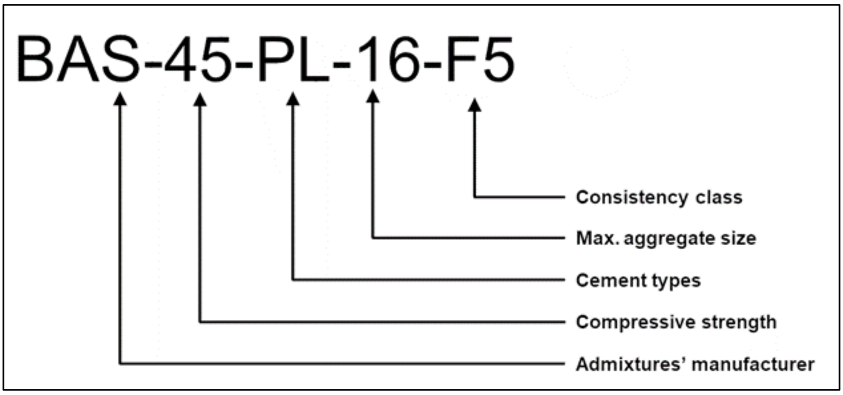


Figure 12. The principle of coding the studied concretes in the "Robust Air" studies.

Table 11. Coding of concrete mixes for different admixture combinations.

Coding variables	Concrete mix coding
Compressive strength and P-factor (*)	45 = C35/45 - P50 37 = C30/37 - P30
Cement types	PL = Plus cement, Finnsementti SR = SR-cement, Finnsementti BR = Rapid - Broceni, Cemex
Max. aggregate size	16 = # 16 mm 8 = # 8 mm
Consistency class	S3 = Slump class S3 F5 = Flow class F5

**) P-factor is used to evaluate the frost resistance of concrete in Finnish codes and standards.*

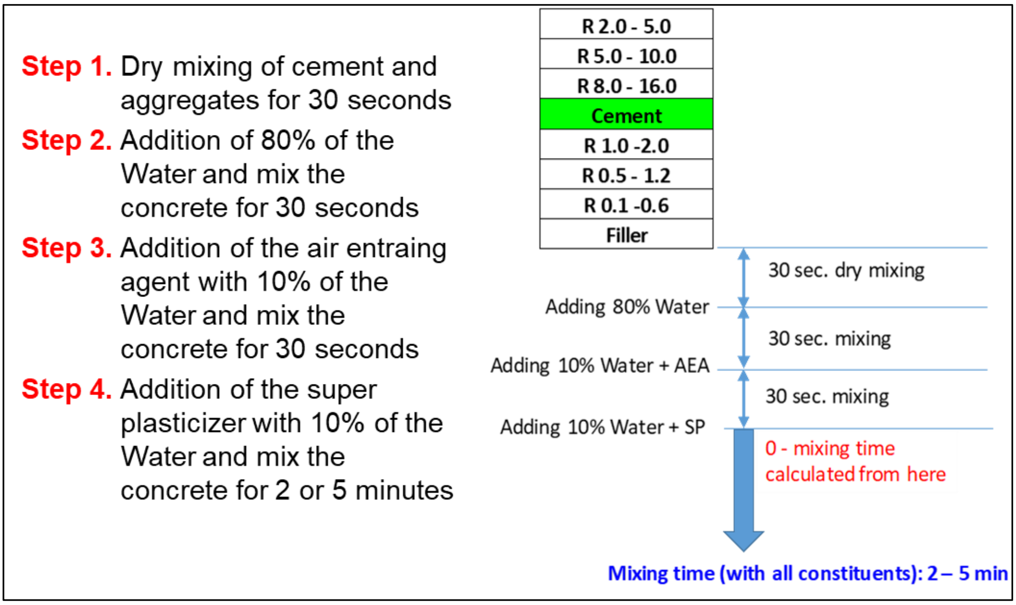
The concrete mixes were designed using the absolute volume equation for concrete mix design as follows:

$$\frac{W_{cement}}{\rho_{cement}} + \frac{W_{aggregate}}{\rho_{aggregate}} + \frac{W_{admixture}}{\rho_{admixture}} + W_{water} + Air = 1\,m^3 \qquad (1)$$

Where:

W = the mass of the material (kg)
ρ = the density of the material (kg/m³)
Air = the air content (m³)

The mixing procedure of the concrete follows the following steps, as shown in Figure 13.



Step 1. Dry mixing of cement and aggregates for 30 seconds

Step 2. Addition of 80% of the Water and mix the concrete for 30 seconds

Step 3. Addition of the air entraing agent with 10% of the Water and mix the concrete for 30 seconds

Step 4. Addition of the super plasticizer with 10% of the Water and mix the concrete for 2 or 5 minutes

Figure 13. Concrete mixing procedure.

The moisture content of the aggregates was assumed to be 0% (oven dry aggregates).

3.2 Tests on fresh and hardened concrete

The properties determined on fresh concrete were air content, density, temperature and consistency. Air-content of concrete was measured by:

- Pressure method according to the “SFS-EN 12350-7 - Testing fresh concrete. Part 7: Air content. Pressure methods” standard.
- Real-Time Air Measurement using CiDRA AIRtrac
- Calculated from the fresh concrete unit weight. The air content of fresh concrete is calculated according to the ASTM C 138“Standard Test Method for Density (Unit Weight), Yield and Air Content (Gravimetric) of Concrete”

$$Air\ content, A = \frac{(T-D)}{T} * 100 \tag{2}$$

where:

A = the air content in the concrete, (%)
D = the density (unit weight) of concrete, (kg/m³)
T = the theoretical density of the concrete computed on air free bases, (kg/m³)

$$T = \frac{M}{V} = \frac{M}{1-A_t} \tag{3}$$

where:

M = the mass of all materials batched – sum of the masses of the cement, the aggregates in the condition used, the mixing water added to the batch and the chemical admixtures, (kg).
V = the absolute volume of the component ingredients in the batch, (m^3)
A_t = the target air content of the batch, (m^3)

Based on equations (3) and (4), the air content is calculated as follow:

$$Air\ content, A = \left(1 - \frac{D}{M} + \frac{D * A_t}{M}\right) * 100 \tag{4}$$

The workability of concrete was tested using two standard:

1. SFS-EN 12350-2 – “Testing fresh concrete. Part 2: Slump-test”
2. SFS-EN 12350-5 - “Testing fresh concrete. Part 5: Flow table test”

The measurements of fresh concrete properties took place immediately after the concrete had been mixed, after 30 minutes, after 60 minutes and after 75 minutes. The schedule of fresh concrete tests and preparing of the hardened concrete test specimens are shown in Figure 14.

The following hardened concrete tests were performed:

- 28 d compressive strength tests on 3 cubes (100*100*100 mm^3) cast immediately after concrete mixing and 3 cubes cast after 75 minutes of mixing and addition of extra dosage of superplasticizer.
- Segregation sensitivity of concrete
  - Density difference between bottom and top parts of 150 mm diameter concrete cylinder with height of about 270 – 300 mm.
  - Difference in air content and paste content determined in thin section analyses of the bottom and top parts
  - Difference in air content determined with use of pressure saturation test analyses of the bottom and top parts

Casting (0 time)	30 minutes from casting	60 minutes from casting	75 minutes from casting
- 30 sec. dry mixing - 30 sec. with 80% of water - 30 sec. with AEA + 10% water - Adding SP + 10% water then mixing for 2 or 5 min	- Mixing for 1 minute	- Mixing for 1 minute	- Adding SP amount = 15 - 25% of the original SP dosage of the batch depending on the workability class - Mixing for 2 minutes
 - For S5 → flow test - tested concrete back to the mixer	 - For S5 → flow test - tested concrete back to the mixer	 - For S5 → flow test - tested concrete back to the mixer	 - For S5 → flow test - tested concrete back to the mixer
 - For S3 → slump test - tested concrete back to the mixer	 - For S3 → slump test - tested concrete back to the mixer	 - For S3 → slump test - tested concrete back to the mixer	 - For S3 → slump test - tested concrete back to the mixer
 - Air content – pressure test - Fresh density (unit weight) - tested concrete to the waste	 - Fresh density (unit weight) - tested concrete back to the mixer	 - Air content – pressure test - Fresh density (unit weight) - tested concrete to the waste	 - Air content – pressure test - Fresh density (unit weight) - testedconcrete to the waste
 - 11.0 kg of concrete vibrated for 30 seconds		 - 11.0 kg of concrete vibrated for 30 seconds	 - 11.0 kg of concrete vibrated for 30 seconds
 Casting 3 cubes / 28d Compressive strength			 Casting 3 cubes / 28d Compressive strength

Figure 14. Schedule for measurements of fresh concrete properties and casting specimens for hardened concrete test.

4 EXPERIMENTAL RESULTS AND ANALYSIS

In the experimental part, the stability of entrained pore structure was investigated. The main interests were in the increase of air content after mixing as well as in the segregation sensitivity of concrete. Two types of segrgation were analyzed. In addition to the segregation of air pores to the top of the structures also aggregate may segregate to the bottom of structure.

The experimental tests were divided into two separate parts:

(i) Effects of concrete properties on air stability (Concrete Tests)
(ii) Effect of different admixture combinations (Admixture Tests)

In the “Concrete Tests”, the effects of concrete properties on the stability of protective pore system were tested. The same admixtures (superplasticizer and air-entraining agent) were used in all the tests. In the “Admixture Tests”, the different admixtures were tested and the concrete properties were kept constant. Totally seven different admixture combinations (superplasticizer and air-entraining agent) were tested.

It is essential to note that the laboratory tests are not presenting exactly the same situation as found in the concrete industry. For example, the aggregates used in the laboratory tests have clearly lower water requirement compared to those normally used in the industry. Therefore, the water-cement ratios are clearly lower compared the practical ones. The phenomena are still the same both in the laboratory and in the industry and therefore the results represent the real situation. However, the effects can be much stronger in the laboratory tests compared to those taking place in normal concrete production. Therefore, consideration is needed when utilizing the tests results in the industrial concrete production.

4.1 Effects of concrete properties on air stability (Concrete Tests)

The effects of concrete properties on the stability of the protective pore system were analyzed using the following variables:

- Two compressive strength classes and P-factors of concrete: C30/37-P30 and C35/45-P50
- Consistency of concrete: 2 levels (Workability classes F5 and S3)
- Maximum aggregate size: 2 levels (8 mm and 16 mm)
- Cement type: 3 different (Plus-cement, SR-cement and Rapid CEM I)

The test concrete combinations are presented in Table 12. All the concretes were prepared using the same air entraining agent and superplasticizer admixture combination (see Chapter 4.1.1).

Table 12. Target properties and gradients of concrete tests.

Concrete Code	Compressive strength grade	Consistency class	Maximum aggregate size	Cement type
37-BR-16-F5	C30/37	F5	16 mm	CEM I
37-BR-16-S3	C30/37	S3	16 mm	CEM I
37-PL-08-F5	C30/37	F5	8 mm	Plus
37-PL-08-S3	C30/37	S3	8 mm	Plus
37-PL-16-F5	C30/37	F5	16 mm	Plus
37-PL-16-S3	C30/37	S3	16 mm	Plus
37-SR-16-F5	C30/37	F5	16 mm	SR
37-SR-16-S3	C30/37	S3	16 mm	SR
45-BR-16-F5	C35/45	F5	16 mm	CEM I
45-BR-16-S3	C35/45	S3	16 mm	CEM I
45-PL-08-F5	C35/45	F5	8 mm	Plus
45-PL-08-S3	C35/45	S3	8 mm	Plus
45-PL-16-F5	C35/45	F5	16 mm	Plus
45-PL-16-S3	C35/45	S3	16 mm	Plus
45-SR-16-F5	C35/45	F5	16 mm	SR
45-SR-16-S3	C35/45	S3	16 mm	SR

4.1.1 Concrete Mix Designs

The mix designs of test concrete were based on the typical cement contents and superplasticizer dosage used for the concretes (salt-frost resistance, P-factor concrete) used mainly in bridge construction. The typical mix designs were asked from three ready-mixed concrete producers participating in the project.

As cement contents, superplasticizer dosages and consistencies of concrete were fixed the adjustment was made with help of water content. The laboratory aggregate fractions used in the tests have lower water requirements compared to typical aggregates used in the industrial production. Therefore, the water-cement values used in the tests are smaller compared to the industrial ones. The mix design of the concretes with different admixtures are shown in Table 13.

Table 13. Mix design of concretes for C30/37-P30 concretes.

Concrete mix	Cement , (kg)	Effective Water, (kg)	Aggregate , (kg)	Air entraining agent , (kg)	Super-plasticizer, (kg)	Target Air content, (%)
37-BR-16-F5	400	155	1752	0.268	4.800	5.5
37-BR-16-S3	400	140	1806	0.268	4.400	5.0
37-PL-08-F5	420	170	1694	0.147	5.040	5.5
37-PL-08-S3	420	160	1721	0.147	5.040	5.5
37-PL-16-F5	400	155	1765	0.140	4.800	5.0
37-PL-16-S3	400	140	1805	0.140	4.800	5.0
37-SR-16-F5	400	155	1752	0.200	4.800	5.5
37-SR-16-S3	400	140	1805	0.240	4.800	5.0

Table 14. Mix design of concretes for C35/45-P50 concretes.

Concrete mix	Cement, (kg)	Effective Water, (kg)	Aggregate, (kg)	Air entrainin g agent , (kg)	Super-plasticizer, (kg)	Target Air content, (%)
45-BR-16-F5	425	155	1729	0.340	5.100	5.5
45-BR-16-S3	425	140	1772	0.179	4.250	5.5
45-PL-08-F5	440	175	1636	0.145	5.280	6.5
45-PL-08-S3	440	155	1689	0.154	5.280	6.5
45-PL-16-F5	425	160	1716	0.149	5.100	5.5
45-PL-16-S3	425	140	1770	0.149	5.100	5.5
45-SR-16-F5	425	155	1729	0.231	5.100	5.5
45-SR-16-S3	425	140	1769	0.234	5.100	5.5

4.1.2 Workability properties of fresh concrete

The workability of concrete was measured using the Slump or Flow test depending on the workability class. The consistency of concrete was adjusted so the value of the particular workability class was achieved immediately (3 min) after mixing. Therefore, the workability of concrete was somewhat stiffer compared to the industrial production where the workability is normally adjusted when concrete is arriving to the construction site (typically 15…60 min after mixing).

In addition to the initial workability measurements, the workability was measured also 30 ja 60 min after initial mixing. Before the measurement, the concrete is mixed in the mixer for 1 min. After the 60 min measurements, some superplasticizer was added and concrete was mixed for 2 min to compensate the workability loss taking place during 60 min. The added superplasticizer dosage was 15…25% from the original SP dosage of the batch depending on the workability class. The target was to achieve the original workability level after the initial mixing, but rather high variation took place.

4.1.2.1 Workability test results

The workability of test concretes as function of time has been presented in Figure 15 and Figure 16. The workability of concrete after the superplasticizer addition was measured at the age of 75 min.

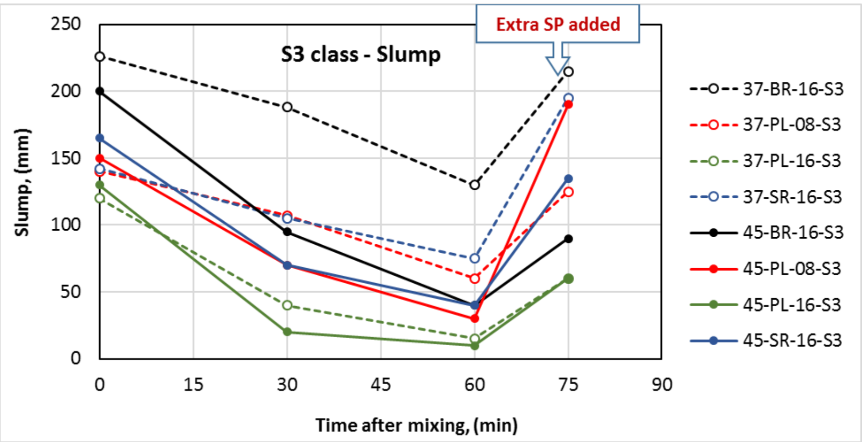


Figure 15. Workability of S3 – class concretes as function of time.

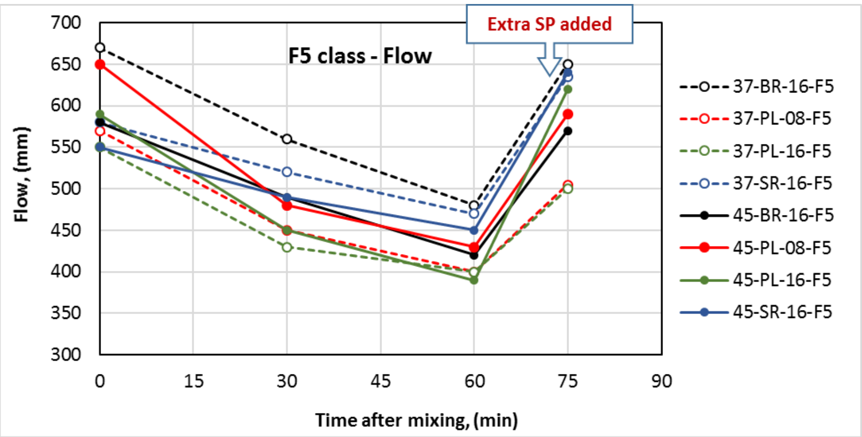


Figure 16. Workability of F5 – class concretes as function of time.

4.1.2.2 Experimental findings of the consistency tests

As it is shown in Figure 15, the average loss of workability for the S3 consistently concretes was more the 50%. The average workability loss for concrete mixes with maximum aggregate size # 8 mm was smaller than the workability loss of concretes with # 16mm at 30 minutes and 60 minutes after mixing. The maximum rate of workability loss was 3.7 mm/min for concrete mix with Plus Cement and #16 mm maximum aggregate size at 30 minutes.

The workability loss of fresh concrete expressed as the rate of loss is presented in Table 15. The results show that the average rate of workability loss for S3 consistency class concrete was 1.8 mm/min during 60 minutes after mixing. The average rate of workability loss for F5 consistency class concrete was 2.7 mm/min during 60 minutes after mixing.

Table 15. Rates of workability loss of fresh concrete after 30 and 60 minutes.

Concrete mix	**Slump value after mixing, (mm)**	**Workability loss, (mm/min)**		**Concrete mix**	**Flow value after mixing, (mm)**	**Workability loss, (mm/min)**	
		30 min	60 min			30 min	60 min
37-BR-16-S3	230	1.3	1.6	37-BR-16-F5	670	3.7	3.2
37-PL-08-S3	140	1.1	1.3	37-PL-08-F5	570	4.0	2.8
37-PL-16-S3	120	2.7	1.8	37-PL-16-F5	550	4.0	2.5
37-SR-16-S3	140	1.2	1.1	37-SR-16-F5	580	2.0	1.8
45-BR-16-S3	200	3.5	2.7	45-BR-16-F5	580	3.0	2.7
45-PL-08-S3	150	2.7	2.0	45-PL-08-F5	650	5.7	3.7
45-PL-16-S3	130	3.7	2.0	45-PL-16-F5	590	4.7	3.3
45-SR-16-S3	170	3.2	2.1	45-SR-16-F5	550	2.0	1.7

4.1.3 Air content in fresh concrete

The air content of concrete was measured as function of time. The measurements took place immediately (3 min) after initial mixing, 30 min and 60 min after mixing. After the 75 min measurements superplasticizer was added and concrete was mixed for 2 min. The air content was measured at the age of 75 min.

The air content of fresh concrete was determined using different methods. The normal pressure method was used. Also, the air content was calculated based on the fresh concrete density. In addition, the air content was measured using CiDRA AIRtrac system and both the Static and Dynamic measurements were recorded.

The pressure method was not used in all the measuring moments because the test consumes concrete and the concrete volume was critical. The use of different test methods has been shown in Table 16.

Table 16. The air content measurements.

Testing age	Pressure method	Calculated air content from the unit weight test	CiDRA AIRtrac
Immediately after mixing (3 min)	X	X	X
30 min after mixing		X	X
60 min after mixing	X	X	X
75 min after mixing (SP added)	X	X	X

4.1.3.1 Pressure method

The results of the pressure method measurements have been presented in Table 17.

Table 17. Air contents of fresh concrete as function of time measured using the pressure method.

Concrete mix		0 min	60 min	75 min	Concrete mix		0 min	60 min	75 min
C35/45 concrete class	45-BR-16-F5	7.2	13.5	10.6	**C30/37 concrete class**	37-BR-16-F5	6.5	15.0	12.9
	45-BR-16-S3	6.6	8.4	8.3		37-BR-16-S3	5.6	15.1	12.0
	45-PL-08-F5	5.5	15.5	7.5		37-PL-08-F5	4.8	14.4	10.6
	45-PL-08-S3	6.8	n/a(*)	6.9		37-PL-08-S3	7.2	10.0	8.4
	45-PL-16-F5	5.8	n/a(*)	5.9		37-PL-16-F5	5.6	13.4	8.5
	45-PL-16-S3	5.4	6.2	5.6		37-PL-16-S3	5.7	8.0	7.2
	45-SR-16-F5	5.6	13.0	7.8		37-SR-16-F5	5.6	14.8	10.0
	45-SR-16-S3	6.5	11.5	8.5		37-SR-16-S3	7.4	11.5	9.0

*) In the beginning of testing program, the air content measuring using pressure methods, was performed only immediately after mixing and at 75 min.

4.1.3.2 Air content calculated from fresh concrete density (unit weight)

The calculated air contents of all the test concretes have been presented in Figure 17, Figure 18, Table 18 and Figure 19.

