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Teemu Ojala

Analyzing the air-entrainment of fresh concrete with an acoustic measurement system

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Author Teemu Ojala

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Abstract

Increased air contents have been reported from the drilled samples of finished concrete structures lately in Finland. The biggest air contents have been measured to be over 15 percent which are resulted in inadequate compressive strengths in the structures. Because it has been found that the air-entrained bubbles are very sensitive, a proper quality control for the whole supply chain in the production of concrete is highly recommended. By improving the quality control these defects could be noticed sooner, which would decrease the expenses from the follow-up repair procedures. The quality control of the concrete is mainly based on old measurement methods that are laborious and time-consuming. The digitalization of the measurement equipment would offer continuous quality control monitoring that could be integrated into automatic defect detecting systems in the future.

This thesis analyses the air-entrainment of fresh concrete using an acoustic measurement system called CiDRA AIRtrac. The system allows measurements in real-time directly in a rotating mixer. The air amount measurements are based on the speed of the sounds where the increased air content leads to a slower travel time in bubbly liquids. Measuring the air amount in a mixer is effortless and fast when compared to the traditional methods that are meant for fresh concrete. On this research, the AIRtrac technology was found to measure the air amount of the fresh concrete accurately when the minimum requirements were met. The biggest factors that affected the measurement precision were the batch size and workability of the concrete. However, these limitations should not affect the measurements outside the laboratory environment where the mixers are used on higher capacity. Even though the traditional methods give more precise measurements, the integration possibilities with digital interfaces makes them applicable for future saving time and labor.

In addition, the continuous measurement opens new possibilities in the development of concrete additives. By analyzing the air content continuously, the technology gives an additional information about the effects of different admixtures that could not be received using older measurement methods. Furthermore, the collected data gives a visual representation of the air development that can be used in analysis of different mixers. The effects of the mixing energy and sequences using concrete chemicals could be also analyzed.

Keywords fresh concrete, air content, air-entrainment, real-time measurement

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Työn nimi Huokostuksen analysoiminen akustisella mittausjärjestelmällä tuoreessa betonissa

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Tiivistelmä

Valmiiden betonirakenteiden laadunvarmistuksen yhteydessä ollaan huomattu, että ilmamäärät ovat olleet huomattavan korkeita. Tämä on aiheuttanut painetta selvittää, mistä nämä nousseet ilmamäärät johtuvat ja miten niistä päästäisiin eroon. Parantamalla laadunvalvontaa tällaiset virheet voitaisiin myös huomata paljon aikaisemmin, ja pahimmissa tapauksissa voitaisiin säästyä rakenteiden korjaustoimenpiteiltä. Betonin laadunvalvonta perustuu kuitenkin tällä hetkellä pääasiassa vanhoihin mittausmenetelmiin, jotka ovat työläitä ja hitaita suorittaa. Mittausmenetelmien digitalisointi tarjoaisi myös mahdollisuuden jatkuvaan betonin laadunvalvontaan, jota voitaisiin automatisoida niin, että poikkeavat arvot huomattaisiin automaattisesti jo tuotantoketjun aikana.

Diplomityössä analysointiin tuoreen betonin ilmahuokostusta käyttäen akustista mittausjärjestelmää. Tämän järjestelmän nimi on CiDRA AIRtrac, joka mahdollistaa reaaliaikaisen ja jatkuvan ilmamäärän mittauksen suoraan betonisekoittimesta. Mittaus perustuu äänennopeuden vaihteluun betonimassassa, jossa äänennopeuden hidastuminen johtuu kasvaneesta ilmamäärästä. Tämä mahdollistaa nopean ja vaivattoman tavan mitata ilmamäärää verrattuna perinteisiin ilmamäärän testausmenetelmiin. Laboratorio-osuudessa testattiin monia erilaisia ilmahuokostettuja betoneita vaihtelevilla ominaisuuksilla käyttäen AIRtrac:a, jonka tuloksia verrattiin paine- ja tiheysmenetelmän tuloksiin. Työssä huomattiin järjestelmän olevan verrattain tarkka, kun valmistajan antamat minimivaatimukset täyttyivät. Päätekijät hyvälle mittaustarkkuudelle olivat laboratoriossa betonin määrä sekoittimessa sekä sen työstettävyys. Vaikka perinteisillä menetelmillä saatiin hieman tarkempia mittaustuloksia, niin digitaalisten laitteiden mahdollistama automaattinen laadunvalvonta tekee niistä tarpeellisia tulevaisuuden laadunvalvonnassa.

Reaaliaikaisen mittauksen avulla voidaan myös analysoida tarkemmin huokostimen ja muiden lisäaineiden vaikutuksia suoraan tuoreessa betonimassassa. Jatkuvan mittauksen keräämistä mittausarvoista voidaan piirtää kuvaajia, joiden avulla voidaan helposti nähdä mahdollisia ongelmakohtia ja optimoida eri sekoittimien ja lisäaineiden yhteistoimintaa. Tämä tarkoittaisi muun muassa erilaisten sekoitusenergian ja -sekvenssin aiheuttamien erojen vertailua betonin lisäaineiden kanssa.

Avainsanat tuore betoni, ilmamäärä, huokostus, reaaliaikainen mittaus

Preface

In this study, a series of air-entrained concretes were analyzed using an acoustic measurement system in a collaboration with the Robust Air contract research project. The goal of the project was to secure the stability of the protective pore system in normal conditions. This means that the air content or pore size distribution would not significantly change after the concrete is mixed.

The Robust Air project contained three parts having an emphasis on the laboratory tests that were integrated to the experimental work for this thesis. The CiDRA AIRtrac was used on all the concretes that were tested on the project. The large amount of the concretes that was tested during the project played a major role in the collection of the measurement data that was used both in the Robust Air project and this thesis. While this thesis focuses on the analysis of the accuracy of the measurement data of the CiDRA AIRtrac, the project aims to explain the observed phenomena that were found during the testing.

The laboratory tests were carried out between the April and July of year 2017. The tests were done in the concrete laboratory of Department of Civil Engineering, Aalto University, Finland.

Special thanks belong to my supervisor and advisor Jouni Punkki, the participants
of the Robust Air project, namely Fahim Al-Neshawy, and the personnel of the civil engineering department who participated in the extensive experimental work.

Espoo, October 2017
Teemu Ojala

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Abbreviations

AEA	air-entraining agent
PCE	polycarboxylate ether
SP	superplasticizer
w/c	water-cement ratio
QC	quality control
HSC	high strength concrete
ME	Microsoft Excel
COD	Coefficient of the Determination
Sr	a repeatability value representing imprecision
r	a repeatability value
SR	a reproducibility value representing imprecision
R	a reproducibility value
IoT	Internet of things

1 Introduction

1.1 Background

The intentional air-entrainment of concrete was introduced in the 1930s. Since then, the air-entrainment has become recommended for nearly all concretes with a key intent of improving freeze-thaw resistance of the hardened concrete. This frost resistant concrete is produced typically by adding an air-entraining agent (AEA) admixture to the concrete during the mixing process. The AEA stabilizes the air bubbles formed during the mixing process and prevents them from coalescing. Furthermore, the adequate dispersion and distribution of the air-entrained voids is attained by using these AEA admixtures. (Kosmatka, et al., 2002)

The air bubbles have significantly smaller diameter than so called entrapped air voids that form in all concretes during the homogenization of the basic components. The air-entrainment has multiple additional beneficial effects on the concrete properties such as decreased risk of bleeding and resistance to deicing chemicals. In addition, the entrained fine air bubbles not only increase the free-thaw resistance but also increase the workability of the concrete. (Kosmatka, et al., 2002)

On the other hand, the air bubbles caused by the air-entrainment process are very sensitive. Many factors affect the air void system in the concrete such as chemical admixtures, mixer type and mixing time. Moreover, the final air content in the hardened concrete is influenced by multiple factors in the whole supply chain such as transportation, pumping and compaction. (Yang, 2012)

Achieving the target air amount in a final structure is extremely important. Since the air amount is directly proportional to the final strength, increased air amount leads to the strength loss of the concrete. On the other hand, too small air content could make the concrete vulnerable to the freeze-thaw deterioration. The purpose of this work is to compile all the available testing methods for measuring the air amount of fresh concrete and compare the results to of a newly introduced measurement technique to the commonly used measurement methods.