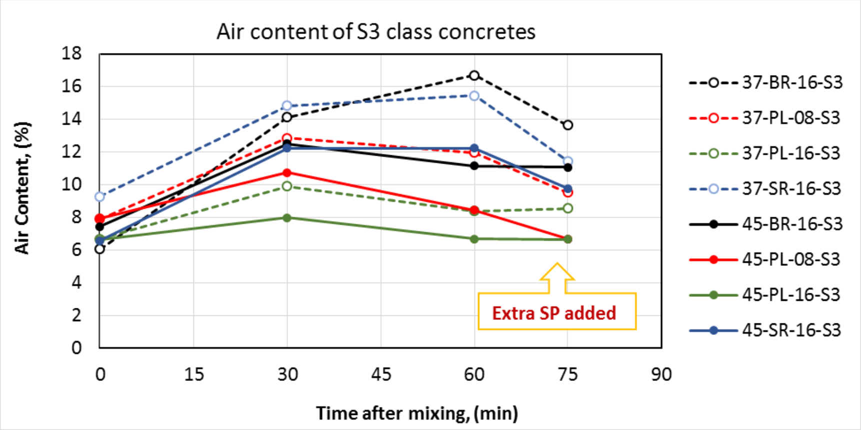


Figure 17. Calculated air contents of the S3 consistency class concretes. The calculation is based on the fresh concrete density (unit weight)

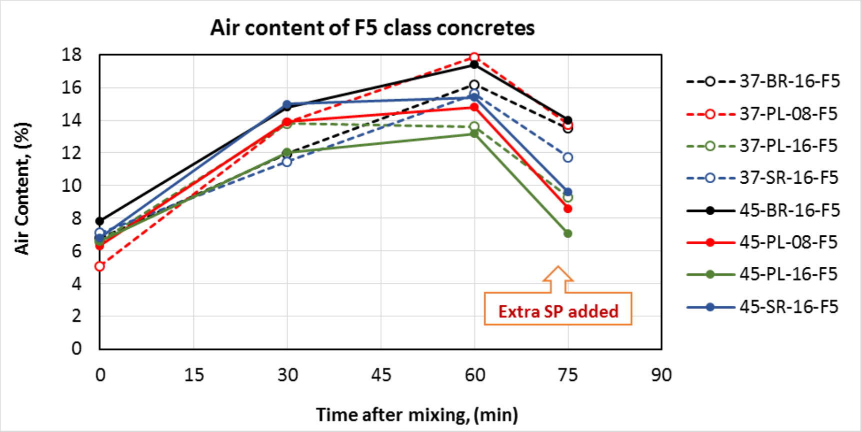


Figure 18. Calculated air contents of the F5 consistency class concretes

Table 18. Calculated air contents of fresh concrete.

Concrete mix		0 min	30 min	60 min	75 min
C30/37 concrete class	**37-BR-16-F5**	6.8	12.0	16.2	13.5
	37-BR-16-S3	6.1	14.1	16.7	13.6
	37-PL-08-F5	5.1	13.9	17.9	13.7
	37-PL-08-S3	7.9	12.8	12.0	9.5
	37-PL-16-F5	6.6	13.8	13.6	9.3
	37-PL-16-S3	6.7	9.9	8.4	8.5
	37-SR-16-F5	7.1	11.5	15.6	11.7
	37-SR-16-S3	9.3	14.8	15.4	11.4
C35/45 concrete class	**45-BR-16-F5**	7.8	14.8	17.4	14.0
	45-BR-16-S3	7.4	12.5	11.2	11.1
	45-PL-08-F5	6.3	13.9	14.8	8.6
	45-PL-08-S3	7.9	10.7	8.4	6.7
	45-PL-16-F5	6.6	12.0	13.2	7.1
	45-PL-16-S3	6.6	8.0	6.7	6.7
	45-SR-16-F5	6.8	15.0	15.4	9.6
	45-SR-16-S3	6.6	12.2	12.2	9.8

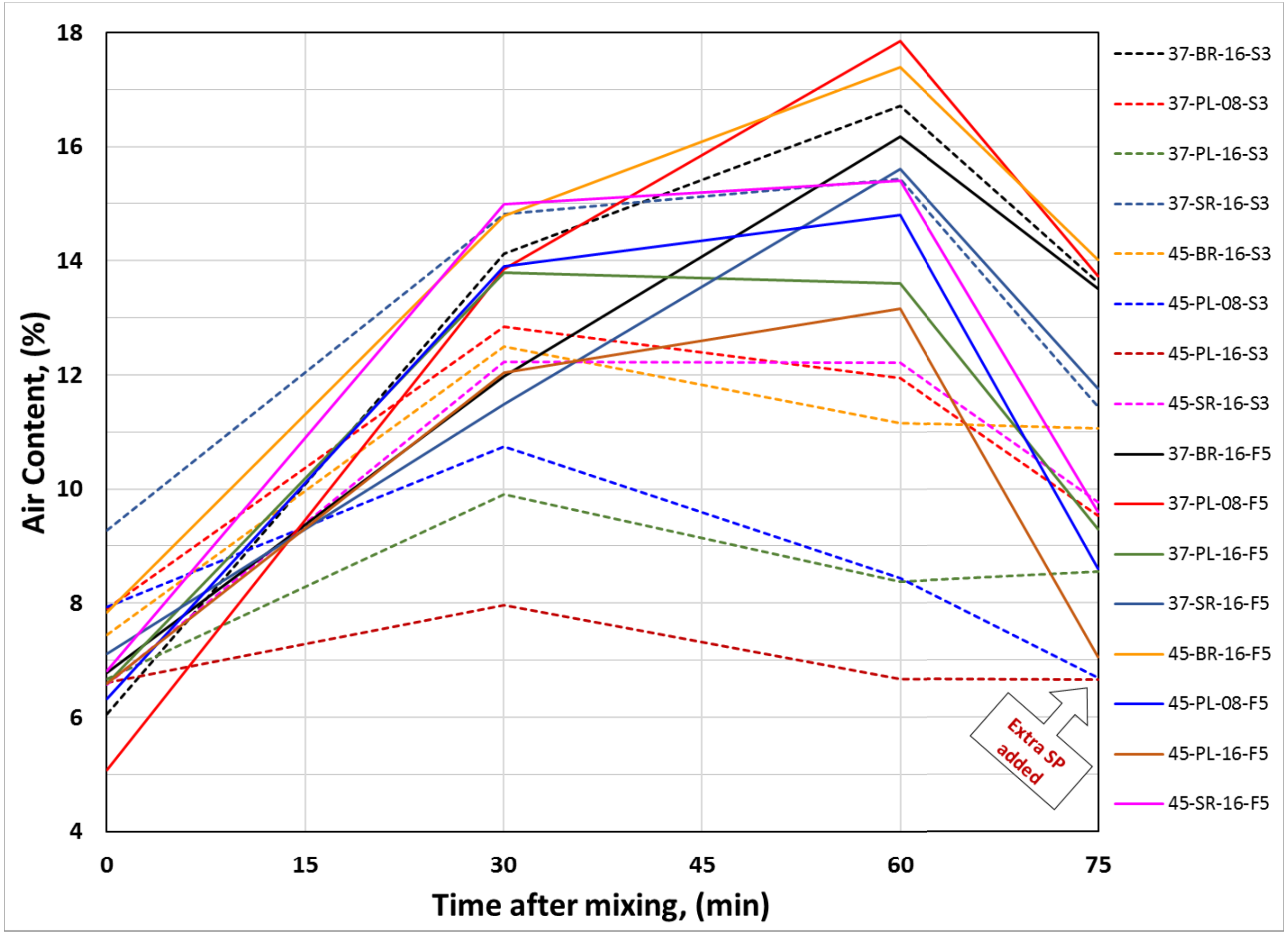


Figure 19. Summary of the calculated air contents of fresh concrete.

4.1.3.3 CiDRA AIRtrac air content monitoring results

The CiDRA AIRtrac is a device (acoustic sensor) for measuring real-time air content of fresh concrete during the mixing process. The AIRtrac device is installed directly on the bottom of concrete mixers and the CiDRA system calculates the air content in fresh concrete as the concrete is being mixed. The calculation of air content in concrete is based on the Wood's model for the speed of sound. When concrete is mixed in a fixed-wall mixer, it will have a static pressure just slightly above atmospheric, always having some level of entrained aeration. Under these conditions and assuming isothermal conditions, the compressibility of the air phase is orders of magnitude larger than the compressibility of the slurry phase, and Wood's equation reduces to Equation 1:

$$c = \sqrt{\frac{P_a}{\phi * (1 - \phi) * \rho}} \tag{5}$$

Where:

c = the speed of sound
P_a = the absolute static pressure,
ϕ = the volumetric fraction of air, and
ρ = the density of the concrete slurry.

Wood's simplified model is only dependent on the static pressure and slurry density. Both of these properties are relatively consistent for most concrete mixing applications, and the small variations that do exist can generally be ignored. Based on the simplification of Wood's model, it is assumed that the air content for concrete slurry depended on the mixture sound speed. (Tregger, et. Al., 2013).

CiDRA AIRtrac continuously measures the air content. However, numerical values are needed for comparison purposes. Two types of air content measurements are considered in the research:

1. **Dynamic air content measurement**, representing the air content in the concrete during high speed mixing. The reading is taken as the median over 5 seconds before the speed is changed.
2. **Static air content measurement**, representing the air content in the concrete without mixing. This reading is also taken as an average over 30 seconds, but before the concrete is at standstill situation or before dumped.

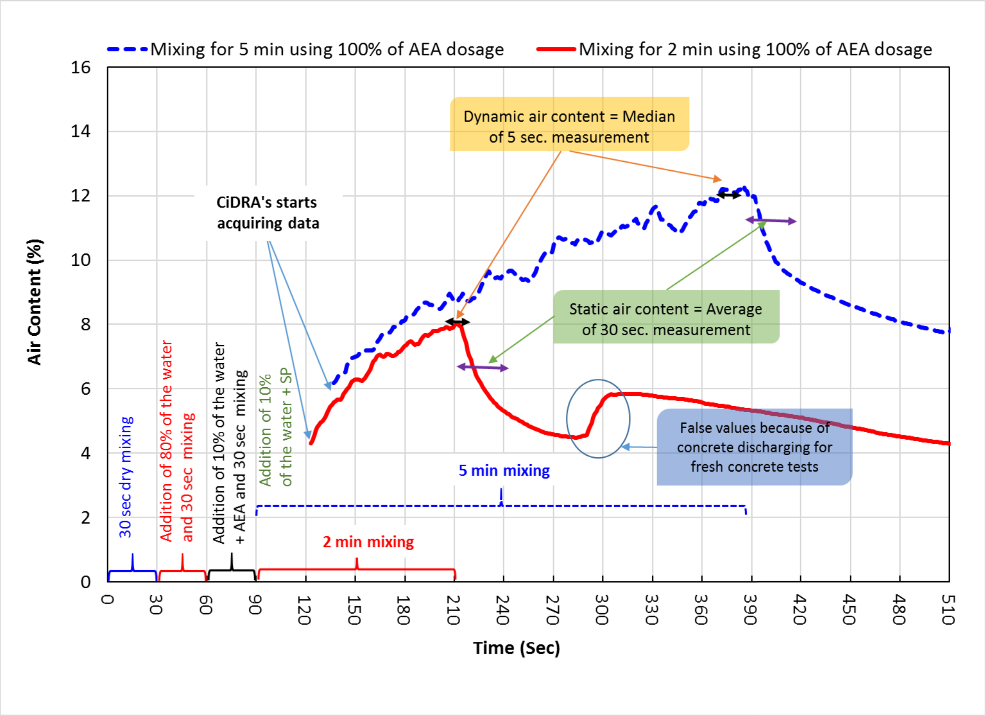
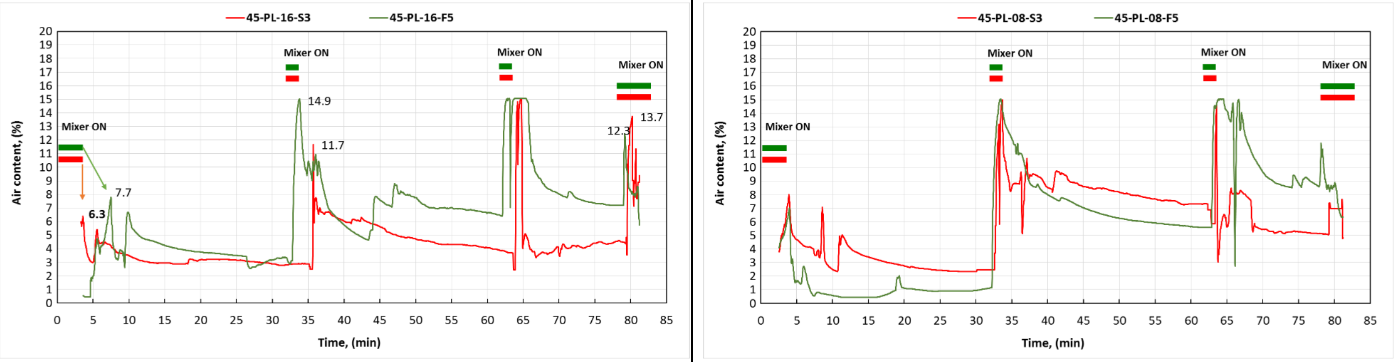


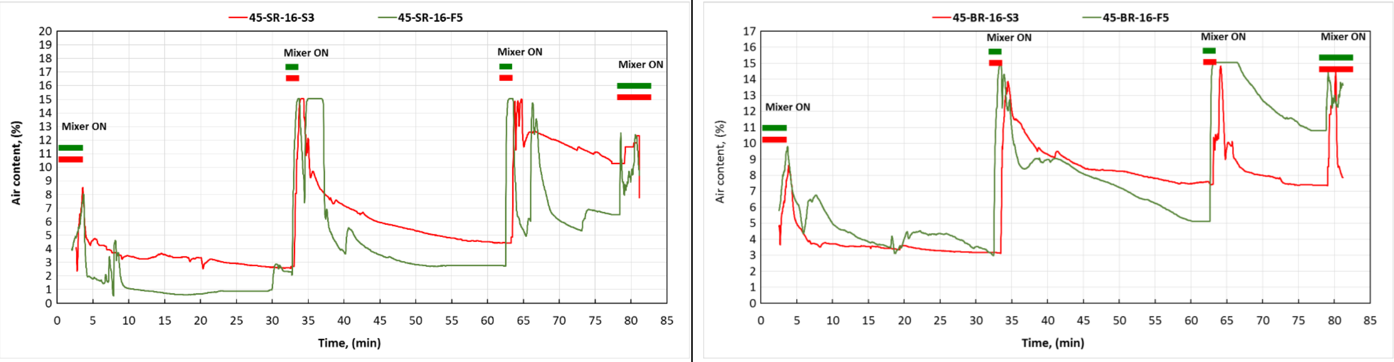
Figure 20. CiDRA AIRtrac measurement procedure and measurement of dynamic and static air content.

Examples of the CiDRA AIRtac monitoring data are presented in Figure 21 and Figure 22. The data received after stopping the mixer is erroneous. The system is not able to measure the air content of concrete when concrete is stored in the laboratory mixer (amount of concrete on the top of the sensor is too low)



C35/45 concrete with Plus Cement and 16 mm maximum aggregate size

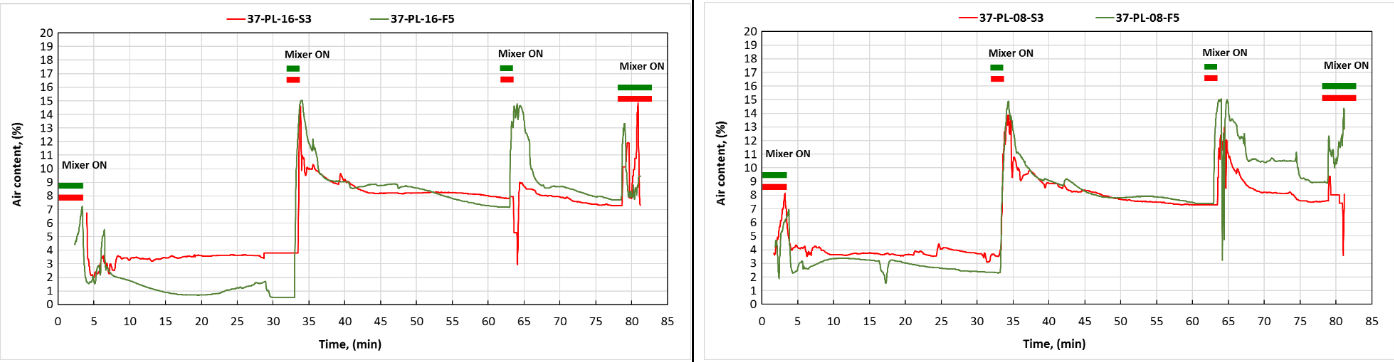
C35/45 concrete with Plus Cement and 08 mm maximum aggregate size



C35/45 concrete with SR-Cement and 16 mm maximum aggregate size

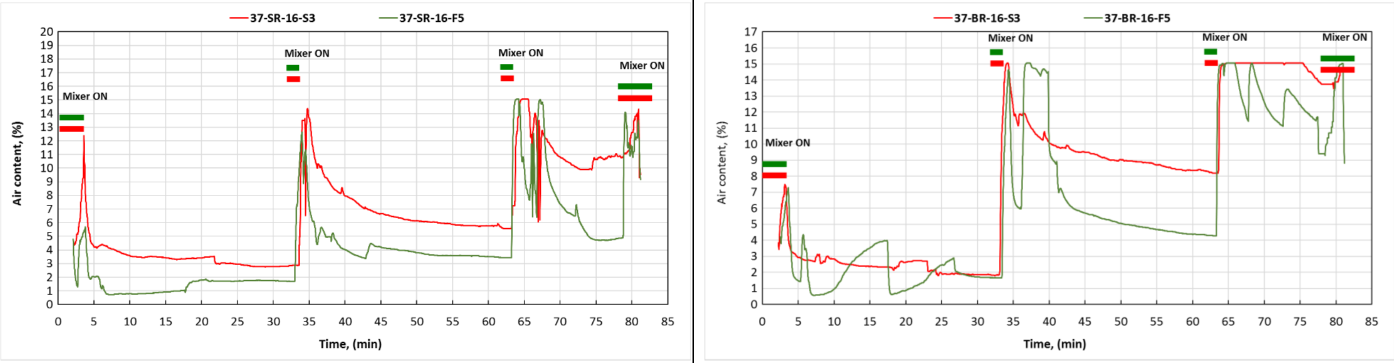
C35/45 concrete with Broceni Cement and 16 mm maximum aggregate size

Figure 21. Monitoring of air content in fresh concrete using CiDRA AIRtrac for C35/45 class concrete.



C30/37 concrete with Plus Cement and 16 mm maximum aggregate size

C30/37 concrete with Plus Cement and 08 mm maximum aggregate size



C30/37 concrete with SR-Cement and 16 mm maximum aggregate size

C30/37 concrete with Broceni Cement and 16 mm maximum aggregate size

Figure 22. Monitoring of air content in fresh concrete using CiDRA AIRtrac for C30/37 class concrete.

4.1.3.4 Comparison of different test methods

The results of CiDRA AIRtac measurements are presented in Table 19 and Table 20, where the values of dynamic and static air content measured by CiDRA AIRtac are compared to the calculated air contents and the pressure method air content.

Table 19. Air content of the C35/45 concrete measured by CiDRA AIRtrac, pressure method and calculated from the unit weight of fresh concrete.

Concrete mix	**Air Content, (%)**				**Measurement method**
	0 min	**30 min**	**60 min**	**75 min**	
45-PL-08-S3	6.8	n/a	n/a-(*)	6.9	Pressure method
	7.9	10.7	8.4	6.7	Calculated value
	7.9	14.9	14.4	7.7	Dynamic CiDRA
	6.2	11.2	4.9	6.0	Static CiDRA
45-PL-16-F5	5.8	n/a	n/a-(*)	5.9	Pressure method
	6.6	12.0	13.2	7.1	Calculated value
	7.6	15.0	15.1	8.5	Dynamic CiDRA
	5.1	12.9	14.0	6.1	Static CiDRA
45-PL-08-F5	5.5	n/a	15.5	7.5	Pressure method
	6.3	13.9	14.8	8.6	Calculated value
	6.9	15.0	15.0	8.8	Dynamic CiDRA
	4.0	14.2	13.5	8.1	Static CiDRA
45-PL-16-S3	5.4	n/a	6.2	5.6	Pressure method
	6.6	8.0	6.7	6.7	Calculated value
	6.1	10.3	15.0	15.1	Dynamic CiDRA
	5.0	7.5	5.5	9.7	Static CiDRA
45-SR-16-F5	5.6	n/a	13.0	7.8	Pressure method
	6.8	15.0	15.4	9.6	Calculated value
	7.7	15.1	15.1	12.2	Dynamic CiDRA
	4.3	12.2	10.3	10.7	Static CiDRA
45-SR-16-S3	6.5	n/a	11.5	8.5	Pressure method
	6.6	12.2	12.2	9.8	Calculated value
	8.4	15.1	15.0	12.3	Dynamic CiDRA
	6.4	12.4	12.3	6.4	Static CiDRA
45-BR-16-F5	7.2	n/a	13.5	10.6	Pressure method
	7.8	14.8	17.4	14.0	Calculated value
	9.8	15.0	15.1	14.9	Dynamic CiDRA
	8.5	13.8	14.9	14.3	Static CiDRA
45-BR-16-S3	6.6	n/a	8.4	8.3	Pressure method
	7.4	12.5	11.2	11.1	Calculated value
	8.5	13.7	14.8	14.3	Dynamic CiDRA
	7.9	13.1	12.6	9.6	Static CiDRA

*) In the beginning of testing program, the air content measuring using pressure methods, was performed only immediately after mixing and at 75 min.

Table 20. Air content of the C30/37 concrete measured by CiDRA AIRtrac, pressure method and calculated from the unit weight of fresh concrete.