1.2 Demand for the research

The current trend of increasing air contents in the finished concrete structures has put pressure on the investigation of the stability of concrete air-entrainment. There are many factors that affect the stability of the air-entrainment in concrete. For example, using new types of admixtures might lead to different challenges in securing the stability of the concrete. Previously, one of the problems has been the decreasing air contents after the initial mixing of the concrete during the transportation and casting. On the contrary, using certain air-entraining agents (AEA) in combination of newer polycarboxylate ether (PCE) based superplasticizers have shown increasing air amounts even though foam killers have been added to the PCE superplasticizers. (Al-Neshawy & Punkki , 2017)

Furthermore, one of the factors is the quality control (QC) of the concrete. The precautionary quality control is mainly based on compressive strength of hardened concrete samples, calculated water–cement (w/c) ratio and measured air amount in the fresh concrete. These testing methods that are related to these parameters are inconvenient and time-consuming in practice. The growing need for fast and reliable measurements demands new measurement techniques that would be impossible to achieve with the traditional methods.

It should be noted that the final air amount in the finished concrete structure is a sum of all the components in the whole supply chain. Therefore, monitoring the air content of concrete as a part of quality control is important from the initial mixing phase to the final moulding phase. The need of continuous quality control makes the digitalization of the measurement necessary making traditional methods unsuitable. Digitalization of the testing methods allows automated real-time monitoring through-out the supply chain, which could even replace the time-consuming and manual tests that are done now.

1.3 Purpose

This work aims to analyze air content of the concrete using an acoustic measurement system that is called CiDRA AIRtrac. The AIRtrac measures the air amount in real-time directly in the mixer while the concrete being mixed. The measurement results from the AIRtrac are compared to the measurements gathered by traditional methods which are commonly used for measuring the air content in fresh concrete.

The continuous measurement of AIRtrac opens new possibilities in analysis of the air-entrainment process. Therefore, this work aims to additionally investigate the behavior of different AEAs and PCE based superplasticizers (SP) during a pro-longed mixing that simulates the transportation of the concrete in a concrete struck.

1.4 Scope of the research

This work gives a brief literature overview about the air-entrainment of the concrete and different testing methods that are used in the analysis of the air-entrainment in fresh concrete. Afterwards, an experimental work was carried out using CiDRA AIRtrac and other traditional testing methods for fresh concrete. The experiment included over 60 concrete batches that were divided into three different series depending on their properties. Then, the results of these different series were analyzed statistically. Because a total amount of the measurements in each of the series was rather large, it allowed an adequate amount of observation points giving good basis for a more statistical analysis approach.

The materials used in the research are readily available in Finland where the testing was executed. The ingredients of the concretes were mostly produced in Finland. One of the three cements and some of the admixtures used in the experimental work were imported to Finland. However, all the ingredients are commonly used in Finnish concrete industry. The variety of the ingredients allowed a wider spectrum of analysis. On the other hand, the variables in the mix designs were kept as low as possible during the experiments.

The experimental work consisted of air-entrained concretes that are commonly suggested to be used in structures directly exposed to deicing salts and freezing temperatures. The exposure classes for these conditions are XF2 and XF4 (BY 65, 2016). In addition, the w/c ratio was kept low (0.33–0.40) with all concrete so that the concretes would have a relatively high admixture amounts with a possibility of exaggerating the effects of these additives.

All the concrete batches were mixed in the same pan-mixer where the sensor probe of the CiDRA AIRtrac was installed. In addition, the mixing procedure and the testing procedures for each measurement method was kept the same. The AIRtrac measured the air amount continuously in the mixer while measurements using the traditional methods were executed according to the measuring procedure. For the method comparison analysis, the measurement values for AIRtrac were calculated afterwards using the data that was collected during the experiments.

1.5 Limiting factors

The measurement unit of the AIRtrac must be installed to a stationary walled-mixer, which restrained the usage of the new system to one mixer. Because the air-entrainment process is dependent on the mixer type, the results might differ when using different kind of mixers. For example, a more efficient mixer that outputs more energy to the concrete mass in the same time amount, breaking the air voids into smaller bubbles faster, could give an accelerated air-entrainment development.

Moreover, the sheer amount of the concrete mixes with different admixtures limited the amount of repeatability tests when investigating the air-entrainment in real-time. On the other hand, the accuracy comparisons of the test methods were mainly focused on the comparison of the point measurements and not in the similarity of the required data over time when using exactly same recipe repeatedly. In other words, the analysis compared the differences of the point observations even though they are inevitably related.

A total of 63 concretes batches were tested during the experimental work. The target air was kept between 5–6.5 % and workability classes were S3 or F5. Having such many batches forced the acceptable air amounts and workability classes exceed the initial target values. In majority of the concretes, the initial air amount, just after the first mixing, was allowed to have an error of about ±1 percentage points. However, because the total time of the experiments were pro-longed, lasting 60 or 75 minutes, the properties of the concrete changed considerably over-time. This in turn, made the target values feel less important since the main goal was to get as many get observation points as possible that were carefully measured and distributed evenly in the whole measurement range.

The w/c ratio of all the concretes that was mixed in all the series was between 0.33 and 0.38 percentages. Having such a low w/c ratio may have exaggerated the effects of the superplasticizer even the total amount of the admixtures was relatively high. In addition, the SP was mostly responsible for the plasticity of the concrete during the experiments. Because the air-entrainment and workability are affected by the co-operation of AEA and SP, the results were affected significantly by different brands and their combinations. However, majority of this work studied only the relationship between the method results, which should not be affected by the brands of the admixtures. The temperature of the concrete laboratory and ingredients used in the experiments was kept constant at room temperature of 20 °C. In addition, the tap water used in the concrete was common by city of Espoo having temperature approximately of 20 °C.

2 The role of air-entrainment in concrete

2.1 *Air-entrainment in concrete*

2.1.1 Principals of air-entrainment in concrete

The main purpose of the air-entrainment of concrete is to prevent the deterioration caused by the freeze-thaw (FT) cycles. During the past decades, many theoretical models have been presented on how the concrete deteriorates from the FT cycles. Even the amount of the models suggests that the deterioration process is a complicated process where one or more factors affects the process. (Kuosa & Vesikari, 2000)

Most commonly frost deterioration is explained by a hydraulic pressure model where the deterioration of the concrete is due to expansion of water in the cement paste when the water in capillary pores freezes. When a dilation pressure exceeds the tensile pressure of the concrete the cracking occurs. These repeated FT cycles have a cumulative effect on the concrete. There are two sources that causes the dilating pressure, namely the freezing of the excess water in the cavities and the diffusion of water in the concrete. (Powers, 1956)

Larger voids that are usually filled with air are not subjected to freezing. The phenomenon starts from largest pores and moves into smaller capillary pores where the gel water freezes. To prevent this from happening, the volume of the capillary pores should be minimized so that the freezable water in the concrete would not exceed the volume of the entrained air voids. (Powers, 1956) These entrained voids are much smaller that unintentionally entrapped air voids. Typically, the size of the entrained air bubbles is significantly smaller than other air voids having an expected diameter of 10 – 1000 µm. (Whiting & Nagi, 1998)

The air-entrained concrete has normally an air volume of 4–8 % of the concrete while normal concrete has only air amount of 1–2 % depending on the properties of the aggregates and other additives. Some special concretes might have even lower (< 1%) air content such as High Strength Concrete (HSC). In addition, air-entrained bubbles should have proper size distribution and distance to each other to have function as intended. (BY 65, 2016) While the air-entrainment functions as a defense again deterioration it decreases the overall strength of the concrete. As seen in the Figure 1, a one percent of air in the concrete relates to about five percent of the final strength loss. (Wright, 1953)

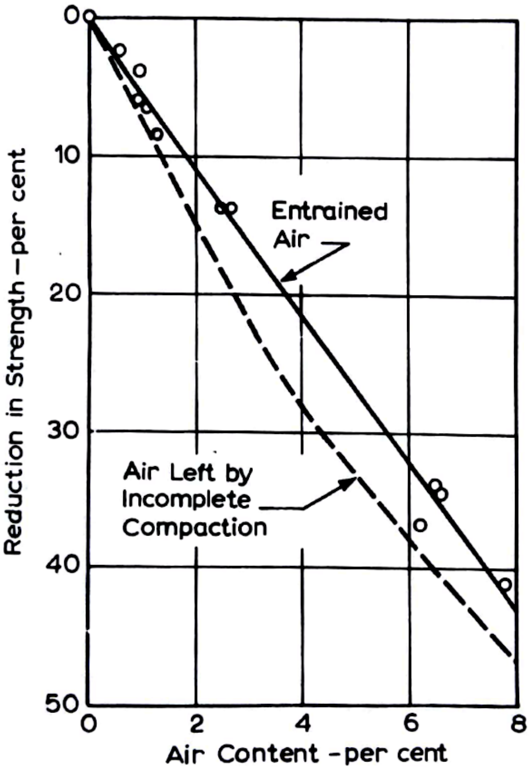


Figure 1. Effect of entrained and accidental air on the strength of concrete (Wright, 1953).