Concrete mix	**Air Content, (%)**				**Measurement method**
	0 min	**30 min**	**60 min**	**75 min**	
37-PL-16-F5	5.6	n/a	13.4	8.5	Pressure method
	6.6	13.8	13.6	9.3	Calculated value
	7.2	15.0	14.6	9.9	Dynamic CiDRA
	3.7	13.9	14.3	10.2	Static CiDRA
37-PL-16-S3	5.7	n/a	8.0	7.2	Pressure method
	6.7	9.9	8.4	8.5	Calculated value
	6.7	14.4	8.9	14.8	Dynamic CiDRA
	3.6	11.3	8.9	8.2	Static CiDRA
37-PL-08-S3	7.2	n/a	10.0	8.4	Pressure method
	7.9	12.8	12.0	9.5	Calculated value
	7.9	13.5	11.2	8.4	Dynamic CiDRA
	6.4	10.6	11.0	7.9	Static CiDRA
37-PL-08-F5	4.8	n/a	14.4	10.6	Pressure method
	5.1	13.9	17.9	13.7	Calculated value
	6.8	14.9	15.0	14.0	Dynamic CiDRA
	3.6	13.9	14.0	10.9	Static CiDRA
37-SR-16-S3	7.4	n/a	11.5	9.0	Pressure method
	9.3	14.8	15.4	11.4	Calculated value
	11.4	14.4	15.1	14.0	Dynamic CiDRA
	8.2	13.5	13.4	9.9	Static CiDRA
37-SR-16-F5	3.7	n/a	14.8	10.0	Pressure method
	7.1	11.5	15.6	11.7	Calculated value
	5.6	12.5	15.1	13.3	Dynamic CiDRA
	3.5	10.7	12.7	10.0	Static CiDRA
37-BR-16-S3	5.6	n/a	15.1	12.0	Pressure method
	6.1	14.1	16.7	13.6	Calculated value
	7.4	15.1	15	15.0	Dynamic CiDRA
	5.6	13.9	15.1	13.5	Static CiDRA
37-BR-16-F5	6.5	n/a	15	12.9	Pressure method
	6.8	12.0	16.2	13.5	Calculated value
	7.2	14.5	15	15.0	Dynamic CiDRA
	4.8	11.6	14.8	8.6	Static CiDRA

Comparison of different tests methods has been presented in Figure 23. The X-Axis represents the results of the pressure method and the Y-axis the other methods used in the tests. The pressure test is the most commonly used method for air content measurements, but it is needed to bear in mind that the pressure method is not giving the “absolute truth” and we simply don’t know the exact air content of concrete. Therefore, the results are not showing the correctness of the test methods, but the correlation between the test methods.

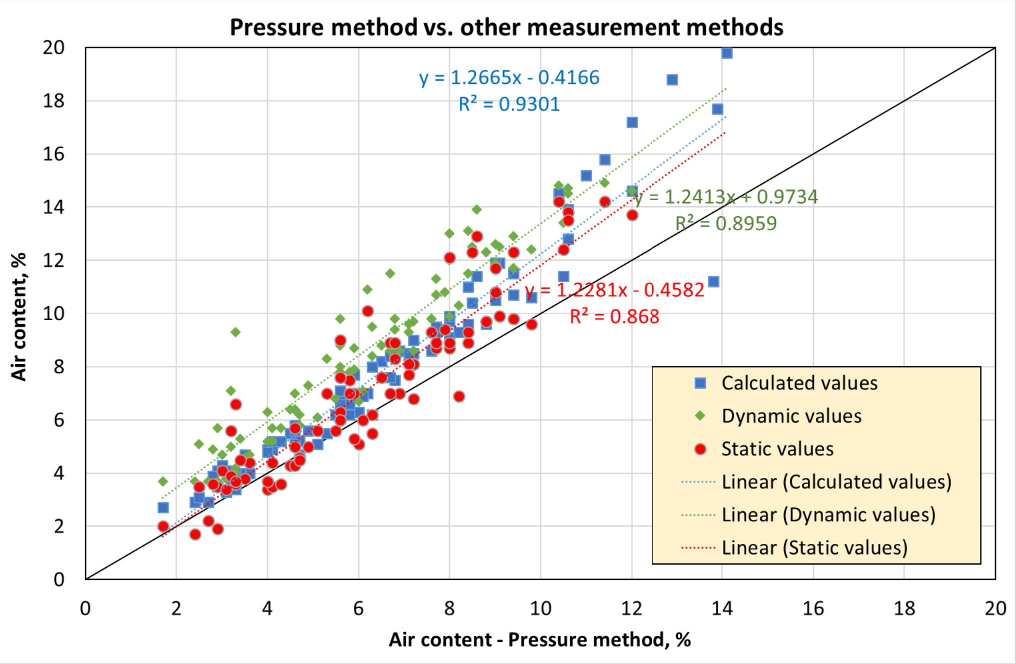


Figure 23. Comparison of different test methods used for air content measurements.

4.1.3.5 Analysis of the air content test results

The air content of fresh concrete increased after the initial mixing except in one case. The air content increased from the initial app. 7% to the level of 13 - 15%. The highest air contents were close to 20% (calculated air content). However, the results contain rather much variation and therefore it is very difficult to separate the effects of the different concrete properties. It appears that the consistency class plays an important role, S3 class concrete showed smaller increase compared to F5 class concrete. The cement type, maximum particle size of aggregate and the compressive strength class played smaller role.

The test results indicated that the air content increases surprisingly easily and also surprisingly much after initial mixing. It was more rule than exception that the air content increased. However, it is worth to note some basic facts which may make effect stronger. A relatively high superplasticizer dosage (1.2% from weight of cement) was used. With lower dosages, the increase will be probably smaller. Also the laboratory mixer is not very effective and therefore the mixing time (2 min) may not reflect the typical mixing efficiency used in the industrial production. On the other hand, the concrete tested in the laboratory were not any extreme ones. The cement contents were relatively high, water-cement ratios were low due to the high-quality laboratory aggregates and the consistencies were inside the specified limit. Also, the consistency was determined immediately after mixing, whereas in practical applications the consistency of concrete is generally determined on construction site, it means some 15…60 min after the initial mixing. Therefore, the consistency immediately after mixing was lower compared to that found typically in the industry. As mentioned the laboratory mixer is not very effective.

However, there are also less effective mixers also in the industrial production and also the mixing times can be shorter than 2 min (typically 90 s, but sometimes only 60 s).

4.1.4 Segregation sensitivity of concrete

In addition to the elevated air contents there are also indications that air may segregate close to casting surface of concrete and thus causing high-porous, low compressive strength zone close to the concrete surface. The highest air contents (> 20%) determined for the hardened concrete are probably caused by this effect. If air is segregating upwards, the same time aggregate may segregate downwards. The segregation of aggregate affects less the compressive strength because the strength is mainly controlled by the strength of cement paste. However, the segregation of aggregate has detrimental effects on the deformation properties of concrete as elastic modulus, shrinkage and creep.

As the segregation of air and the segregation of aggregate may take place simultaneously, the density cannot necessarily used for determination of air content. Both types of segregation affect significantly the density of concrete.

4.1.4.1 Density differences in the cylindrical test specimens

The sensitivity of concrete for segregation was analyzed by comparing the densities of the bottom and top part of the cylindrical test specimens. The compaction is concrete was tried to standardize as much as possible.

Figure 24. Example of the specimens used for sensitivity of concrete for segregation test.

The test specimens were prepared immediately after mixing, 60 min after mixing and 75 min after mixing. The test procedure includes:

- Weighing of the test cylinders in air and under water (Average density)
- Grinding the top and bottom surface of the specimens
- Sawing the top and bottom parts
- Weighing the top and bottom parts in air and under water

The density of different parts was calculating using the following formula:

$$Density, (kg/m^3) = \frac{Weight\ in\ air, (kg)}{Weight\ in\ air - weight\ under\ water} \tag{6}$$

The density differences between different parts of the hardened concrete cylinder are shown in Table 21 to Table 23 and Figure 25 to Figure 27.

Table 21. Result of the sensitivity of concrete for segregation test. a) Specimens cast immediately after mixing.

Concrete mix	**Density of hardened concrete, (kg/m³)**			
	0 min after casting			
	Top	**Average**	**Bottom**	**Difference between bottom and top**
37-BR-16-F5	2119	2129	2151	32
37-BR-16-S3	2328	2320	2330	2
37-PL-08-F5	2290	2290	2294	3
37-PL-08-S3	2245	2251	2250	5
37-PL-16-F5	2291	2297	2308	17
37-PL-16-S3	2333	2328	2350	16
37-SR-16-F5	2361	2385	2435	74
37-SR-16-S3	2271	2277	2297	26
45-BR-16-F5	2277	2278	2308	31
45-BR-16-S3	2317	2314	2330	13
45-PL-08-F5	2280	2281	2300	20
45-PL-08-S3	2240	2265	2315	75
45-PL-16-F5	2255	2293	2362	107
45-PL-16-S3	2248	2328	2348	100
45-SR-16-F5	2296	2324	2368	73
45-SR-16-S3	2313	2312	2322	9

Table 22. Result of the sensitivity of concrete for segregation test. b) Specimens cast 60 min after mixing.

Concrete mix	**Density of hardened concrete, (kg/m³)**			
	60 min after mixing			
	Top	**Average**	**Bottom**	**Difference between bottom and top**
37-BR-16-F5	2067	2083	2102	35
37-BR-16-S3	2078	2076	2082	4
37-PL-08-F5	2064	2068	2066	2
37-PL-08-S3	2147	2157	2174	27
37-PL-16-F5	2131	2127	2141	10
37-PL-16-S3	2278	2276	2298	20
37-SR-16-F5	2172	2126	2183	11
37-SR-16-S3	2128	2126	2153	25
45-BR-16-F5	2036	2042	2053	17
45-BR-16-S3	2235	2236	2251	15
45-PL-08-F5	2074	2070	2078	4
45-PL-08-S3	2192	2198	2234	42
45-PL-16-F5	2081	2105	2163	82
45-PL-16-S3	2334	2348	2351	17
45-SR-16-F5	2078	2069	2115	37
45-SR-16-S3	2227	2220	2231	4

Table 23. Result of the sensitivity of concrete for segregation test. b) Specimens cast 75 min after mixing.

Concrete mix	Density of hardened concrete, (kg/m³)			
	75 min after mixing			
	Top	Average	Bottom	Difference between bottom and top
37-BR-16-F5	2096	2127	2199	104
37-BR-16-S3	2138	2142	2161	23
37-PL-08-F5	2120	2127	2138	17
37-PL-08-S3	2197	2204	2213	17
37-PL-16-F5	2235	2239	2237	1
37-PL-16-S3	2272	2275	2289	17
37-SR-16-F5	2122	2181	2288	166
37-SR-16-S3	2202	2205	2251	49
45-BR-16-F5	2131	2148	2154	24
45-BR-16-S3	2238	2236	2250	12
45-PL-08-F5	2224	2226	2236	12
45-PL-08-S3	2264	2265	2288	24
45-PL-16-F5	2221	2265	2334	113
45-PL-16-S3	2355	2341	2337	-18
45-SR-16-F5	2243	2264	2295	52
45-SR-16-S3	2257	2262	2272	15

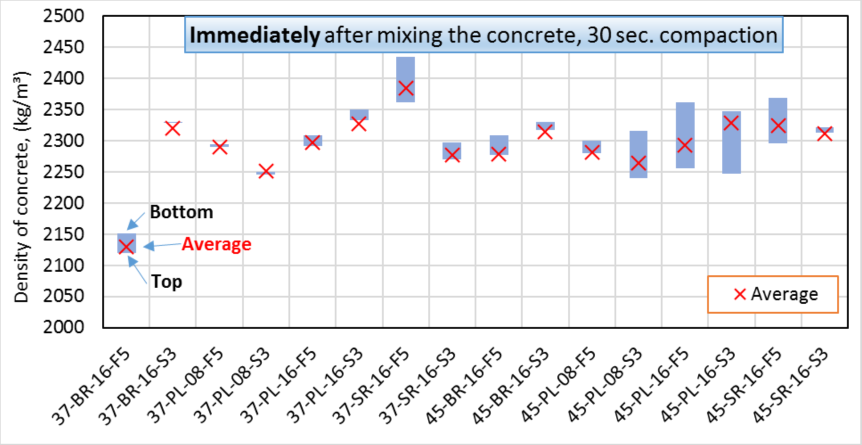


Figure 25. Density differences immediately after mixing.

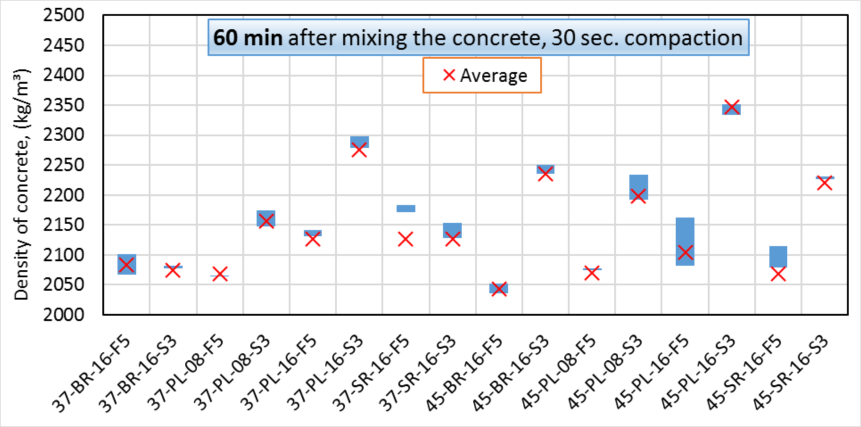


Figure 26. Density differences 60 minutes after mixing.

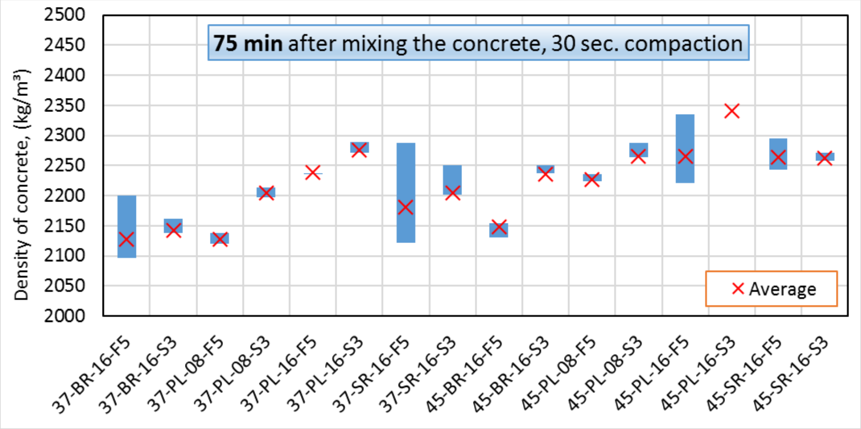


Figure 27. Density differences 75 minutes after mixing.

4.1.4.2 Air content of hardened concrete

In order to analyze the segregation inside the concretes in more detail thin section analyses were carried out. Thin section analysis gives the air quality parameters (spacing factor and specific surface are of the pores), but it gives the estimation for the air content of hardened concrete as well as for the paste volume. However, it is needed to remember that the air content or paste volume measured from thin section are not very accurate due to the small area of the thin section.

In addition, the air content of hardened concrete was determined also with help of the pressure saturation - according to the old Finnish standard SFS-4475. The specimens were weighted in air and under water, then dried at a temperature of 105 °C till the weight loss was smaller than 0.05%/24h. After drying, the specimens were saturated with water at normal pressure until the weight change was smaller than 0.05%/24h. Then the specimens were moved to the pressure vessel, where water was intruded into them at pressure of 15 MPa (150 bar). The air content of the hardened concrete was calculated according to following equation:

$$Air\ content, A = \frac{W_p - W_s}{W_{air} - W_w} * 100 \tag{7}$$

where:

A = the air content of hardened concrete, (%)
W_p = the weight of specimen after the pressure saturation, (kg)
W_s = the saturated weight of concrete, (kg)
W_{air} = weight of the sample in air before drying, (kg)
W_w = weight of the sample under water before drying, (kg)

The thin section analysis and pressure saturation tests were carried out for samples made immediately after mixing. The results are presented in Figure 28 and Figure 29, more details are presented in Appendix B.

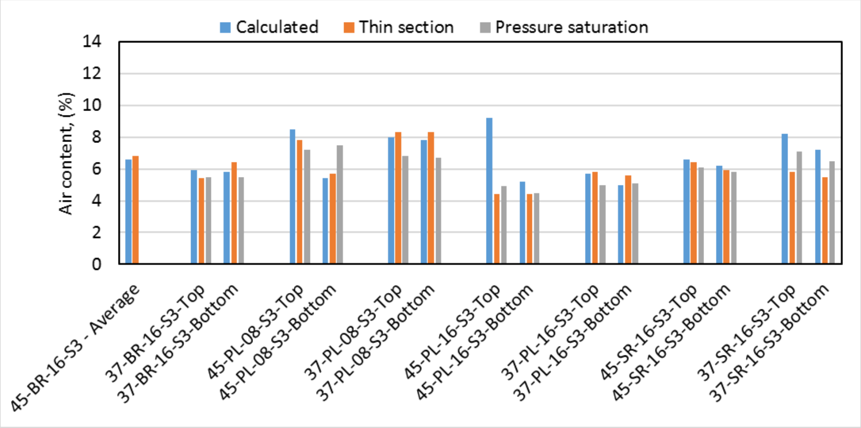


Figure 28. Air contents result from different segregations tests for the S3 consistency class concretes.

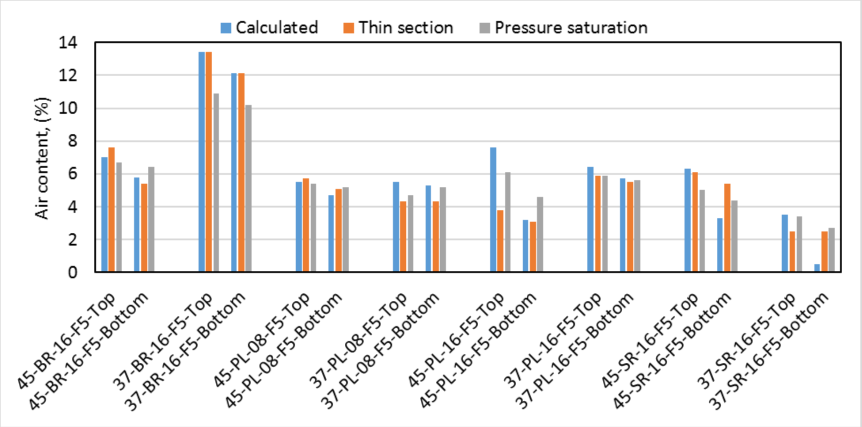


Figure 29. Air contents result from different segregations tests for the F5 consistency class concretes.

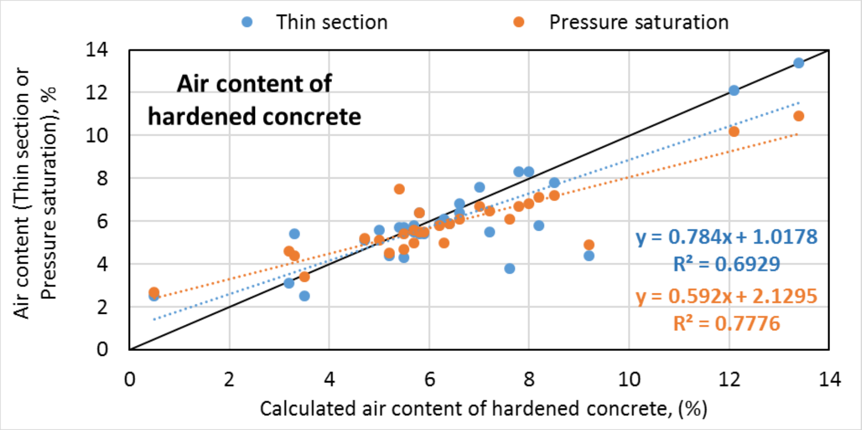


Figure 30. Comparison of air content of hardened concrete using different tests methods.

In Figure 30, the different methods used measuring air content of hardened concrete have been compared. The calculated air content (X-axis) is based on the assumption that the only source for the density difference is the air content. The figure shows rather good correlation between the test method, except in some cases the calculated air content is too high. This is most probably due to the aggregate segregation effect. If there is no segregation of aggregate, the different test methods correlated rather well with each other. But if there are segregation, the calculated air content over-estimates the air content. It should be noted that the segregation affects only the results inside the test specimen, the air content results of the whole specimen (chapter 4.1.3) are not affected by the segregation.

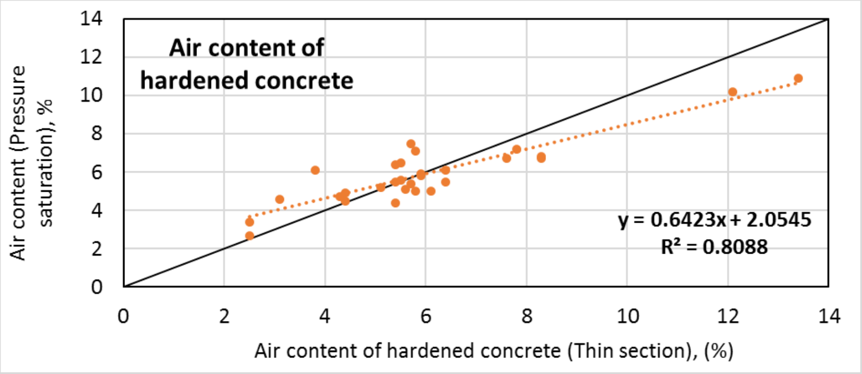


Figure 31. Correlation between air contents determined using thin section analysis and pressure saturation test.

Figure 31 shows the correlation between the air contents measured using thin section analyses and the pressure saturation. The methods are giving relatively similar results. With lower air contents, thin section appears to give slightly lower air content values and with high air contents, slightly higher values.

In case, 60 min and 75 min after mixing only the calculated air contents were determined and the results are given in Table 24. There were no thin section or pressure saturation tests were carried out for specimens cast at 60 min and 75 min after mixing.

Table 24. Calculated air contents of the segregations tests. The test specimens were cast immediately, 60 min and 75 min after mixing. (top = top part, avg. = average air content, bot. = bottom part).