Air-entraining admixtures are added to the concrete to stabilize the microscopic air bubbles that are introduced by the motion of the mixer. The bubbles are formed when the shear forces of the paddles break the air voids into small air-void system. The AEAs are surface active substances that decrease the surface tension between the water and the air increasing the probability of the formation of the air bubbles. However, the main function of the AEA is to stabilize the small air bubbles binding them next to the cement particles. An illustration of this AEA mechanism in concrete is shown in the Figure 2. The hydrophobic end of the AEA is oriented towards the air bubbles and the hydrophilic head towards the cement particles. (Whiting & Nagi, 1998)

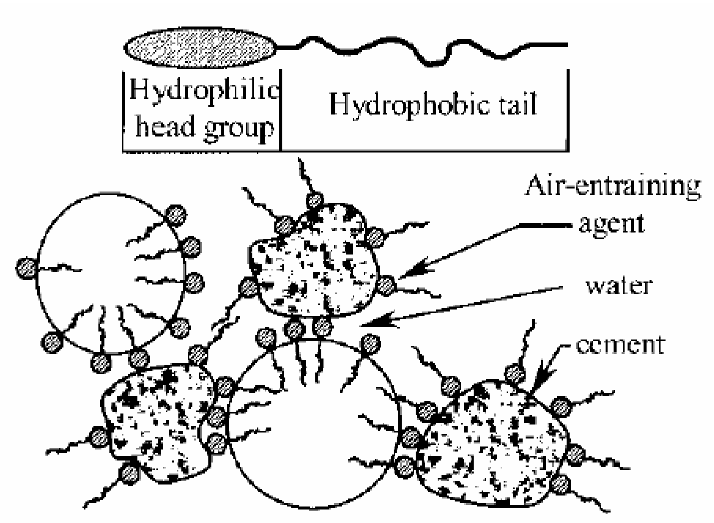


Figure 2. Illustration of the AEA mechanism (Ansari, et al., 2002).

Increasing the dosage of the AEA enables a bigger surface area that can be stabilized. On the other hand, the increased stabilization capacity allows for not only larger amount but also larger total surface area of the air bubbles that might change the distribution of the bubbles to the worse. Because of this, the AEA dosage should not be increased without a specific reason. (Kuosa & Vesikari, 2000)

Generally, a good AEA should:

- form an elastic film to the boundary of the air and water
- reduce the surface tension
- prevent the transfer of the air through the boundary layer
- sustain the properties over-time
- bond the air-entrained bubbles into the cement particles
- not affect essentially to the properties of concrete (Pigeon & Pleau, 1995).

2.1.2 Factors affecting the air-entrainment in concrete

The air bubbles are formed when the concretes is initially mixed. The motion of cement paste and aggregates split the trapped air into smaller bubbles that are stabilized by the AEA. Therefore, the mixer plays a key role in air-entrainment process and ensuring the uniformity of the finished product. The specifications of the mixer such as the total number of revolutions and their speed have an effect in the mixing time. Other factors are the size of the batch in relations to the capacity of the mixer drum and the design and condition of the mixer itself. The mixing procedure may have negative effects. For example, a simultaneous batching sequence lowers the air content. Running the mixer only on partial or minimum capacity may have negative effects on air-entrainment. (Kosmatka, et al., 2002)

Many properties of the concrete affect the air-entrainment process and the air amount in the mixed concrete. Because the air bubbles are formed in the water of concrete, having low w/c ratio makes the entraining air more difficult. However, higher w/c ratios can reduce the durability of concrete because the air voids come coarser. Furthermore, higher temperature increases the size of the bubbles making them unstable and more likely to lose air. (Kosmatka, et al., 2002)

In addition, the following ingredient properties will have effects on air content:

- alkali content of cement
- fineness of cement
- cement content in mixture
- maximum aggregate size
- sand-to-total aggregate ratio
- sand grading
- water chemistry (Kosmatka, et al., 2002).

The purpose of the water-reducing admixture is to produce concrete with a certain workability at lower w/c ratio that would not otherwise be possible. The first organic materials that increased the fluidity of the concrete were made in the 1930s. (Rixom & Mailvaganam, 1986)

The water-reducing admixtures have an effect on the air-entrainment of concrete. Certain SPs that are particularly based on the melamine and naphthalene formaldehyde sulphonates, increase the dosage-demand of the AEA to compensate the loss of the air bubble caused by the water-reducer. This can be due to a deliberate measure or a side effect of the loss of surface tension in the concrete. (Rixom & Mailvaganam, 1986)

The admixtures used in the experiments were polycarboxylate ether based superplasticizers that drastically reduce the water-demand and are most commonly used in concrete production in Finland. Before these new admixture, problems with the air stability were noticed, which caused the concrete to lose the air while transferred into construction site. However, it has been now noted that these newer SPs tend to hold or even increases the air amount too well compared to previously used admixtures. (Al-Neshawy & Punkki , 2017)

The workability of the concrete is related to the air amount. The concrete loses its plasticity progressively with time as the hydrations process consumes the water. Furthermore, all the steps after the mixing affect the workability negatively. (Rixom & Mailvaganam, 1986) While the air-entraining increases the workability when the air bubbles act as like small grains decreasing the friction between the concrete particles, the sudden loss of the air content might affect the workability and homogeneity of the concrete. In addition, a sudden increase of the workability might lower the capability of the concrete to hold the previously stabilized air bubbles apart from each other, which might lead to a sudden air loss after the workability change.

2.1.3 Background of air measurement techniques

The success of the air-entrainment is usually described using attributes such as air amount, the specific surface area of the air voids and the distribution of the voids. These attributes are related to each other by the size distribution of the air voids. Air amount is described as an air volume percent in the concrete meaning that the measured air amount includes both the entrained and the entrapped air. The amount of the entrapped air is related to the workability of the concrete and the intensity of the compaction. (Kuosa & Vesikari, 2000)

The testing methods that were introduced in this chapter are work intensive and user sensitive. Because the methods are laborious and need a special equipment, most of the quality control tests are made in the concrete factory. This leaves the rest of the supply chain of the concrete unconsidered. Even though the air amount is within the limits, the air content might change during the transportation and casting. For example, air amounts of six percent have been measured in the mixing site, but in the construction site, the air might have increased to 10 percent. Furthermore, the drilled samples have shown over 15 percent air content in finished structures that can be two and a half times more than originally intended. This leads to reduction of the compressive strength and other mechanical properties of the completed structure.

The lack of the constants governs the concrete industry. Moisture content of the aggregates is continuously changing over-time. The moisture in stockpiles differs even though the weather conditions stay about the same. Further in the production line, the mixing of the concrete tends to be as quickly as possible, which might lead to unstable concrete mix. The improper mixing for certain admixtures might be one of the reason to the increased air amounts in finished concretes. Joint use of AEAs and SPs may have unwanted effects that makes the examination of the additives essential not only in the mixing site but only over-time. These effects should be emphasized when new admixtures and their combinations are used in concrete.

While this work focuses on analysis of the air amount in the concrete, ensuring the frost resistance of the concrete should take all the attributes such as including the distribution of the air voids or their size consideration. However, many of the testing method are limited strictly to air amount measurement. The measurement methods the air amounts are represented using mainly the American standards but the principals are the same in the European standards. In the experimental work, the tests were executed using European standards.