Concrete mix	**Calculated air content of hardened concrete, (%)$^{(1)}$**								
	Immediately after mixing			**60 min after casting**			**75 min after casting**		
	top	**avg.**	**bot.**	**top**	**avg.**	**bot.**	**top**	**avg.**	**bot.**
37-BR-16-F5	13.4	13.0	12.1	15.5	14.8	14.1	14.3	13.1	14.1
37-BR-16-S3	5.9	6.2	5.8	16.0	16.1	15.8	13.6	13.4	15.8
37-PL-08-F5	5.4	5.5	5.3	14.8	14.6	14.7	12.5	12.2	14.7
37-PL-08-S3	8.0	7.8	7.8	12.0	11.6	10.9	10.0	9.7	10.9
37-PL-16-F5	6.4	6.1	5.7	12.9	13.1	12.5	8.7	8.5	12.5
37-PL-16-S3	5.7	5.9	5.0	7.9	8.0	7.1	8.2	8.0	7.1
37-SR-16-F5	3.5	2.5	0.5	11.0	13.4	10.8	13.3	10.9	10.8
37-SR-16-S3	8.2	8.0	7.2	14.0	14.0	13.0	11.0	10.9	13.0
45-BR-16-F5	7.0	7.0	5.8	16.9	16.6	16.2	13.0	12.3	16.2
45-BR-16-S3	6.5	6.6	6.0	9.8	9.8	9.2	9.7	9.8	9.2
45-PL-08-F5	5.5	5.5	4.7	14.1	14.2	13.9	7.8	7.7	13.9
45-PL-08-S3	8.5	7.5	5.4	10.5	10.2	8.8	7.5	7.5	8.8
45-PL-16-F5	7.6	6.0	3.2	14.7	13.7	11.4	9.0	7.2	11.4
45-PL-16-S3	9.2	6.0	5.2	5.7	5.2	5.0	4.9	5.5	5.0
45-SR-16-F5	6.3	5.1	3.3	15.1	15.5	13.6	8.4	7.6	13.6
45-SR-16-S3	6.6	6.6	6.2	10.0	10.3	9.9	8.8	8.6	9.9

1) = The air content is calculated using the density of test specimens and assuming that the only source for the density difference is the changing air content.

4.1.4.3 Experimental Findings of the segregation sensitivity tests

The effects of different concrete ingredient on the segregation sensitivity of concrete are presented in Table 25 and Figure 32. The effects can be summarized as follow:

i. The effect of concrete strength class was not so high because of the amount of cement used for concrete was 400 kg/m³ for C30/37 concretes and 425 kg/m³ for C35/45 concretes
ii. The concretes mixes with SR-cement (fineness of 380 – 410 m²/kg) had tendency to segregate more than concretes with Plus cement (fineness of 420 – 470 m²/kg) and Broceni Cement.
iii. The concretes with larger maximum aggregate size (16 mm) tended to segregate more than the concretes with smaller aggregate size (8 mm). The average density differences were 37.0 and 20.7 kg/m³ for the 16 mm and 8 mm maximum aggregate size respectively.
iv. The concretes with higher consistency class were more sensitive to segregation. The average density differences were 43.2 and 22.5 kg/m³ for the consistency class F5 and S3 respectively.

Table 25. Effect of concrete mix components on the segregation sensitivity of concrete.

Concrete components		**Average density difference between bottom and top (kg/m³)**	**Maximum density difference between bottom and top (kg/m³)**
Compressive strength class	C30/37	30	166
	C35/45	37	113
Cement type	Broceni cement	26	104
	Plus cement	30	113
	SR-cement	45	166
Max. aggregate size	8 mm	21	75
	16 mm	37	166
Consistency class	F5	43	166
	S3	23	100

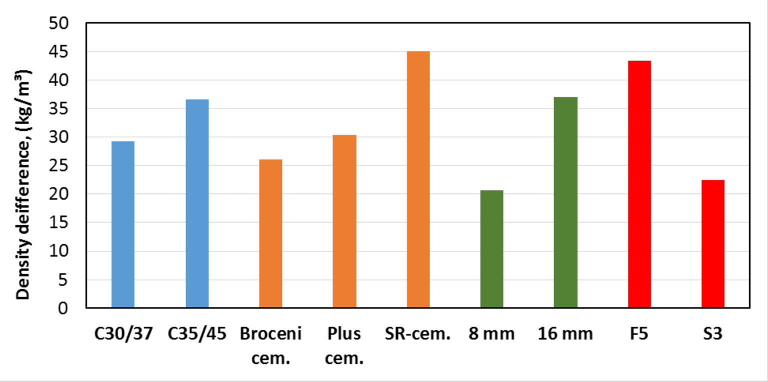


Figure 32. Average values of the density differences between the top and bottom parts of the cylinder specimens.

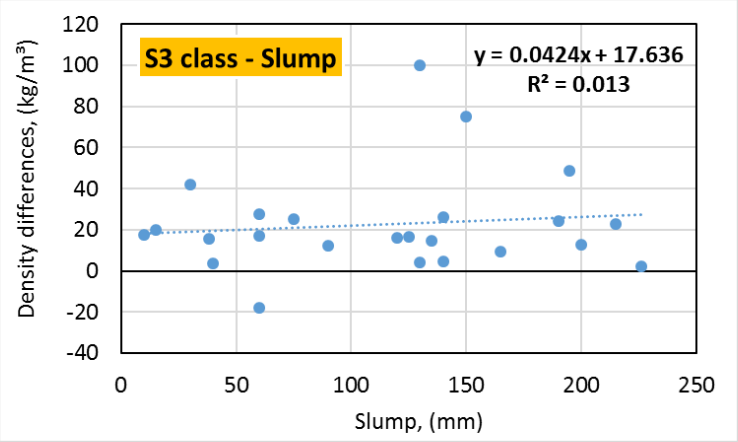


Figure 33. The effects of concrete slump on the segregation sensitivity of concrete.

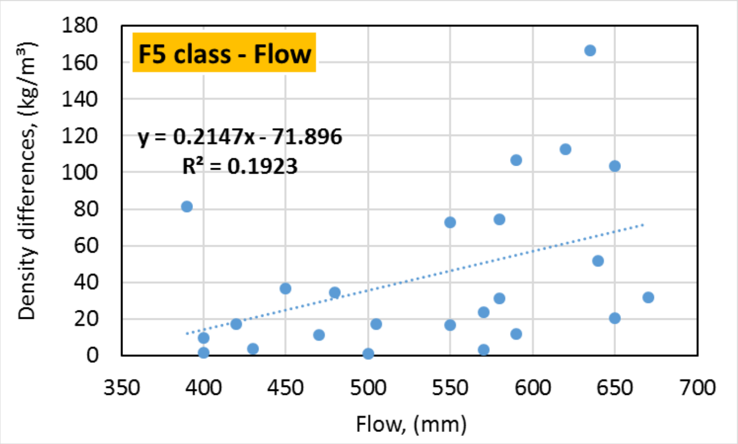


Figure 34. The effect of concrete flow on the segregation sensitivity of concrete.

In case of S3 concrete, the slump value did not correlate with the density difference. In case of F5 concrete, a slight correlation was observed. The highest flow values increased the risk for the density difference.

Generally, rather large density differences of concrete were observed. The density differences are probably caused by the same phenomena as the increasing air content of concrete. If the protective pore structures is not stable enough, air content may increase after mixing and the compaction effect may cause changes in the air content of hardened concrete.

According to the test results, the density difference is due to both the segregation of air and segregation of aggregate. Air is moving upwards and coarse aggregate is moving downwards.

The tests are not accurate and extensive enough to estimate the shares of air and aggregate segregation.

4.1.5 Compressive strength of concrete

Compressive strength and densities of concrete were measured at 28 days of age, according to the “EN 12390-3:2009 - Testing hardened concrete. Compressive strength of test specimens” using 100*100*100 mm³ cubes. The test specimens were cast immediately after concrete mixing and 75 minutes after casting. The specimens were kept in their molds and covered for one day with a plastic sheet after casting and then stored in the same condition (RH of 95% and temperature of 20±2 °C) until the testing age.

4.1.5.1 Compressive strength test results

The results of the compressive strengths and densities are shown in Figure 35.

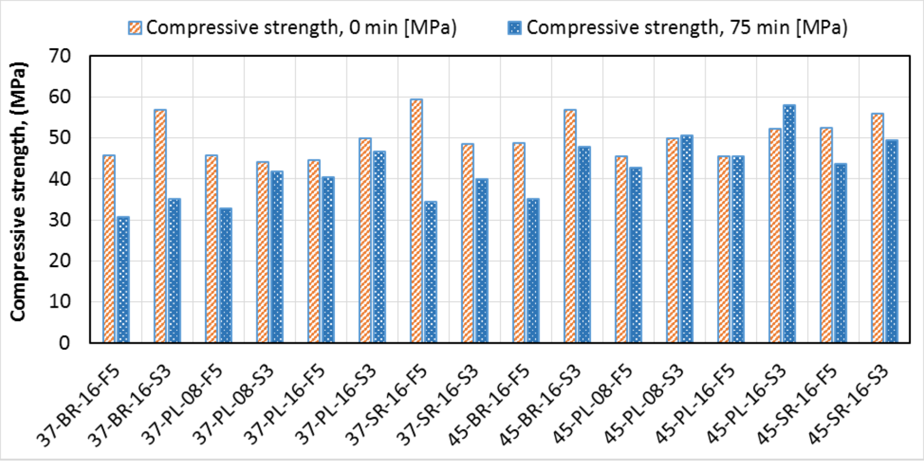


Figure 35. 28 days compressive strength test results.

4.1.5.2 Experimental Findings of compressive test results

As it was expected, the increment of the air content of concrete decreases the compressive strength of concrete. As shown in Figure 35, the average compressive strength values for concrete specimens cast immediately after mixing are higher than the specimens cast after 75 minutes because of the increment of air content at 75 min (with addition of superplasticizer dosage) compared to the initial values. As shown in Figure 37, the average reduction in compressive strength is about 5% occurs due to each 1% by volume of entrained air in the concrete mixes (1%-unit air corresponds on the average 2.27 MPa in compressive strength).

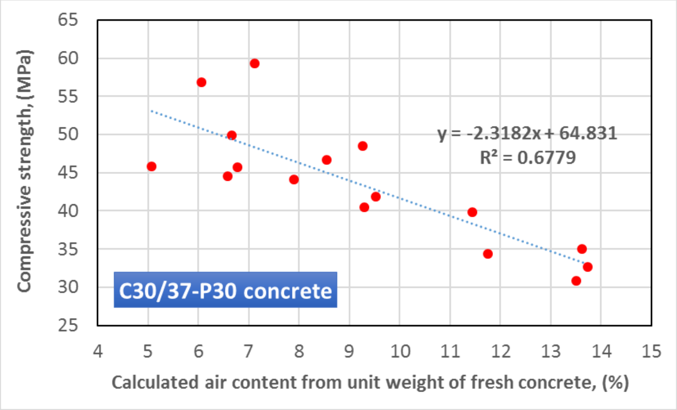


Figure 36. Compressive strength of concrete vs. calculated air values of fresh concrete for C30/37-P30 concretes.

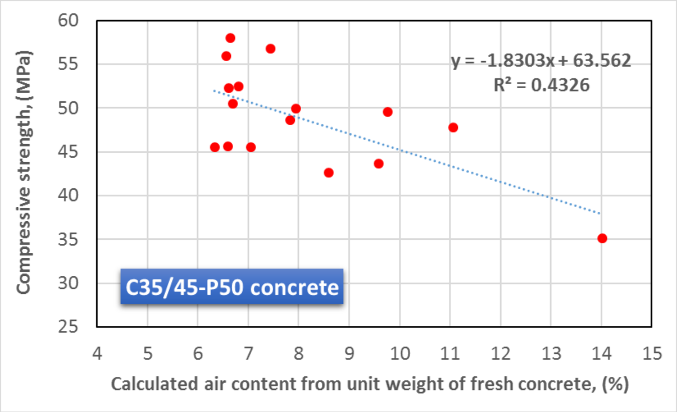


Figure 37. Compressive strength of concrete vs. calculated air values of fresh concrete for C30/37-P30 concretes.

4.2 Effects of different admixture combinations (Admixture tests)

The aim of the admixture tests was to analyze the effects of the different admixtures for the stability of the protective pore system. Two different cement types and two different consistency classes were used, see Table 26. The three test concretes were:

- Plus-cement – F5
- CEM I, Broceni – F5
- Plus-cement – S3

The concrete compositions inside each concrete were kept constant except the dosages of superplasticizer and air-entraining agent were adjusted in order to achieve the desired consistency and the air content.

Totally seven different admixture combinations were tested. One of the admixture combinations (BASF) was tested already in 4.1 “Concrete Tests”. The tests procedures were basically similar to the “Concrete Test” procedure except that more tests with CiDRA AIRtrac were made. The tests included also a longer mixing time (5 min) and in addition the normal AEA dosage as well as 50% dosage was used.

Table 26. Coding of concrete mixes for different admixture combinations.

Coding variables	Concrete mix coding
Admixtures code and manufacturer	BAS = BASF Oy FIN = Finnsementti Oy HAB = Ha-Be Betonchemie GmbH & Co. MAP = MAPEI SEM = Semtu Oy SIK = Oy Sika Finland Ab GCP = GCP Applied Technologies
Compressive strength and P-factor	45 = C35/45 - P50
Cement types	PL = Plus cement, Finnsementti Oy BR = Rapid - Broceni, Cemex
Max. aggregate size	16 = # 16 mm
Consistency class	S3 = Slump class S3 F5 = Flow class F5

4.2.1 Concrete Mix Design

For testing the effect of different chemical admixtures on the stability of air content of concrete, the following concrete mixes presented in Table 27 were investigated. The dosages of superplasticizer and air-entraining agent are presented in Table 28.

Table 27. Mix design of concretes with different admixtures.

Mix design	Cement (kg)	Effective Water (kg)	Aggregates (kg)	Air Entraining Agent, (kg)	Super-plasticizer, (kg)	Target Air content, (%)
BAS-45-PL-16-S3	425	140	1770	0.149	5.100	5.5
BAS-45-PL-16-F5	425	160	1716	0.149	5.100	5.5
BAS-45-BR-16-F5	425	155	1729	0.231	5.100	5.5
FIN-45-PL-16-S3	425	140	1766	0.234	5.100	5.5
FIN-45-PL-16-F5	425	160	1716	0.149	6.290	5.5
FIN-45-BR-16-F5	425	155	1729	0.140	5.313	5.5
GCP-45-PL-16-S3	425	140	1772	0.383	3.400	5.5
GCP-45-PL-16-F5	425	160	1720	0.213	5.185	5.5
GCP-45-BR-16-F5	425	155	1733	0.850	2.975	5.5
SIK-45-PL-16-S3	425	140	1770	0.340	4.845	5.5
SIK-45-PL-16-F5	425	160	1716	0.850	3.613	5.5
SIK-45-BR-16-F5	425	155	1730	0.230	5.100	5.5
HAB-45-PL-16-S3	425	140	1768	0.417	4.335	5.5
HAB-45-PL-16-F5	425	160	1718	0.196	4.760	5.5
HAB-45-BR-16-F5	425	155	1731	0.230	4.420	5.5
MAP-45-PL-16-S3	425	140	1770	0.808	3.825	5.5
MAP-45-PL-16-F5	425	160	1717	0.323	5.440	5.5
MAP-45-BR-16-F5	425	155	1731	0.786	4.250	5.5
SEM-45-PL-16-S3	425	140	1767	0.264	5.653	5.5
SEM-45-PL-16-F5	425	160	1715	0.808	4.123	5.5
SEM-45-BR-16-F5	425	155	1728	0.145	5.738	5.5

Table 28. Admixture dosages used in the admixture tests.

Concrete mix	W/C - Ratio	Air Entraining Agent type	AEA/Cement (%)	Super-plasticizer Type	SP/Cement (%)
BAS-45-PL-16-S3	0.33	MasterAir 100	0.04	MasterGlenium SKY 600	1.20
BAS-45-PL-16-F5	0.38		0.04		1.20
BAS-45-BR-16-F5	0.36		0.05		1.20
FIN-45-PL-16-S3	0.33	Ilma-Parmix	0.06	VB-Parmix	1.20
FIN-45-PL-16-F5	0.38		0.04		1.48
FIN-45-BR-16-F5	0.36		0.03		1.25
GCP-45-PL-16-S3	0.33	Darex AEA T (LP)	0.09	ADVA Flow 444-L	0.80
GCP-45-PL-16-F5	0.38		0.05		1.22
GCP-45-BR-16-F5	0.36		0.20		0.70
SIK-45-PL-16-S3	0.33	Sika Air-Pro V5	0.08	Sikament -RSX (25%)	1.14
SIK-45-PL-16-F5	0.38		0.20		0.85
SIK-45-BR-16-F5	0.36		0.05		1.20
HAB-45-PL-16-S3	0.33	Pantapor 2020 (LP)	0.10	Pantahit TB100 (FM)	1.02
HAB-45-PL-16-F5	0.38		0.05		1.12
HAB-45-BR-16-F5	0.36		0.05		1.04
MAP-45-PL-16-S3	0.33	Mapeair 50	0.19	Dynamon SX-23	0.90
MAP-45-PL-16-F5	0.38		0.08		1.28
MAP-45-BR-16-F5	0.36		0.18		1.00
SEM-45-PL-16-S3	0.33	Master Air 102	0.06	Sem Flow MC	1.33
SEM-45-PL-16-F5	0.38		0.19		0.97
SEM-45-BR-16-F5	0.36		0.03		1.35

4.2.2 Workability properties of fresh concrete

The measurements of fresh concrete properties took place immediately after the concrete had been mixed, after 30 minutes and after 60 minutes. After 75 minutes of mixing, an extra dosage of superplasticizer (15 – 25% from the batch amount of superplasticizer) was added, the concrete was mixed for two minutes and then the slump or flow test was performed.

4.2.2.1 Consistency test results

The results for slump loss of concretes are shown in Figure 38 to Figure 40. The data are recorded and being shown to observe the effect of different type of superplasticizers and slump loss.

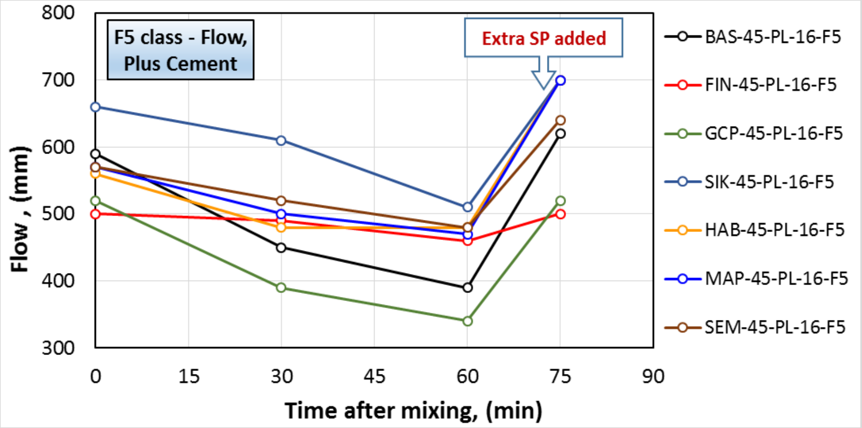


Figure 38. Workability test results for F5 consistency class concrete mixes, where Plus Cement was used.

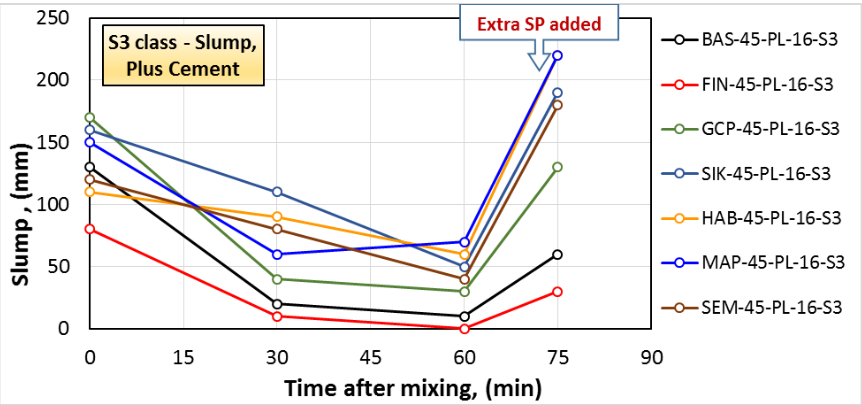


Figure 39. Workability test results for F5 consistency class concrete mixes, where Broceni-Cemex Cement was used.

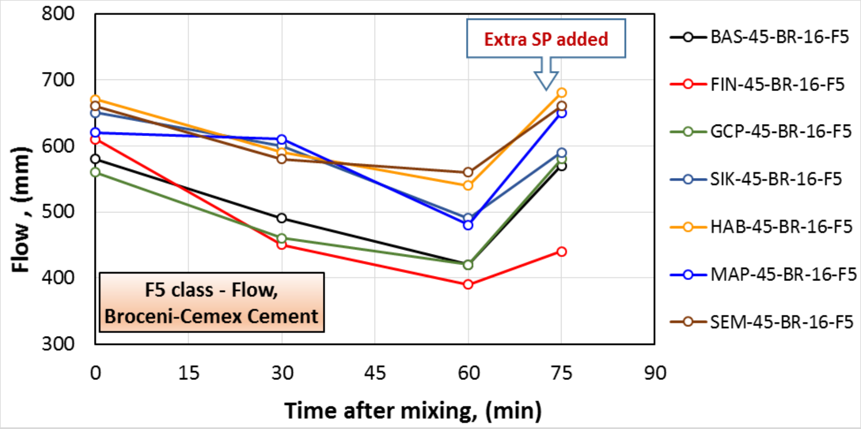


Figure 40. Workability test results for S3 consistency class concrete mixes, where Plus Cement was used.

4.2.2.2 Experimental Findings of consistency test results

As it is shown in Figure 38 to Figure 40 and Table 29, the addition of superplasticizer had an effect on the loss of workability. The phenomenon of workability loss is normally assumed to be associated with the adsorption of superplasticizer admixture by the hydrated phases.

It is noticed that the average workability loss for F5 consistency class concrete using Plus Cement was 2.5 mm/min during the first 30 min and 1.9 mm/min during 60 minutes. For the concrete mixes with CEM-I Broceni-CEMEX Cement and F5 consistency class, the average workability loss was 2.8 mm/min during the first 30 min and 2.5 mm/min during 60 minutes.

The effectives of different types of admixtures on the workability loss based on the consistency class of the concrete mix is presented in Figure 42.

Table 29. Workability test results, workability loss for different admixture.

Concrete mix		**Flow/Slump Time after mixing (min)**			**Workability loss (mm/min)**		**Workability after adding extra SP dosage at 75 min after mixing.**	
		0	30	60	at 30 min	at 60 min	SP dosage / cement (%)	75 min flow / slump (mm)
Plus cement and F5 consistency class	BAS-45-PL-16-F5	590	450	390	4.7	3.3	0.018	620
	FIN-45-PL-16-F5	500	490	460	0.3	0.7	0.019	500
	GCP-45-PL-16-F5	520	390	340	4.3	3.0	0.011	520
	SIK-45-PL-16-F5	660	610	510	1.7	2.5	0.018	700
	HAB-45-PL-16-F5	560	480	480	2.7	1.3	0.016	700
	MAP-45-PL-16-F5	570	500	470	2.3	1.7	0.015	700
	SEM-45-PL-16-F5	570	520	480	1.7	1.5	0.020	640
Broceni-Cemex cement and F5 consistency class	BAS-45-BR-16-F5	580	490	420	3.0	2.7	0.011	570
	FIN-45-BR-16-F5	610	450	390	5.3	3.7	0.011	440
	GCP-45-BR-16-F5	560	460	420	3.3	2.3	0.007	580
	SIK-45-BR-16-F5	650	600	490	1.7	2.7	0.010	590
	HAB-45-BR-16-F5	670	590	540	2.7	2.2	0.009	680
	MAP-45-BR-16-F5	620	610	480	0.3	2.3	0.008	650
	SEM-45-BR-16-F5	660	580	560	2.7	1.7	0.012	660
Plus cement and S3 consistency class	BAS-45-PL-16-S3	130	20	10	3.7	2.0	0.018	60
	FIN-45-PL-16-S3	80	10	0	2.3	1.3	0.022	30
	GCP-45-PL-16-S3	170	40	30	4.3	2.3	0.013	130
	SIK-45-PL-16-S3	160	110	50	1.7	1.8	0.017	190
	HAB-45-PL-16-S3	110	90	60	0.7	0.8	0.019	220
	MAP-45-PL-16-S3	150	60	70	3.0	1.3	0.015	220
	SEM-45-PL-16-S3	120	80	40	1.3	1.3	0.021	180

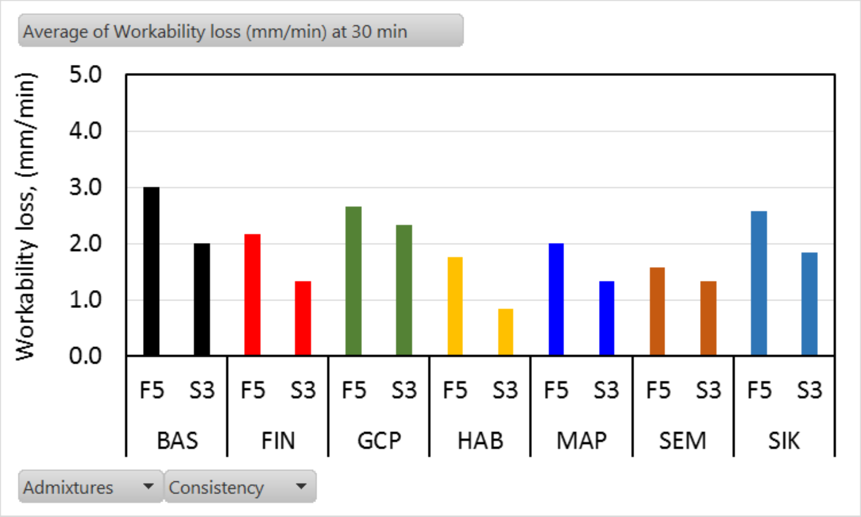


Figure 41. Effects of admixture and consistency class on the workability loss of concrete at 30 minutes after mixing.

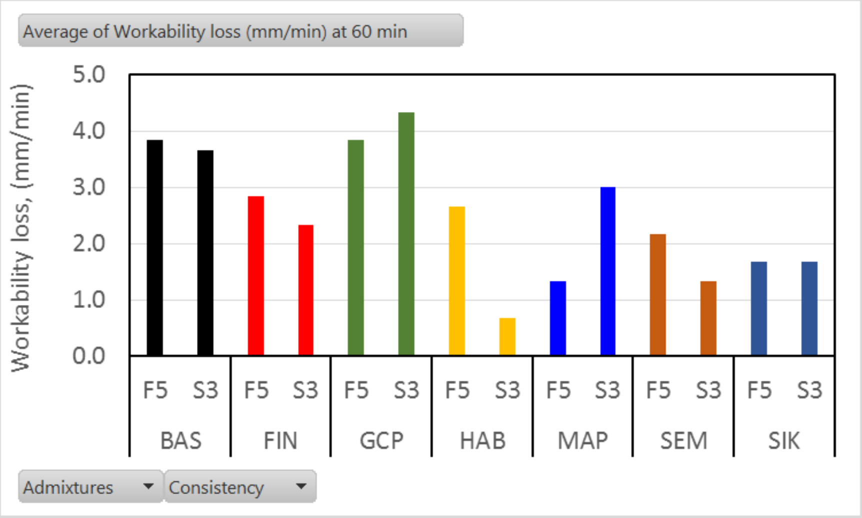


Figure 42. Effects of admixture and consistency class on the workability loss of concrete at 60 minutes after mixing.

4.2.3 Air content in concrete

The air content of fresh concretes with different chemical admixtures was measured immediately after mixing, at 60 minutes and 75 minutes after mixing. An extra dosage of superplasticizers was added and concrete was mixed for 2 min before measuring the air content at 75 minutes.

As presented in section 4.1.3, the air content of fresh concrete was measured using the following methods:

1. Pressure method according to the SFS-EN 12350-7 standard.
2. Calculated from the fresh concrete unit weight according to the ASTM C 138 Standard.
3. Real-Time Air Measurement using CiDRA AIRtrac.

4.2.3.1 Pressure method measurement

The pressure method was not used in all the measuring moments because the test consumes concrete and the concrete volume was critical. The use of different test methods has been shown in Table 16 at section 4.1.3.

Table 30. Air contents of fresh concrete with different chemical admixtures as function of time measured using the pressure method.

Concrete mix	**Measured Air, pressure test (%)**		
	0-min	**60-min**	**75-min**
BAS-45-BR-16-F5	7.2	13.5	10.6
BAS-45-PL-16-F5	5.8	n/a (*)	5.9
BAS-45-PL-16-S3	5.4	6.2	5.6
FIN-45-BR-16-F5	6.6	5.6	6.5
FIN-45-PL-16-F5	6.9	5.7	7.2
FIN-45-PL-16-S3	6.0	4.0	3.5
GCP-45-BR-16-F5	6.6	3.0	2.2
GCP-45-PL-16-F5	5.9	3.1	2.7
GCP-45-PL-16-S3	11.0	3.0	2.9
HAB-45-BR-16-F5	5.9	14.5	8.7
HAB-45-PL-16-F5	4.2	9.8	2.8
HAB-45-PL-16-S3	4.1	2.8	3.9
MAP-45-BR-16-F5	5.5	7.6	5.5
MAP-45-PL-16-F5	5.6	8.1	3.0
MAP-45-PL-16-S3	5.3	5.4	4.6
SEM-45-BR-16-F5	7.0	10.5	7.7
SEM-45-PL-16-F5	7.0	9.5	5.6
SEM-45-PL-16-S3	6.2	5.8	4.5
SIK-45-BR-16-F5	6.4	11.0	7.2
SIK-45-PL-16-F5	6.3	11.0	1.5
SIK-45-PL-16-S3	4.3	5.8	4.8

*) In the beginning of testing program, the air content measuring using pressure methods, was performed only immediately after mixing and at 75 min

4.2.3.2 Calculated air content from unite weight

The calculated air contents have been presented in Figure 43 - Figure 45. The figures show the results of all concretes mixed with different chemical admixtures.

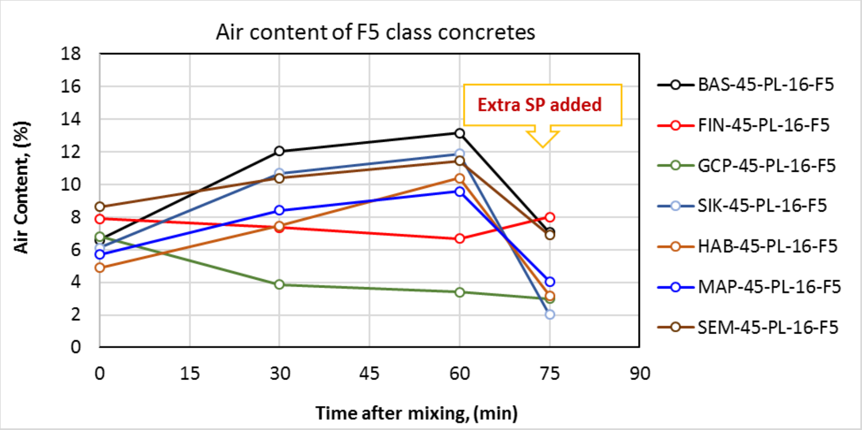


Figure 43. Calculated air contents for F5 consistency class concrete mixes, where Plus Cement was used.

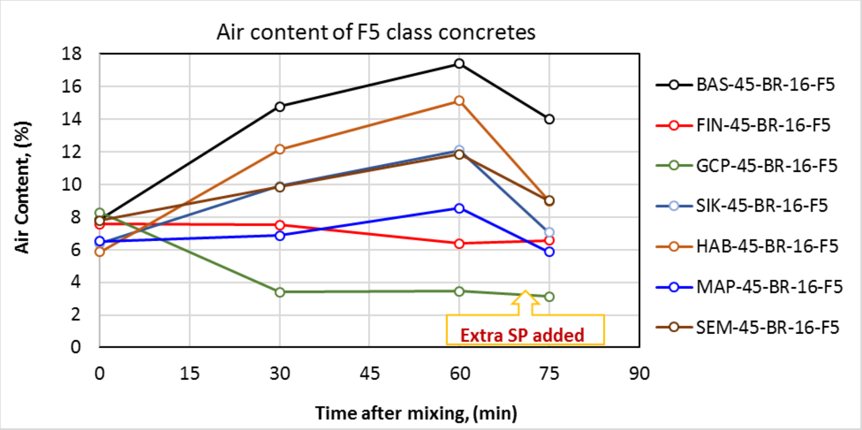


Figure 44. Calculated air contents for F5 consistency class concrete mixes, where Broceni-Cemex Cement was used.

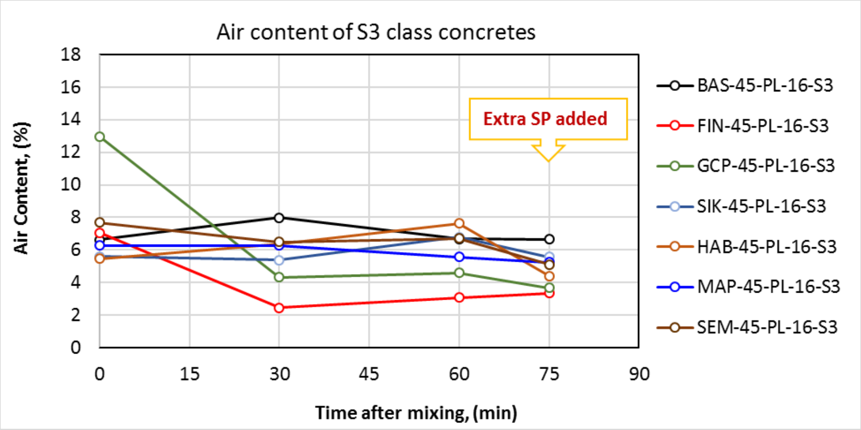


Figure 45. Calculated air contents for S3 consistency class concrete mixes, where Plus Cement was used

The admixtures dosages varied to some extent. It could be assumed that higher admixture dosages increase risk for the elevated air content. The effects of air entraining agent and superplasticizers dosages on the increase of air content of concrete are presented in Figure 46 and Figure 47. The slightly different admixture dosages used in the present study are not explaining the increase of air content. However, if admixture dosages would vary on the lager range, the situation could be different. Also, the concentrations of admixture should be taken in account.

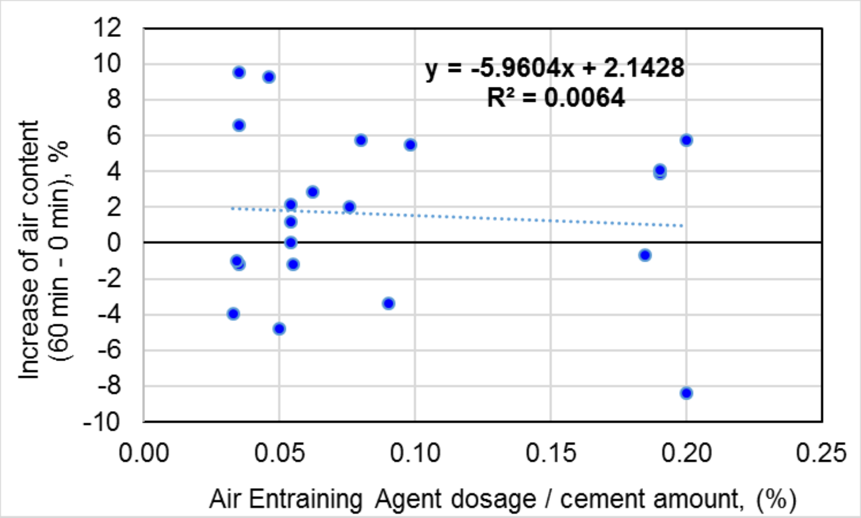


Figure 46. Effects of Air Entraining Agent dosage on the increment of air content in concrete.

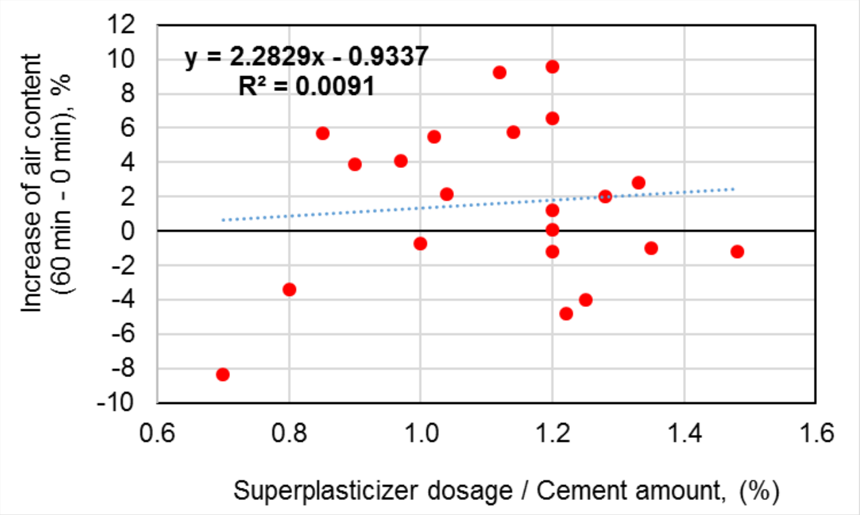


Figure 47. Effects Superplasticizer dosage on the increment of air content in concrete.

4.2.3.3 CiDRA AIRtrac air content monitoring results

An additional test series was carried out in which the air content of fresh concrete was measured for different mixing times and different amounts of AEA dosage as follow:

1) Concrete mixes with 100% of the AEA dosage and 2 minutes initial mixing time.
2) Concrete mixes with 100% of the AEA dosage and 5 minutes initial mixing time.
3) Concrete mixes with 50% of the AEA dosage and 2 minutes initial mixing time.
4) Concrete mixes with 50% of the AEA dosage and 5 minutes initial mixing time.

The air content of fresh concretes with different chemical admixtures was measured immediately after mixing, at 30 minutes and 60 minutes after mixing. The results of air content measurements are shown in Figure 48 to Figure 51.

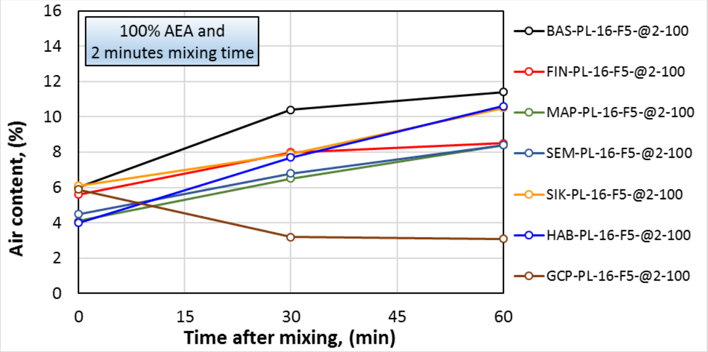


Figure 48. Air contents, the pressure method, for concretes with 100% AEA dosage and initial mixing time of 2 minutes.

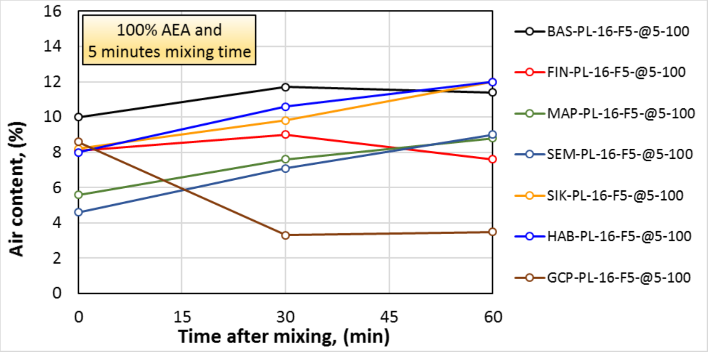


Figure 49. Air contents, the pressure method, for concretes with 100% AEA dosage and initial mixing time of 5 minutes.

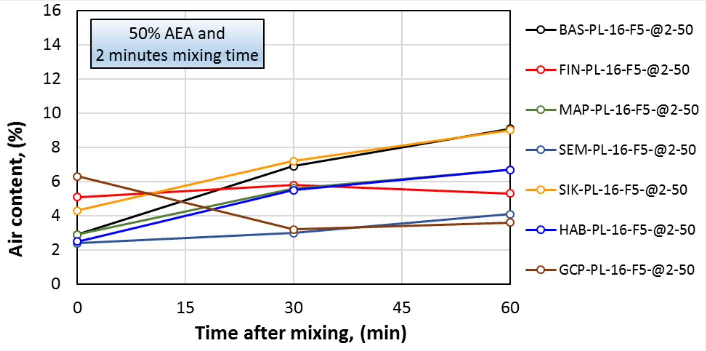


Figure 50. Air contents, the pressure method, for concretes with 50% AEA dosage and initial mixing time of 2 minutes.

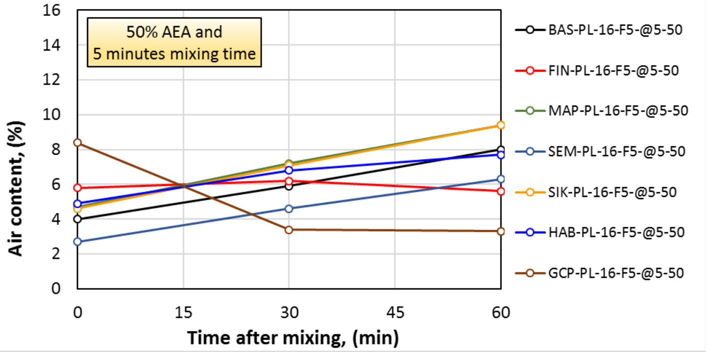


Figure 51. Air contents, the pressure method, for concretes with 50% AEA dosage and initial mixing time of 5 minutes.

The results of CiDRA AIRtac measurements are presented in Figure 52.