2.2 Measurement methods for air content in fresh concrete

2.2.1 Pressure method

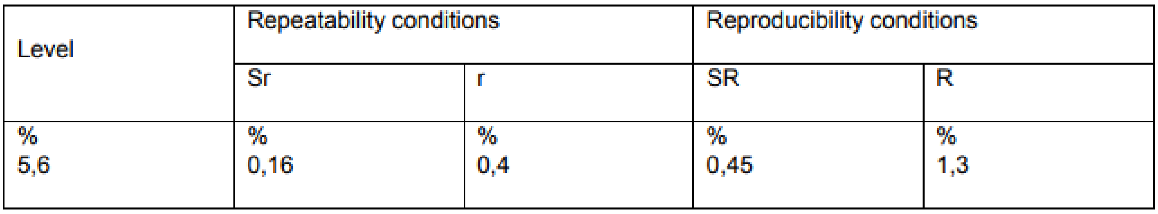
According to *ASTM C 231 Standard "Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method"* standard, the pressure method is the most common test to measure the air content in fresh concrete and is based on the Boyle's law. The method has stayed the same over decades and consists of releasing pressurized air into pot that is filled with compacted concrete and filled up with water. Pressure method measures both the entrained and the entrapped air in the fresh concrete and does not give information about size distribution of the air bubbles. Nevertheless, it is one of the most common quality control method that can be executed virtually everywhere. The pressure method was conducted according to the European standard *SFS-EN 12350-7 – Testing fresh concrete. Part 7: Air content.* The Picture 1 shows the equipment used in the pressure method test.

Picture 1. Pressure method equipment used in the experiments

The reading from the pressure pot might not represent the true air content value since there is always measurement error from accuracy and precision induced by the instrument. This means that measured values may not give the true values and can be very user-dependent. Moreover, the preparation of the reading in labor intensive and is sensitive to user error. Taking a descriptive sample and proper compaction will have a notable effect on the reading of the final measurement value.

Moreover, the measuring accuracy of the air pot is limited because of the different accuracy over the measurement range. Usually the error increases as the air amount increases. The standard *SFS-EN 12350-7 – Testing fresh concrete. Part 7: Air content. Pressure methods* standard gives precision data about the water column method that is shown in the Table 1. Because pressure gauge method includes many same elements as the water column method, the data can be used for predicting the precision of the gauge method also.

Table 1. Precision data for water column method given in the standard *SFS-EN 12350-7.*



Level	Repeatability conditions		Reproducibility conditions	
	Sr	r	SR	R
% 5,6	% 0,16	% 0,4	% 0,45	% 1,3

Furthermore, in the table, the imprecision of the measurement method is descripted using derivations of the standard deviations, notated as Sr and SR, where a smaller value means better precision. The repeatability value (r) tells the difference between two test results from the same sample by one operator using the same apparatus within the shortest interval time feasible. The difference should not exceed the value of r on average not more than once in 20 cases in normal conditions. Furthermore, the reproducibility value of R tells the likelihood of exceeding the reproducibility value on average not more than once in 20 cases in normal conditions when two operators use their own apparatus on the same sample obtained within the shortest feasible time interval.

2.2.2 Volumetric method

Volumetric method (Picture 2) determines the air content of freshly mixed concrete. According to the *ASTM C 173 "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method"* standard, unlike the pressure method, the measurement is not affected by the air present inside the porous aggregate particles. This makes the volumetric method especially more suitable for concretes containing light-weight aggregates or other atypical aggregates than the pressure method.

Picture 2. Volumetric air meter. (Kosmatka, et al., 2002)

On the other hand, the method is more technically demanding. Having a need to use a sufficient addition of isopropyl alcohol and checking if the foam is present makes the method less streamlined. Using a Roll-o-meter bowl a fresh concrete sample is firstly consolidated to a bowl that is then filled with water and alcohol until the bowl is full. Secondly, the bowl is agitated, stabilized and finally a measurement value is read from the scale.

2.2.3 Gravimetric method

Gravimetric method is used to determine the air amount in fresh concrete using a unit weight of the concrete sample. The actual air content is then calculated from the initial values. The calculation procedure was done according to the *ASTM C 138 "Standard Test Method for Density (Unit Weight), Yield and Air Content (Gravimetric) of Concrete"* standard.

The Equation 1 and 2 shows how the air amount is calculated from the unit weight.

$$Air\ content, A = \frac{(T-D)}{T} \cdot 100 \tag{1}$$

where the A is the air content is the concrete (%), D is the density (unit weight) of the concrete (kg/m^3) and T is the theoretical density of the concrete computed on air free bases (kg/m^3).

$$T = \frac{M}{V} = \frac{M}{1 - A_t} \tag{2}$$

where the M is the mass of the all materials in batch (kg), V the absolute volume of the component ingredients in the batch (m^3) and A_t is the target air content of the batch (m^3).