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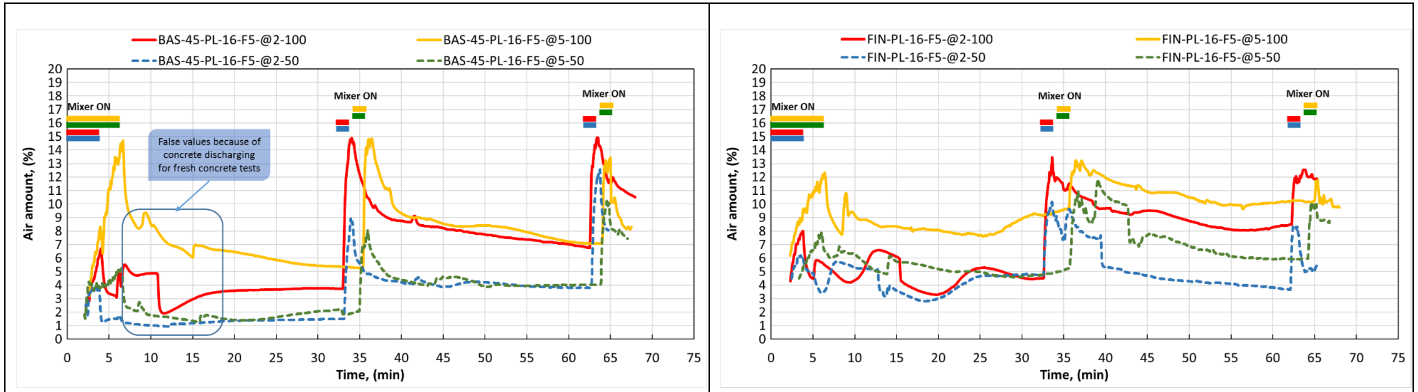
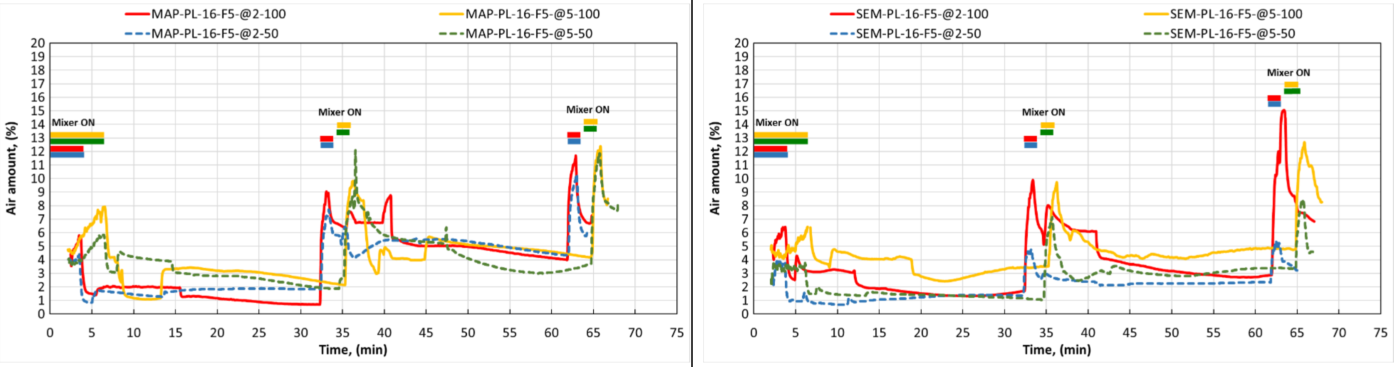


MasterGlenium SKY 600 and MasterAir 100

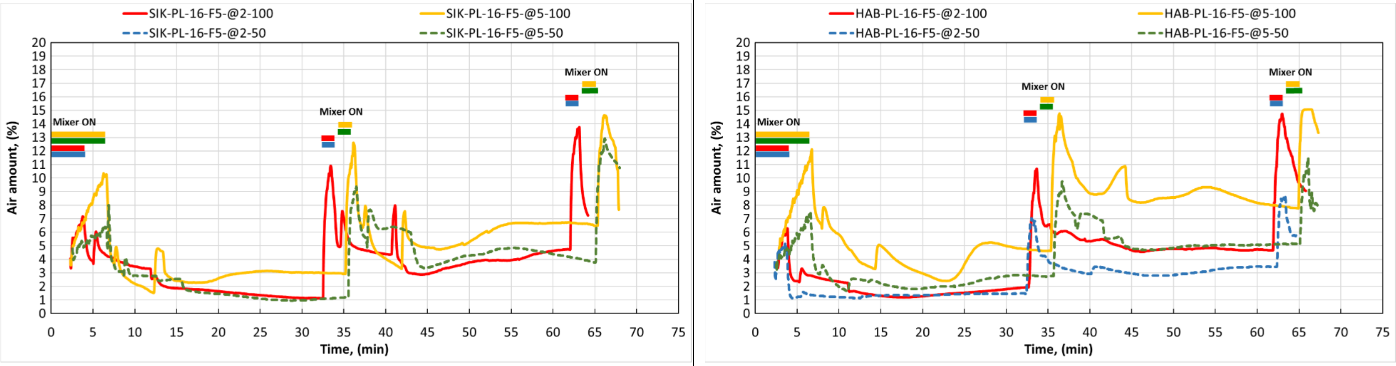
VB-PARMIX and ILMA-PARMIX



Dynamon SX-23 and Mapeair 50

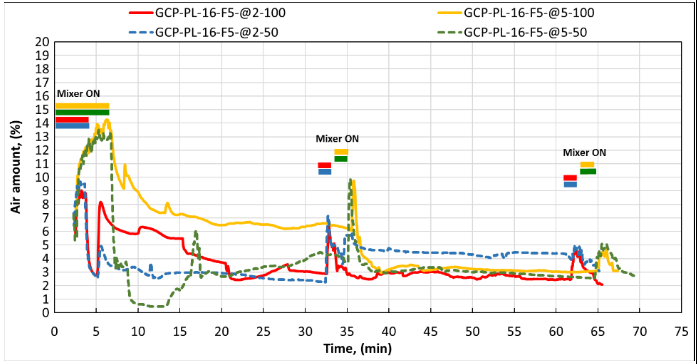
Sem Flow MC and MasterAir 102

Figure 52. CiDRA AIRtrac - Comparison of mixing times and admixture dosages (Part 1/2)



Sikament -RSX (25%) and Sika Air-PRO v5

PANTAHIT and PANTAPOR 2020



Darex AEA T (LP) and ADVA Flow 444-L

Figure 52. CiDRA AIRtrac - Comparison of mixing times and admixture dosages (part 2/2)

4.2.3.4 Comparison of different test methods.

The results of CiDRA AIRtac measurements are presented in Table 31 to Table 33, where the values of dynamic and static air content measured by CiDRA AIRtac are compared to the calculated air contents and the pressure method air content.

Table 31. Air content of the S3 consistency class concrete measured by CiDRA AIRtrac, pressure method and calculated from the unit weight of fresh concrete.

Concrete mix	**Measurement method**	**Air Content, (%)**			
		0 min	**30 min**	**60 min**	**75 min**
BAS-45-PL-16-S3	Pressure method	5.4	n/a	6.2	5.6
	Calculated value	6.6	8.0	6.7	6.7
	Dynamic value - CiDRA	6.1	10.3	15.0	15.1
	Static value - CiDRA	5.0	7.5	5.5	9.7
FIN-45-PL-16-S3	Pressure method	6.1	n/a	4.0	3.5
	Calculated value	7.0	2.5	3.1	3.3
	Dynamic value - CiDRA	11.3	8.0	5.4	13.3
	Static value - CiDRA	10.5	6.5	4.3	7.5
MAP-45-PL-16-S3	Pressure method	5.3	n/a	5.4	4.2
	Calculated value	6.3	6.3	5.6	5.2
	Dynamic value - CiDRA	7.9	5.3	4.8	4.4
	Static value - CiDRA	5.1	5.0	4.6	4.2
SEM-45-PL-16-S3	Pressure method	6.2	n/a	5.8	4.5
	Calculated value	7.7	6.5	6.7	10.1
	Dynamic value - CiDRA	8.8	8.1	7.1	5.1
	Static value - CiDRA	7.7	8.1	6.9	4.2
SIK-45-PL-16-S3	Pressure method	4.3	n/a	5.8	4.8
	Calculated value	5.6	5.4	6.8	5.6
	Dynamic value - CiDRA	5.8	6.8	8.1	6.9
	Static value - CiDRA	4.9	6.7	7.2	4.8
HAB-45-PL-16-S3	Pressure method	4.1	n/a	6.8	3.9
	Calculated value	5.5	6.4	7.6	4.4
	Dynamic value - CiDRA	5.1	6.1	7.3	8.4
	Static value - CiDRA	3.2	5.8	6.4	4.8
GCP-45-PL-16-S3	Pressure method	11.0	n/a	3.0	2.9
	Calculated value	13.0	4.3	4.6	3.7
	Dynamic value - CiDRA	15.1	8.8	3.0	2.1
	Static value - CiDRA	13.9	3.1	1.8	1.8

Table 32. Air content of the F5 consistency class concrete mixed with Plus Cement measured by CiDRA AIRtrac, pressure method and calculated from the unit weight of fresh concrete.

Concrete mix	Measurement method	**Air Content, (%)**			
		0 min	**30 min**	**60 min**	**75 min**
BAS-45-PL-16-F5	Pressure method	5.8	n/a	n/a	5.9
	Calculated value	6.6	12.0	13.2	7.1
	Dynamic value - CiDRA	7.6	15.0	15.1	8.5
	Static value - CiDRA	5.1	12.9	14.0	6.1
FIN-45-PL-16-F5	Pressure method	6.9	n/a	5.7	7.2
	Calculated value	7.9	7.3	6.7	8.0
	Dynamic value - CiDRA	11.4	11.1	9.1	12.2
	Static value - CiDRA	9.7	9.9	8.0	11.2
MAP-45-PL-16-F5	Pressure method	5.6	n/a	8.1	3.0
	Calculated value	5.7	8.4	9.6	4.1
	Dynamic value - CiDRA	7.6	10.8	11.3	9.3
	Static value - CiDRA	3.2	8.3	10.5	4.9
SEM-45-PL-16-F5	Pressure method	7.0	n/a	9.5	5.6
	Calculated value	8.6	10.4	11.5	6.9
	Dynamic value - CiDRA	11.9	12.7	13.7	8.2
	Static value - CiDRA	9.2	11.0	12.6	7.5
SIK-45-PL-16-F5	Pressure method	6.3	n/a	11.0	1.5
	Calculated value	6.1	10.7	11.9	2.0
	Dynamic value - CiDRA	9.1	12.9	13.6	3.5
	Static value - CiDRA	5.5	7.4	9.9	2.4
HAB-45-PL-16-F5	Pressure method	4.2	n/a	9.8	2.8
	Calculated value	4.9	7.5	10.4	3.2
	Dynamic value - CiDRA	6.6	7.6	11.8	8.6
	Static value - CiDRA	4.7	7.3	10.5	8.5
GCP-45-PL-16-F5	Pressure method	5.9	n/a	3.1	2.7
	Calculated value	6.8	3.9	3.4	3.0
	Dynamic value - CiDRA	8.7	5.0	3.8	5.9
	Static value - CiDRA	5.3	3.9	3.4	3.8

Table 33. Air content of the F5 consistency class concrete mixed with Breconi Cement measured by CiDRA AIRtrac, pressure method and calculated from the unit weight of fresh concrete.

Concrete mix	Measurement method	**Air Content, (%)**			
		0 min	**30 min**	**60 min**	**75 min**
BAS-45-BR-16-F5	Pressure method	7.2	n/a	13.5	10.6
	Calculated value	7.8	14.8	17.4	14.0
	Dynamic value - CiDRA	9.8	15.0	15.1	14.9
	Static value - CiDRA	8.5	13.8	14.9	14.3
FIN-45-BR-16-F5	Pressure method	6.6	n/a	5.6	6.5
	Calculated value	7.6	7.5	6.4	6.6
	Dynamic value - CiDRA	10.6	10.5	11.1	10.6
	Static value - CiDRA	9.5	9.8	9.3	9.6
MAP-45-BR-16-F5	Pressure method	5.5	n/a	7.6	5.5
	Calculated value	6.6	7.0	8.8	5.9
	Dynamic value - CiDRA	8.1	11.2	11.0	8.6
	Static value - CiDRA	7.1	10.3	11.6	3.3
SEM-45-BR-16-F5	Pressure method	5.5	n/a	7.6	5.5
	Calculated value	6.5	6.9	8.5	5.9
	Dynamic value - CiDRA	8.1	11.2	11.0	8.6
	Static value - CiDRA	7.1	10.3	11.6	3.3
SIK-45-BR-16-F5	Pressure method	6.4	n/a	11.0	7.2
	Calculated value	6.4	9.9	12.1	7.1
	Dynamic value - CiDRA	8.6	13.0	14.6	13.1
	Static value - CiDRA	5.9	9.2	12.9	12.5
HAB-45-BR-16-F5	Pressure method	5.9	n/a	14.5	8.7
	Calculated value	5.9	12.2	15.1	9.0
	Dynamic value - CiDRA	9.5	14.8	15.0	12.5
	Static value - CiDRA	5.8	9.8	13.1	8.8
GCP-45-BR-16-F5	Pressure method	6.6	n/a	3.0	2.2
	Calculated value	8.3	3.4	3.5	3.1
	Dynamic value - CiDRA	11.2	6.1	6.0	5.1
	Static value - CiDRA	8.2	4.8	4.7	3.8

As in the case of the “Concrete Tests”, different methods were used for measuring air content of fresh concrete. In Figure 53, The X-Axis represents the calculated air content from unit weight of fresh concrete and the Y-axis the results from pressure test and CiDRA monitoring tests. The results are showing the highest correlation between the pressure and unit weight test methods and lower correlation between. CiDRA monitoring and unit weight test methods.

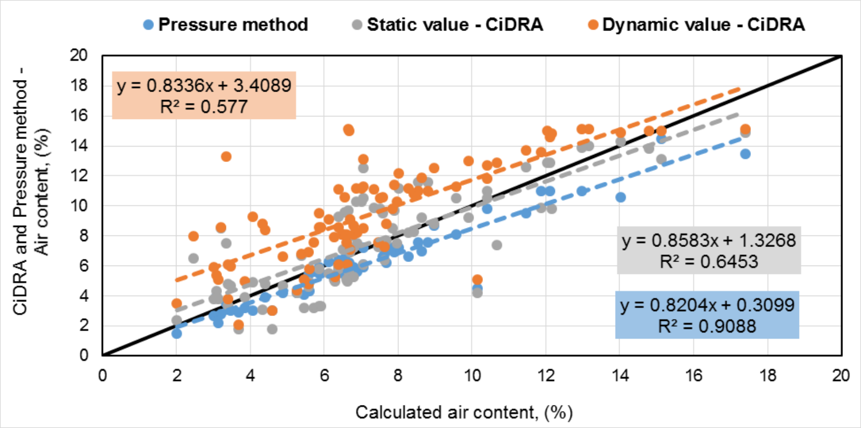


Figure 53. Comparison of different test methods used for air content measurements for concretes with different mixture combinations.

4.2.3.5 Experimental Findings of the air content measurement results

The results of the Admixture tests differed to some extent from those of the “Concrete Tests” (Chap. 4.1). In the “Concrete Tests” most (15 of 16) concretes showed a clear increase of air content after the initial mixing. In the Admixture tests some admixture combinations showed the same increasing tendency of air content, but there were also some admixtures combination with rather constant air content and some admixture combination with reducing air content.

For the S3 consistency class, the air content of fresh concrete was almost stable for most of the admixture combinations used except for the two cases. For the F5 consistency class concretes, the air content of fresh concrete increased after the initial mixing for most of the admixture combinations except in two case the air content decreases. As seen the consistency class played an important role. The cement type and the compressive strength class played smaller roles.

The tests showed rather clear differences between the different admixtures. However, based on the present, limited test series it is not possible to rank the admixtures tested. Only 3 concrete compositions were used and the mix design was not optimal for all the admixtures. Any way, the tests clearly reveal that the significant increase of air content can be limited to a reasonable level with admixture technology.

CiDRA AIRtrac was utilized in analyzing the effects of the mixing time and the AEA dosage. The results indicate that air content is increasing up the 5 min mixing time. In most of the cases the increase was rather linear. Also the AEA dosage showed rather natural effects in the tests. With several admixtures 2 min mixing with normal AEA dosage gave approximately the same air content as 5 min mixing time with 50% AEA dosage. The interesting observation is what happens during the secondary mixing at 30 or 60 min. In most of the cases the lower AEA dosage gave clearly lower increase of the air content because of the secondary mixing.

4.2.4 Segregation sensitivity of concrete

The sensitivity of concrete for segregation was analyzed by comparing the densities of the bottom and top part of the cylindrical test specimens, as presented in section 4.1.4. The compaction is concrete was tried to standardize as much as possible.

4.2.4.1 Density differences in the cylindrical test specimens

The tests were carried out on specimens cast immediately after mixing, 60 min after mixing and 75 min after mixing. The density differences between different parts of the hardened concrete cylinder are shown in Figure 54 to Figure 57.

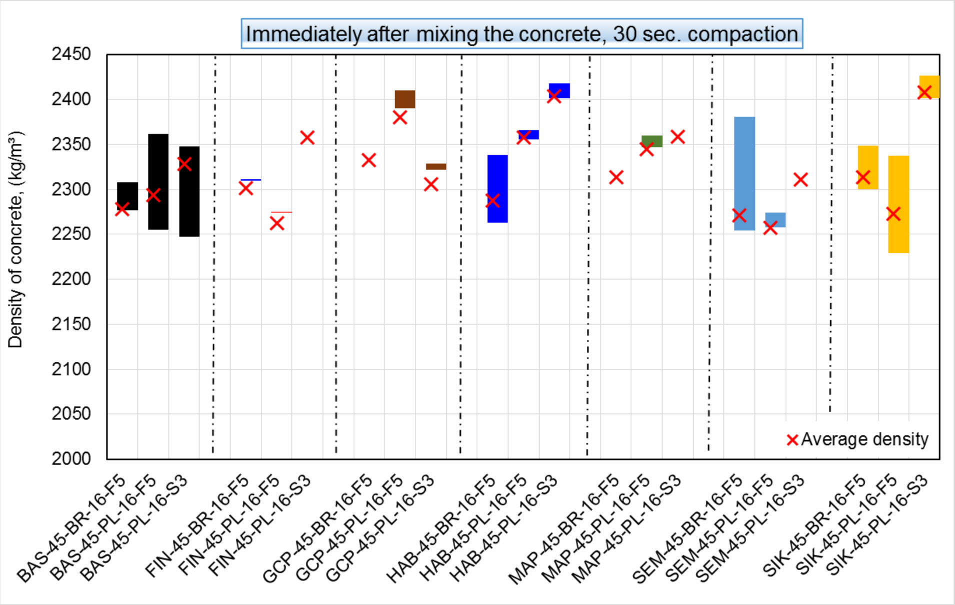


Figure 54. Density differences immediately after mixing for concrete mixes with different chemical admixtures

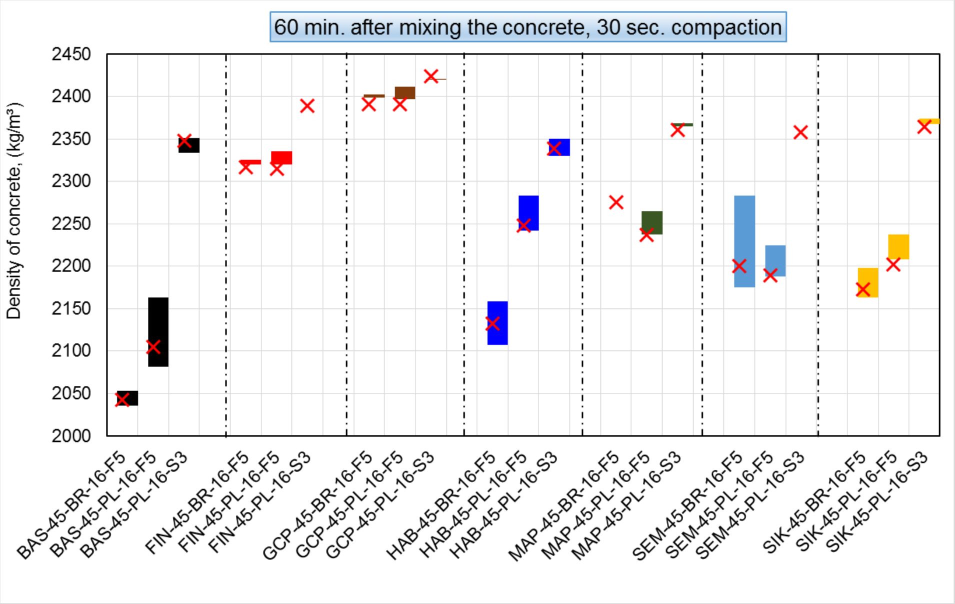


Figure 55. Density differences 60 minutes after mixing for concrete mixes with different chemical admixtures.

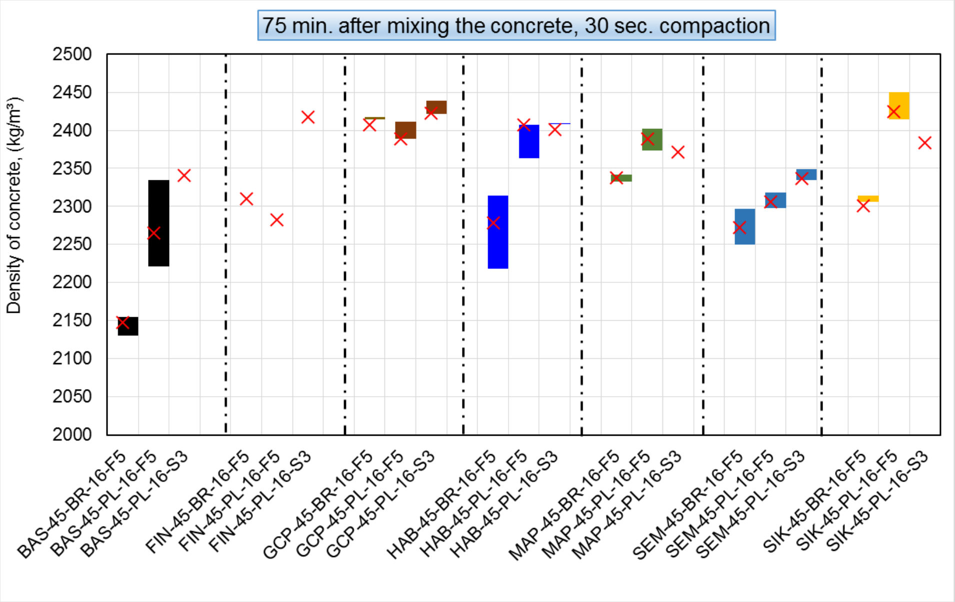


Figure 56. Density differences 75 minutes after mixing for concrete mixes with different chemical admixtures.

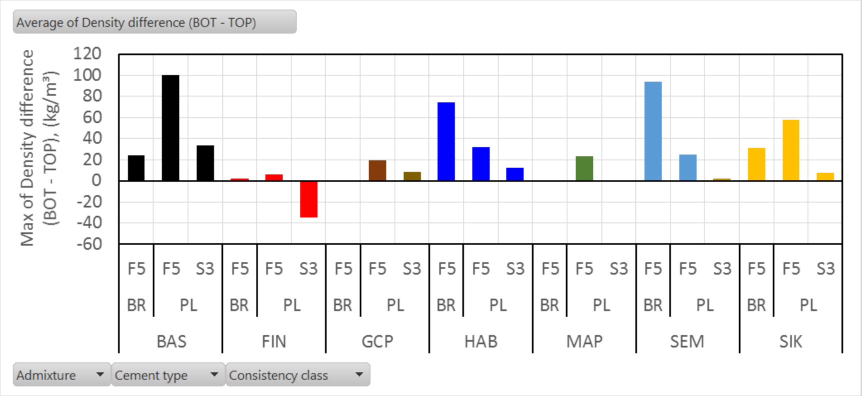


Figure 57. The effect of admixture types, cement types and the consistency class of the segregation sensitivity of concrete mixes.

The effects of air content increment on the segregation sensitivity of concrete specimens that were cast immediately after casting and specimens cast after 60 minutes are shown in Figure 58 and Figure 59 respectively. A slight correlation between the increase of air content and the density difference can be observed. This suggests that both are caused by the same phenomena: the instability of the protective pore system.

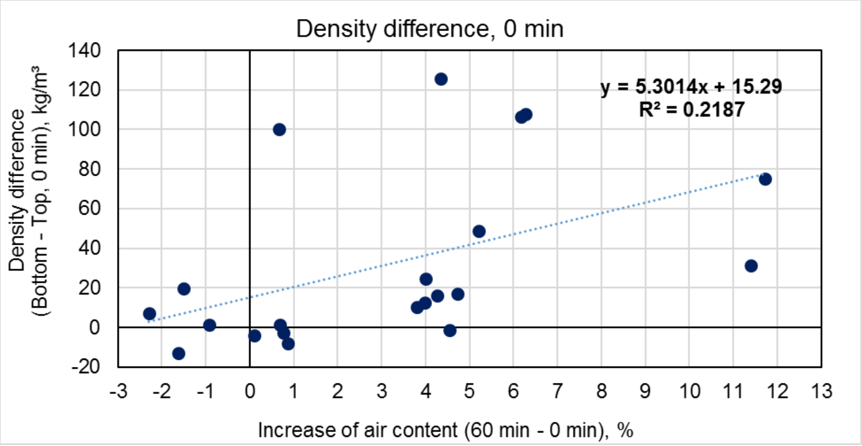


Figure 58. The effects of air content increment of the density difference between the top and bottom parts of concrete specimens that were cast immediately after mixing and compacted for 30 sec.

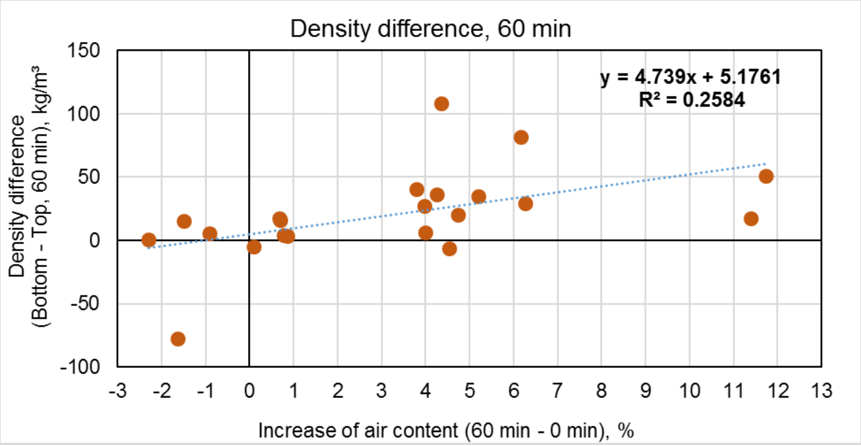


Figure 59. The effects of air content increment of the density difference between the top and bottom parts of concrete specimens that were cast 60 minutes after mixing and compacted for 30 sec.

4.2.4.2 Air content and paste content of hardened concrete

The air content measurement of hardened concrete was carried out with the following tests:

- Thin section analysis of concrete specimens
- Calculated air content based on the unit weight of hardened concrete
- Air content of hardened concrete using the pressure saturation test - according to the old Finnish standard SFS-4475.

The thin section analysis, unit weight test and pressure saturation tests were carried out for samples made immediately after mixing. The results are presented in Table 34.

Table 34. The average air contents and cement paste contents of the segregations tests. The tests specimens were cast immediately after mixing of concrete.

Concrete mix	Calculated air content, (%) (1	Air content, thin section, (%) (2	Air content, Pressure saturation, (%)	Cement paste volume, (%)
BAS-45-BR-16-F5 - Top	*7.0*	*7.6 = 6.6+1.0*	*6.7*	*27*
BAS-45-BR-16-F5 - Bottom	*5.8*	*5.4 = 5.1+0.4*	*6.4*	*29*
BAS-45-PL-16-F5 - Top	*7.6*	*3.8 = 3.8 + 0.0*	*6.1*	*35*
BAS-45-PL-16-F5 - Bottom	*3.2*	*3.1 = 3.0 + 0.1*	*4.6*	*27*
BAS-45-PL-16-S3 - Top	*9.2*	*4.4 = 2.7+1.7*	*4.9*	*28*
BAS-45-PL-16-S3 - Bottom	*5.2*	*4.4 = 2.7+1.8*	*4.5*	*28*
FIN-45-BR-16-F5	*6.0*	*8.6 = 7.4+1.2*	*n/a*	*31*
FIN-45-PL-16-F5	*7.3*	*5.7 = 5.4+0.2*	*n/a*	*29*
FIN-45-PL-16-S3	*4.7*	*5.9 = 3.9+2.1*	*4.7*	*27*
GCP-45-BR-16-F5	*4.9*	*2.6 = 1.6+1.1*	*2.3*	*34*
GCP-45-PL-16-F5	*2.6*	*5.6 = 2.4+3.2*	*3.7*	*30*
GCP-45-PL-16-S3	*6.9*	*6.5 = 5.0+1.5*	*5.9*	*34*
HAB-45-BR-16-F5	*6.6*	*4.7 = 4.3+0.4*	*5.6*	*10*
HAB-45-PL-16-F5	*3.4*	*3.9 = 2.2+1.7*	*n/a*	*33*
HAB-45-PL-16-S3	*2.9*	*6.3 = 1.9+4.4*	*3.2*	*29*
MAP-45-BR-16-F5	*5.6*	*2.8 = 2.2+0.6*	*n/a*	*29*
MAP-45-PL-16-F5	*4.0*	*4.9 = 4.6+0.4*	*n/a*	*29*
MAP-45-PL-16-S3	*4.8*	*4.3 = 3.1+1.2*	*n/a*	*28*
SEM-45-BR-16-F5	*7.2*	*6.1 = 4.6+1.5*	*6.9*	*26*
SEM-45-PL-16-F5	*7.5*	*7.2 = 6.6+0.6*	*6.4*	*19*
SEM-45-PL-16-S3	*6.6*	*5.8 = 4.4+1.4*	*5.7*	*21*
SIK-45-BR-16-F5	*5.6*	*6.0 = 5.0+1.0*	*n/a*	*21*
SIK-45-PL-16-F5	*6.9*	*8.3 = 5.4+2.8*	*n/a*	*19*
SIK-45-PL-16-S3	*2.8*	*3.6 = 2.1+1.5*	*3.4*	*29*

1) The air content is calculated using the density of test specimens and assuming that the only source for the density difference is the changing air content.
2) Total pore volume = Protective pore volume + Compaction pores

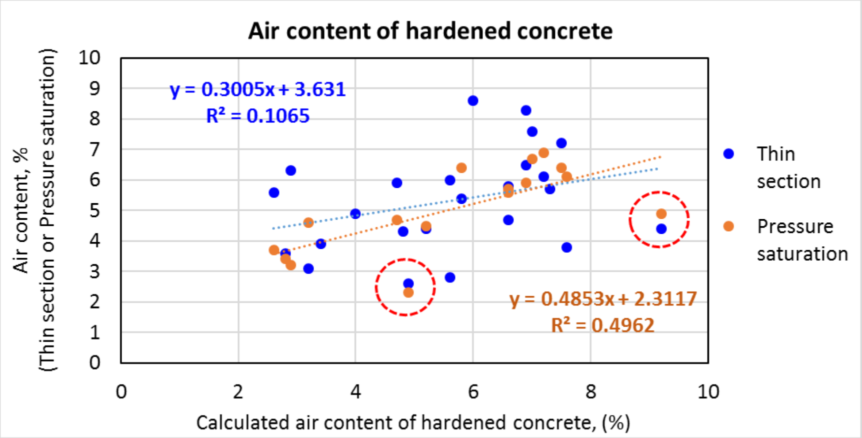


Figure 60. Comparison of air content of hardened concrete using different tests methods.

In Figure 60 couple of concretes have clearly higher calculated air content compared to air content determined using pressure saturation or thin section. In those cases, it is probable that some aggregate segregation has taken place and therefore the calculated air content is erroneous. If removing 2 concretes, a coefficient of determination (R^2) of 0.84 between calculated and pressure saturation air content could be achieved.

4.2.4.3 Pore size analysis

The pore structure of hardened concretes with different chemical admixtures was analyzed by thin section analysis for specimens cast immediately after mixing of concrete and compacted for 30 seconds. The samples for thin-section analysis were taken from the middle part of concrete specimens except for the specimens prepared using the BASF admixture combination, samples were taken from the top and bottom parts. The quantitative results of specific surface area and spacing factor of the pore system are presented in Table 35. The relationship between the air content of hardened concrete and spacing factor is presented in Figure 61.

Table 35. Quantitative characterization of concrete pore structure by thin section analysis.

Concrete mix	**Calculated air content, (%)**	**Specific surface area, (mm^2/mm^3)**	**Spacing factor, (mm)**
BAS-45-BR-16-F5, top	7.0	30	0.14
BAS-45-BR-16-F5, bottom	5.8	42	0.12
BAS-45-PL-16-F5, top	7.6	44	0.14
BAS-45-PL-16-F5, bottom	3.2	42	0.15
BAS-45-PL-16-S3, top	9.2	36	0.18
BAS-45-PL-16-S3, bottom	5.2	50	0.13
FIN-45-BR-16-F5	6.0	31	0.16
FIN-45-PL-16-F5	7.3	24	0.18
FIN-45-PL-16-S3	4.7	22	0.24
GCP-45-BR-16-F5	4.9	25	0.28
GCP-45-PL-16-F5	2.6	19	0.49
GCP-45-PL-16-S3	6.9	22	0.25
HAB-45-BR-16-F5	6.6	49	0.10
HAB-45-PL-16-F5	3.4	23	0.32
HAB-45-PL-16-S3	2.9	28	0.29
MAP-45-BR-16-F5	5.6	30	0.17
MAP-45-PL-16-F5	4.0	36	0.20
MAP-45-PL-16-S3	4.8	32	0.19
SEM-45-BR-16-F5	7.2	20	0.26
SEM-45-PL-16-F5	7.5	25	0.19
SEM-45-PL-16-S3	6.6	25	0.21
SIK-45-BR-16-F5	5.6	25	0.21
SIK-45-PL-16-F5	6.9	27	0.19
SIK-45-PL-16-S3	2.8	29	0.25

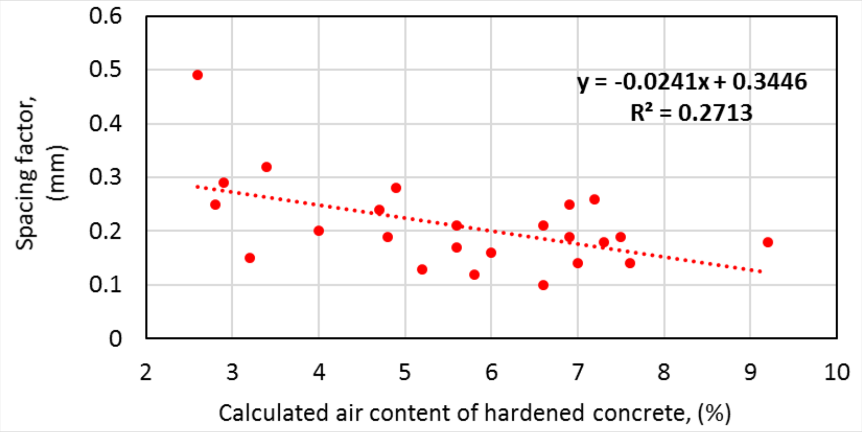


Figure 61. Hardened concrete air content vs. spacing factor.

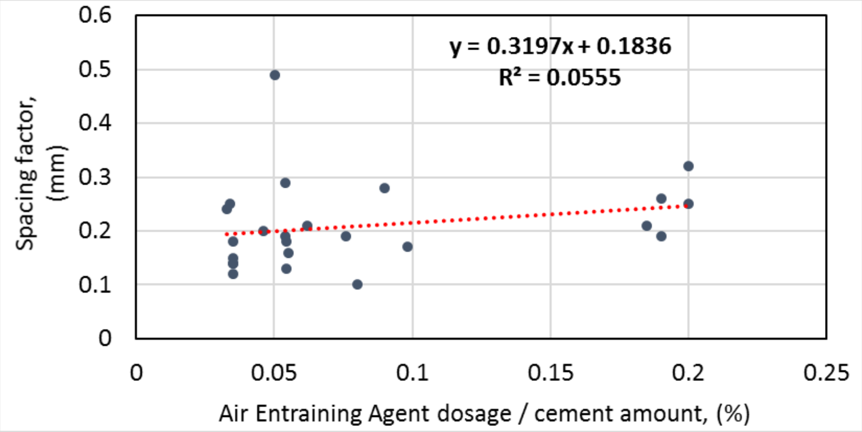


Figure 62. Air Entraining dosage w.r.t cement amount vs. spacing factor.

The quality of the air void system in concrete is quantified by the spacing factor. The air content of concrete slightly correlated with the spacing factor, as shown in Figure 61, while the dosage of air entraining agent did not affect the spacing factor, as shown in Figure 62.

4.2.4.4 Experimental Findings of the segregation sensitivity tests

The results have been summarized in Figure 57. As can be seen, the S3 consistency class concrete showed smaller segregation sensitivity compared to F5 class concrete for most types of admixtures and all types of cement. The average density difference with S3 concrete was 5 kg/m^3, whereas with F5 concretes the respective value was 35 kg/m^3.

Also differences between different admixtures can be observed. With some admixtures a difference of 100 kg/m^3 was exceed, but some other admixtures gave only very small difference. The density difference appears to correlate with the increase of the air content after mixing. The correlation is not strong, but in most cases, the same admixtures gave both high increase of air content and high-density difference.

The method used for analyzing the density difference is not standardized and requires further development. Therefore, the results are needed to interpret with care. Anyway, it sounds rather alarming if rather typical compaction method can give such high density differences inside the concrete.

4.2.5 Compressive strength of concrete

Compressive strength and densities of concrete were measured at 28 days of age. The test specimens were cast immediately after concrete mixing and 75 minutes after casting, as shown in Figure 14 at section 3.2. The specimens were kept in their molds and covered for one day with a plastic sheet after casting and then stored in the same condition (RH of 95% and temperature of 20±2 °C) until the testing age.

4.2.5.1 Compressive strength test results

The results of the compressive strengths and densities are shown in Figure 63

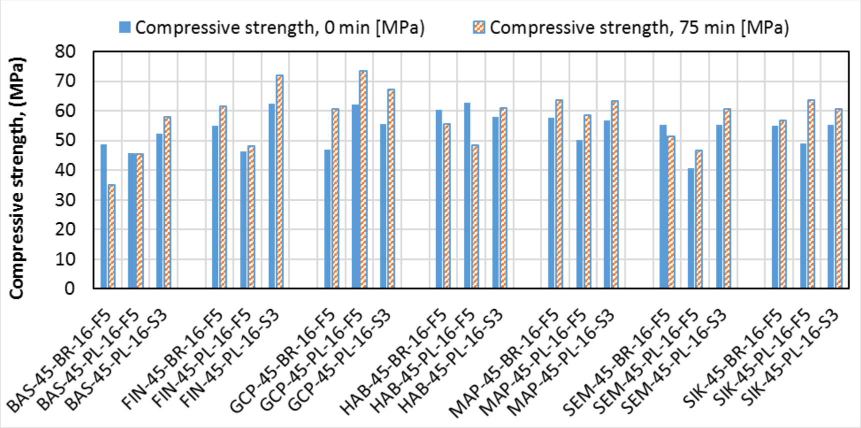


Figure 63. 28 days compressive strength test results for concretes with different chemical admixtures. The strength class: C35/45.

4.2.5.2 Experimental Findings of compressive test results

As shown in Figure 64, the increment of the air content of concrete decreases the compressive strength of concrete as expected. The average reduction in compressive strength is about 4.7% occurs due to each 1% by volume of entrained air in the concrete mixes.

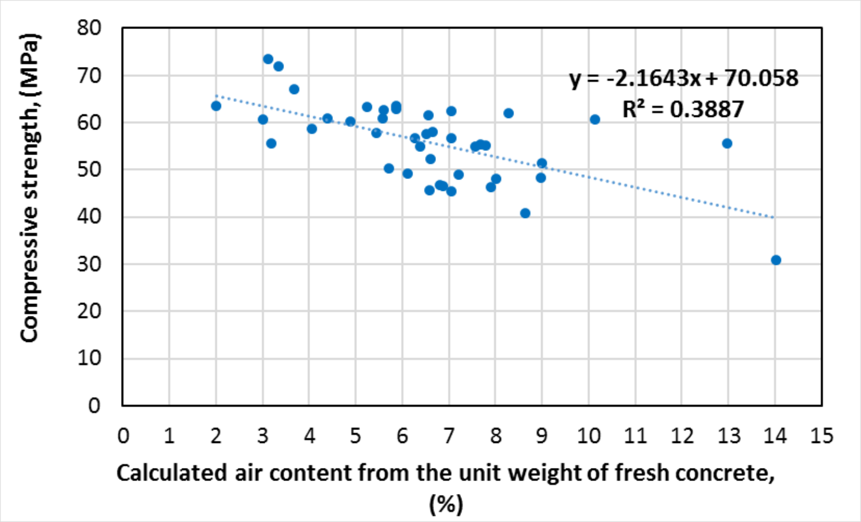


Figure 64. Compressive strength of concrete with different chemical admixtures vs. calculated air values of fresh concrete. The strength class: C35/45.

5 TESTS AT CONCRETE INDUSTRY

The condition in the laboratory tests are not exactly the same as in the industrial ready-mix concrete production. The main differences are the mixer, aggregates and water-cement ratios of the concrete. The mixer used in laboratory tests was not very effective one and therefore some of the effects can be different. For example, the increase of air content after initial mixing is probably larger when the mixing efficiency is lower. The laboratory aggregates have lower water demand compared to those used in the industry. The lower water demands lead to lower water-cement ratios when superplastizer dosage and cement content wanted to keep similar as in the industry.

In order to confirm the phenomenon observed in the laboratory tests Finnish concrete industry was asked to carry out some own tests with air-entrained concrete (P-factor concrete). The tests were organized by the Confederation of Finnish Construction Industries RT.

The testing principles were as follows:

- RM-concrete producer is producing the normal air-entraining concrete using the normal production procedures. From the concretes the following information was asked:
    - Mixer type
    - Concrete strength grade and P-factor
    - Target air content
    - Water-cement ratio
    - Consistency class
    - Batch volume
    - Binder composition (type of cement / additive) and the amounts
    - Admixtures (Name, dosages, and dilution of AEA)
    - Temperature of concrete
- After the normal mixing time the following tests/information were asked:
    - Mixing time
    - Air content
    - Measured consistency (test method and value)
- After the normal mixing the mixing was continued so that the total mixing of 6 min was achieved. The following information was asked:
    - Mixing time
    - Air content
    - Measured consistency (test method and value)

Totally 35 tests were carried out. The number of tests is too low to make any comprehensive analyses.

On the average, the air content increased 1.7% between the normal mixing time and 6 min. The highest increase was 7.5% and the smallest -0.3% (decreased 0.3%).

The distribution of the results has been presented in Figure 65. The highest measured air content after 6 min mixing was 12.0%.

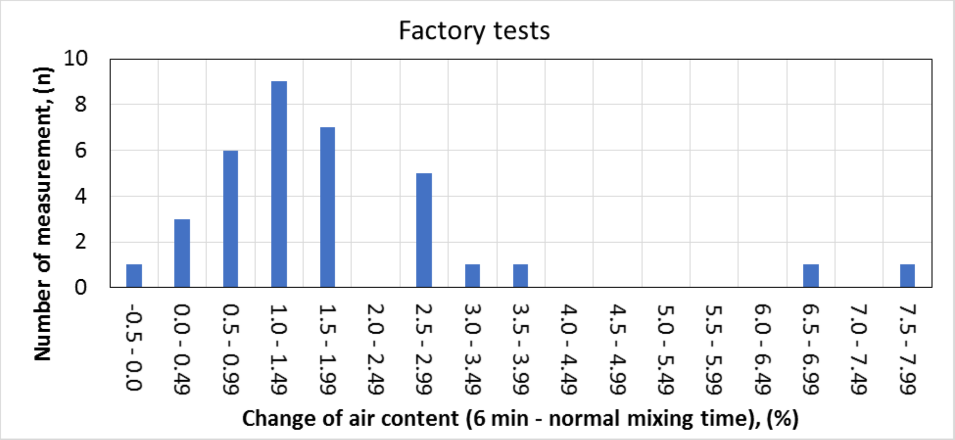


Figure 65. Distribution of the air content increase in the factory tests.

The normal mixing time was on the average 127 s and varied between 85 and 220 s. If the increase of 3%-unit is considered as limit value for abnormal increase. 4/35 (= 11%) of the cases were abnormal. Because of the nature of the problem, the reported results do not necessarily reflect perfectly the real situation.

Because of the limited number of tests, it is not possible to analyze the factors affecting the increase of air content in detail. The most potential factors based on the laboratory tests were the consistency of the concrete and the mixing time of concrete (normal mixing time). Figure 66 and Figure 67 show the correlation of the above-mentioned factors on the increase of the air content.

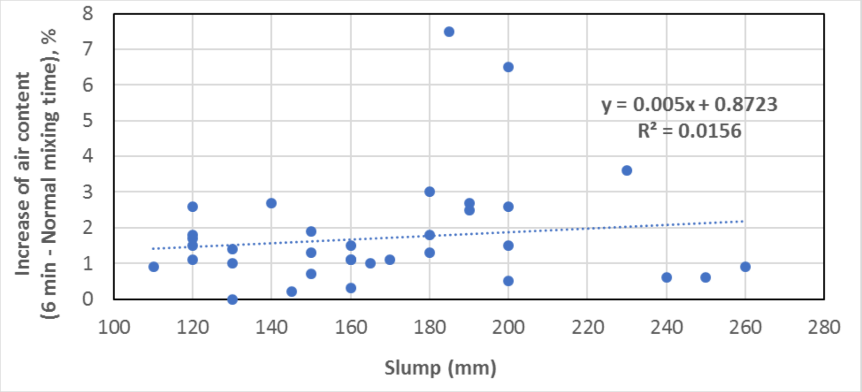


Figure 66. Effect of concrete consistency (slump value) on the increase of the air content in the factory tests.

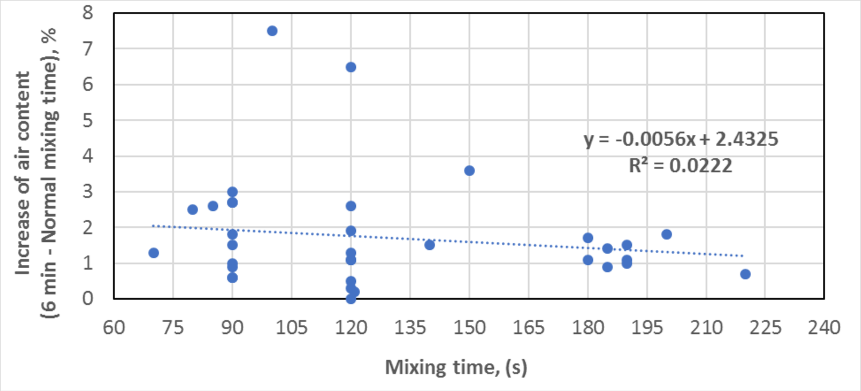


Figure 67. Effect of mixing time (normal mixing time) on the increase of the air content in the factory tests.

As seen from Figure 66 and Figure 67, no significant correlations on the increase of air content can be found. Based on these two figures it can be stated that the increase of air content was reasonable when slump value was 180 mm or lower or the mixing time was 150 s or longer. However, these assumptions miss scientific proof.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A large number of concrete tests were carried out in order to analyze the factors affecting the stability of the protective pore systems. The concrete properties were varied in the “Concrete Tests” and the admixtures were varied in the “Admixture Tests”. Clear increase of the air content after the initial mixing of concrete was observed, the highest measured air contents were close to 20%.

The increase of air content is a complex issue and several factors are affecting the phenomena. However, based on our tests the increase of the air content after the initial mixing can be explained as follows:

1. Each concrete has a maximum air content which could be called also as *Air content potential*. The Air content potential depends on the admixture combination (superplasticizer, air entraining agent and their dosage), but it also depends on the concrete composition such as water-cement ratio and cement content and type. In addition, the consistency of concrete affects the Air content potential.

2. Relatively long initial mixing time is needed to achieve the Air content potential. The normal mixing times used in the RM-concrete industry for air-entrained concrete (60…90 s) is not probably enough to achieve the Air content potential. In the laboratory tests, 5 min mixing time was not enough.

3. If the Air content potential is not reached during the initial mixing, there is a risk that the air content will increase later for example during the transportation or at construction site when the concrete is mixed in the truck. The truck mixing is not normally effective enough to reach the Air content potential, but significantly increase of air content may take place. It is also possible that pumping and casting may increase the air content when the initial mixing process has not been effective enough.

In addition to the above-mentioned phenomena, there are probably also some other aspects included. Occasionally air content continues increasing after initial mixing even though the initial mixing time has been rather long. In such cases, the superplasticizer is probably playing the major role, the foam killer may lose its power and air content is increasing.

6.2 General guidelines for stability of air content in concrete

In order to avoid an extensive increase of air content after the initial mixing of concrete, the target is to achieve the major part of the Air content potential already during the initial mixing process. This is not very easy task because increasing the mixing time is not a practical solution in the RM-concrete industry. The other alternative is to improve the efficiency of the mixing so that higher part of the Air content potential can be achieved during the initial mixing process. Also, the admixtures are needed to develop so that a shorter mixing will be needed.

Even though the mixing efficiency (mixing time & efficiency of the mixer) cannot be modified so that the Air content potential is fully reached already during the initial mixing, the risks related to elevated air contents can be significantly reduced. Firstly, the high concrete consistencies should be avoided. The risk increases with fluid consistencies. When the fluid consistencies are needed, special care should be taken to secure the air content on the construction site. Secondly, the target air content should be kept on reasonable level. At the concrete mixing station, the target air contents should preferably be on the level of 5% and at the construction site the measured air contents should not exceed 6%. Too high air contents should be avoided because they increase the risk for elevated air contents.

The producer should also be familiar with the tendency of the particular concrete (with particular admixtures) to create air after the initial mixing process. The preliminary tests required by the Finnish Transportation Agency reveal the increase of air content of concrete. Also, the test with 6 min mixing time gives a good estimation for the air content which can be achieved later at the construction site or from the structure.

The situation becomes less critical if a more effective mixing process combined with lower AEA dosage can be used. Figure 68 illustrates the situation. The same air content can be achieved with lower AEA dosage when a more effective mixing process can be used (longer mixing time or more effective mixer). The benefit is achieved when a larger part of the Air content potential is achieved already during the initial mixing process.

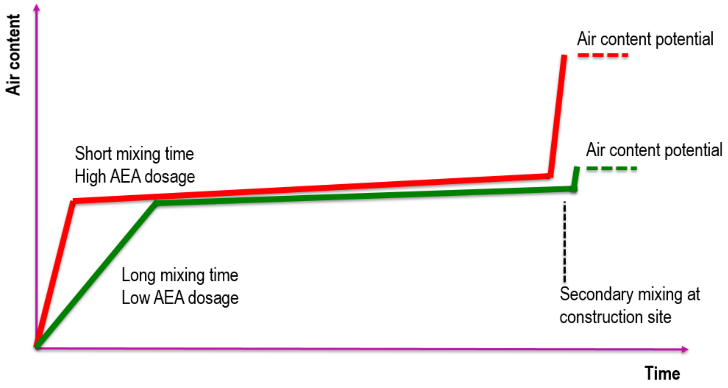


Figure 68. Illustrated effects of the mixing time (mixing efficiency) and the AEA dosage on the increase of the air content after mixing.

On the practical level, the following actions are needed to reduce the problems with the elevated air contents:

1. Admixtures are needed to develop so that a reasonable mixing time gives the air content which represents the main part of the Air content potential.
2. Concrete mixers are needed to develop so that air content will be formed effectively enough.
3. Concrete producer must test and know the Air content potential of each the air-entrained concrete produced. More focus is needed to set on the air content at the construction site. Preliminary testing procedure required by the Finnish Transportation Agency will reveal the problems with the stability of air entrainment. However, the requirements have not been systematically followed. Also, the test with 6 min mixing time gives an indication for the air content potential.
4. High consistencies should be avoided with air-entrained concretes whenever possible. Special care is needed with very fluid concrete consistencies.
5. The target air contents are needed to keep on the reasonable level. The high salt-freeze resistance should be rather achieved with a lower water-cement ratio that with a high air content.
6. The requirements for frost resistance concrete are needed to update in order not the promote too high air contents. Above to certain air content level a higher air content is not improving the frost resistance of concrete. This should be taken into account in the requirements. Also the role of the spacing factor should be reconsidered, the requirement of small spacing factor easily leads to unnecessary high air contents.
7. Quality control of concrete manufacturing is needed to develop so that the air contents at the construction site can be observed. Quality control should be continuous and automatic.

6.3 Recommendations for further studies

The present project was rather compact and the main target was to understand better the phenomena behind the elevated air content of concrete. The project time table did not allow very deep-going research on the topic. The project gave more information about the phenomena and the further studies should be focused on the following topics.

1. **Admixture development**. Superplasticizing and air-entraining admixtures are needed to develop so that the risk for elevated air contents will be minimal. The results of the Admixture tests indicate that this kind of behavior is possible.
2. **Concrete mixer development**. Mixing of air-entrained concrete has not probably been in the main role when concrete mixers have been developed / optimized. Based on the results, it appears that a more effective mixing process is needed to guarantee good air-entraining.
3. **Manufacturing of air-entrained concrete**. It appears that the know-how of the manufacturing of air-entrained concrete has been worsening lately. For years, air-

entrained concretes did not cause any significant problems, but lately it has been rather problematic. Development activities are needed in the manufacturing process of air-entrained concrete structures including the concrete manufacturing but also the in-situ operations.

4. **Variation of concrete**. The project results showed higher variation in concrete properties as normally assumed. The present level of variation is needed to clarify, otherwise all the analyses are on the weak basement. It is needed to investigate whether the high variation is connected only on the present air-entrained concrete.
5. **Quality control of concrete**. Quality control of concrete manufacturing is needed to update to the present technology level. The manual measurements, especially air content, workability and w/c-ratio, do not fulfil the present requirement of the frequency, speed and operator sensitivity. IoT based measuring systems covering the whole manufacturing process of concrete structures are needed to develop.
6. **Requirements for frost resistance concrete**. The present Finnish requirements for frost resistance concrete are needed to evaluate and possible update. The present requirements favor high air contents. Research activities are needed to define appropriate requirements for frost resistance concrete

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EUROPEAN STANDARDS USED:

EN 12350, Testing fresh concrete, including:

- Part 1, Sampling
- Part 2, slump test
- Part 5, Flow table test
- Part 6, Density
- Part 7, Air content – pressure methods

EN 12390, Testing hardened concrete, including:

- Part 1, Shape, dimensions and other requirements of specimens and moulds
- Part 2, Making and curing specimens for strength tests
- Part 3, Compressive strength of test specimens
- Part 4, Compressive strength – specification for testing machines
- Part 7, Density of hardened concrete

APPENDICES

APPENDIX A - COMBINED AGGREGATE FOR CONCRETE

Table A-1. Concrete class C35/45 and 16 mm maximum aggregate size

Fraction	**Portion (%)**	**0,125**	**0,25**	**0,5**	**1**	**2**	**4**	**8**	**16**	**32**	**64**
filler 96	**8**	42	81	93	97	98	100	100	100	100	100
R 0,1 - 0,6	**12**	3	21	76	100	100	100	100	100	100	100
R 0,5 - 1,2	**12**	0	2	6	70	100	100	100	100	100	100
R 1,0 - 2,0	**15**	0	1	2	7	79	100	100	100	100	100
R 2,0 - 5,0	**15**	0	0	1	1	1	47	100	100	100	100
R 5,0 - 10,0	**18**	0	0	0	0	0	3	82	100	100	100
R 8,0 - 16,0	**20**	0	0	0	0	0	0	5	99	100	100
Combined aggregates [%]		**4**	**9**	**18**	**29**	**44**	**55**	**78**	**100**	**100**	**100**

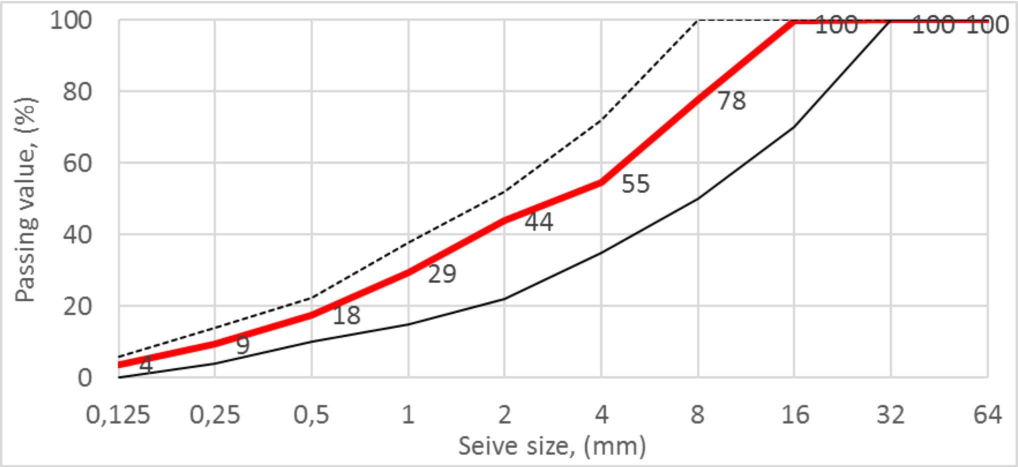

Figure A-1. Combination of aggregates used for strength class C35/45 and 16 mm maximum aggregate size.

Table A-2. Concrete class C35/45 and 8 mm maximum aggregate size

Fraction	Portion (%)	0,125	0,25	0,5	1	2	4	8	16	32	64
filler 96	12	42	81	93	97	98	100	100	100	100	100
R 0,1 - 0,6	10	3	21	76	100	100	100	100	100	100	100
R 0,5 - 1,2	14	0	2	6	70	100	100	100	100	100	100
R 1,0 - 2,0	20	0	1	2	7	79	100	100	100	100	100
R 2,0 - 5,0	22	0	0	1	1	1	47	100	100	100	100
R 5,0 - 10,0	22	0	0	0	0	0	3	82	100	100	100
R 8,0 - 16,0	0	0	0	0	0	0	0	5	99	100	100
Combined aggregates [%]		5.5	12	20	33	52	67	96	100	100	100

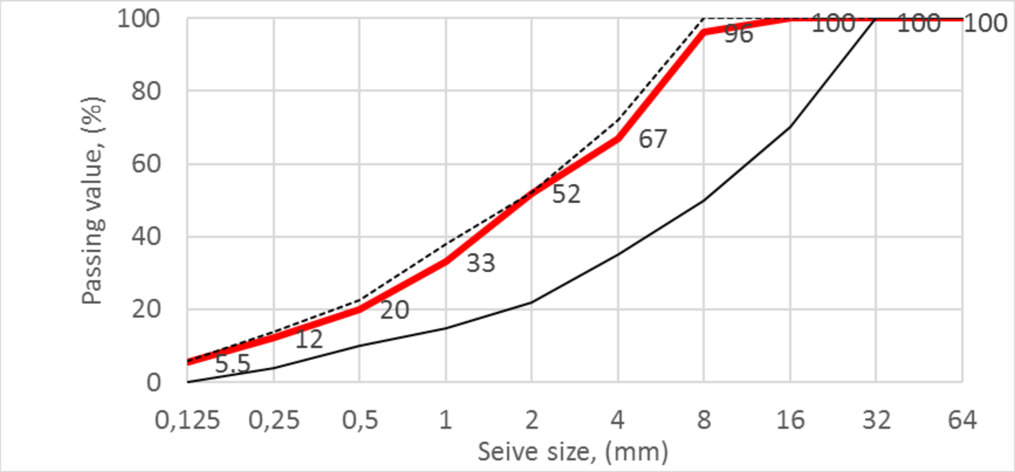

Figure A-2. Combination of aggregates used for strength class C35/45 and 8 mm maximum aggregate size.

Table A-3. Concrete class C30/37 and 16 mm maximum aggregate size

Fraction	Portion (%)	0,125	0,25	0,5	1	2	4	8	16	32	64
filler 96	8	42	81	93	97	98	100	100	100	100	100
R 0,1 - 0,6	9	3	21	76	100	100	100	100	100	100	100
R 0,5 - 1,2	9	0	2	6	70	100	100	100	100	100	100
R 1,0 - 2,0	15	0	1	2	7	79	100	100	100	100	100
R 2,0 - 5,0	15	0	0	1	1	1	47	100	100	100	100
R 5,0 - 10,0	12	0	0	0	0	0	3	82	100	100	100
R 8,0 - 16,0	32	0	0	0	0	0	0	5	99	100	100
Combined aggregates [%]		**4**	**9**	**15**	**24**	**38**	**48**	**68**	**100**	**100**	**100**

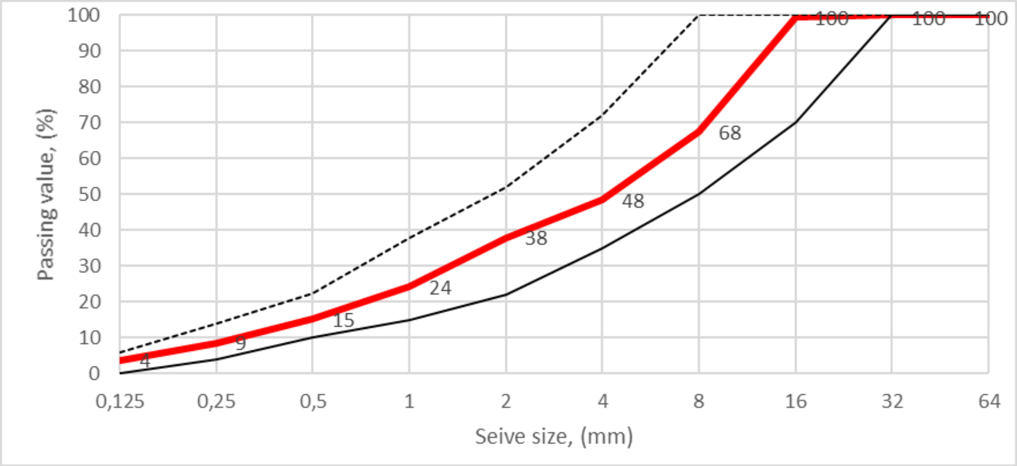

Figure A-3. Combination of aggregates used for strength class C30/37 and 16 mm maximum aggregate size.

Table A-4. Concrete class C30/37 and 8 mm maximum aggregate size

Fraction	**Portion (%)**	**0,125**	**0,25**	**0,5**	**1**	**2**	**4**	**8**	**16**	**32**	**64**
filler 96	12	42	81	93	97	98	100	100	100	100	100
R 0,1 - 0,6	12	3	21	76	100	100	100	100	100	100	100
R 0,5 - 1,2	14	0	2	6	70	100	100	100	100	100	100
R 1,0 - 2,0	20	0	1	2	7	79	100	100	100	100	100
R 2,0 - 5,0	20	0	0	1	1	1	47	100	100	100	100
R 5,0 - 10,0	22	0	0	0	0	0	3	82	100	100	100
R 8,0 - 16,0	0	0	0	0	0	0	0	5	99	100	100
Combined aggregates [%]		5.5	13	22	35	54	68	96	100	100	100

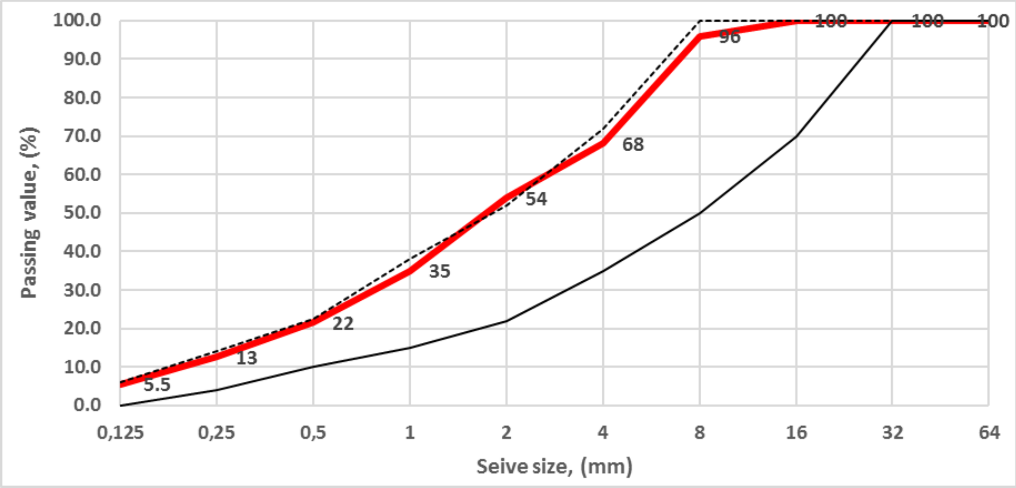

Figure A-4. Combination of aggregates used for strength class C30/37 and 8 mm maximum aggregate size.

APPENDIX B – COMPRESSIVE STRENGTH OF CONCRETE

Table B-1. Compressive strength and density of concrete at 28 days.

Concrete mix		**Compressive strength, (MPa)**		**Density, (kg/m³)**	
		0 min	75 min	0 min	75 min
C30/37	**37-BR-16-F5**	45.8	30.8	2273	2092
	37-BR-16-S3	56.8	35.1	2316	2144
	37-PL-08-F5	45.8	32.7	2285	2125
	37-PL-08-S3	44.2	41.9	2204	2191
	37-PL-16-F5	44.6	40.4	2295	2201
	37-PL-16-S3	49.9	46.7	2318	2260
	37-SR-16-F5	59.3	34.4	2364	2145
	37-SR-16-S3	48.5	39.9	2285	2260
C35/45	**45-BR-16-F5**	48.7	35.1	2270	2119
	45-BR-16-S3	56.8	47.8	2325	2258
	45-PL-08-F5	45.6	42.6	2247	2200
	45-PL-08-S3	50.0	50.5	3231	2216
	45-PL-16-F5	45.6	45.5	2292	2286
	45-PL-16-S3	52.3	58.0	2292	2296
	45-SR-16-F5	52.5	43.6	2287	2196
	45-SR-16-S3	55.9	49.5	2327	2304

Table B-2. Compressive strength and density of concrete with different admixtures at 28 days.

Concrete mix	**Compressive strength, (MPa)**		**Density, (kg/m³)**	
	0 min	**75 min**	**0 min**	**75 min**
BAS-45-BR-16-F5	48.7	35.1	2270	2119
BAS-45-PL-16-F5	45.6	45.5	2292	2286
BAS-45-PL-16-S3	52.3	58.0	2292	2296
FIN-45-BR-16-F5	55.0	61.7	2309	2303
FIN-45-PL-16-F5	46.3	48.2	2313	2280
FIN-45-PL-16-S3	62.4	71.8	2394	2429
GCP-45-BR-16-F5	46.8	60.7	2300	2361
GCP-45-PL-16-F5	62.1	73.4	2342	2367
GCP-45-PL-16-S3	55.6	67.1	2337	2389
HAB-45-BR-16-F5	60.2	55.6	2360	2355
HAB-45-PL-16-F5	62.8	48.3	2325	2220
HAB-45-PL-16-S3	57.8	60.8	2361	2360
MAP-45-BR-16-F5	57.6	63.6	2339	2298
MAP-45-PL-16-F5	50.3	58.7	2323	2325
MAP-45-PL-16-S3	56.6	63.2	2334	2358
SEM-45-BR-16-F5	55.2	51.3	2260	2233
SEM-45-PL-16-F5	40.8	46.5	2249	2239
SEM-45-PL-16-S3	55.3	60.7	2300	2331
SIK-45-BR-16-F5	55.0	56.7	2288	2280
SIK-45-PL-16-F5	49.1	63.5	2277	2390
SIK-45-PL-16-S3	55.3	60.7	2300	2331

Lately, elevated air contents up to 15% have been observed in Finland. To investigate air content elevation, Robust Air contract research project was established at Aalto University. Aim of the project was to secure the stability of the protective pore system in normal conditions.

The research includes laboratory tests and some tests in the Finnish concrete industry. In the laboratory tests, the concrete properties were altered and combinations of different concrete admixtures were investigated.

Results show that the mixing process of the air-entrained concrete is not necessarily effective enough. It is possible that only part of the entrained air is formed during the mixing process and there is a risk for elevated air content when the concrete is mixing in the concrete truck.

Recommendations were given to minimize the risk for elevated air contents including development of admixtures, concrete mixers, quality control systems and requirements of frost resistance concrete.

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