Combining the equations 1 and 2 gives the Equation 3 where all the variables are known.

$$Air\ content, A = \left(1 - \frac{D}{M} + \frac{D \cdot A_t}{M}\right) \cdot 100 \tag{3}$$

2.2.4 Chase Indicator

Chase indicator *(AASHTO T 199, Standard Method of Test for Air Content of Freshly Mixed Concrete by the Chace Indicator)* is a simple and inexpensive technique to check the approximate air content in fresh concrete. A brass cup is filled with mortar sample from the fresh concrete that has a maximum particle size of 10 mm. A glass indicator is inserted to the cup that is then filled up with alcohol and agitated with rolling motions. Afterwards, a measurement is read from the indicator and the value is corrected with the tables given in the standard. However, this method should not be used as a substitute for more accurate measurement methods because the sample size is so small giving only a semi-quantitative information about the air content.

2.2.5 Air Void Analyzer

An Air Void Analyzer (AVA), shown in the Picture 3, can be used to measure the air-void structure while the concrete is still fresh. Giving information about air content, specific surface and spacing factor the testing method gives more information as rest of the fresh concrete testing methods. However, the testing method takes time about 25 minutes or less which is considerably more than the other traditional methods.

The spacing factor and the specific surface are determined typically according to *ASTM C 457 "Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete"* standard. However, the standard requires a sample from the hardened concrete that is prepared properly.

Picture 3. The equipment used in an air-void analyzer. (Kosmatka, et al., 2002)

The AVA method utilizes the Stoke’s Law in the measurements. The air bubbles in the mortar samples are transferred to a release liquid. The release liquid releases then the bubbles through a column of water where larger bubbles rise faster than smaller bubbles. The rising bubbles are then collected under a plate which weight is monitored. The weight is recorded over-time from which the distribution of the air bubbles along with the other attributes can be calculated afterwards.

3 Experiment work

3.1 *Concrete mixes*

3.1.1 Available aggregates

The concrete mix designs were made using six different aggregate sizes that were available in the laboratory. The specifications of these aggregates can be seen in the Table 2. The aggregates were washed natural granitic gravel that were dried. In addition, the aggregates were sieved to make a grading curve that was used in the concrete design. A total of four combined aggregates were designed to accompany the selected strength classes and maximum aggregate sizes that can be seen in the Appendix 1. The coarse gravel was not used in the concretes that had the maximum aggregate size of 8 millimeters.

Table 2. The specification of the aggregates available in the laboratory.

Aggregate type	Diameter (mm)	Moisture content (%)
Sand	0.1 – 0.6	0
	0.5 – 1.2	0
	1 – 2	0
Gravel	2 – 5	0
	5 – 10	0
Coarse Gravel	8 – 16	0

3.1.2 Cements used in the mixes

The Table 3 lists the three different types of cement that were used in the designed concretes in the experimental work. Two cements, namely Plus cement and SR cement, were produced in Finland by Finnsementti. The third cement was imported from Latvia and is called RAPID Latvia produced by CEMEX Ltd, Broceni in Latvia.

Table 3. The cement types used in the experiment work.

Cement name	Cement type	Concrete code
Plus cement, Finnsementti	CEM II/B-M (S-LL) 42,5 N	PL
SR cement, Finnsementti	CEM I 42.5 N – SR3	SR
RAPID Latvia, Broceni, Cemex	CEM I 52.5 N	BR

3.1.3 Mix designs of the concrete

The concretes used in the experiments were designed to have typical amounts of materials to be used in bridge construction where cement and superplasticizer amounts are rather high. Since the laboratory aggregates need less water than aggregates in typical concrete industry, the w/c ratios used in concrete designs are slightly lower than normal.

The mix designs for the concrete can be seen in the Appendix 2. The designed concretes can be divided into following categories:

- by the compressive strength and P-factor of the concrete C30/37- P30 and C35/45-P50
- by consistency of the concrete using workability classes of F5 and S3
- by maximum aggregate size of 8 and 16 mm
- by three cement types.

The designed concretes were coded using a system seen in the Figure 3. It divides the concretes by an admixture manufacturer, compressive strength, cement type, maximum aggregate size, workability class, dosage amount of AEA and initial mixing time.

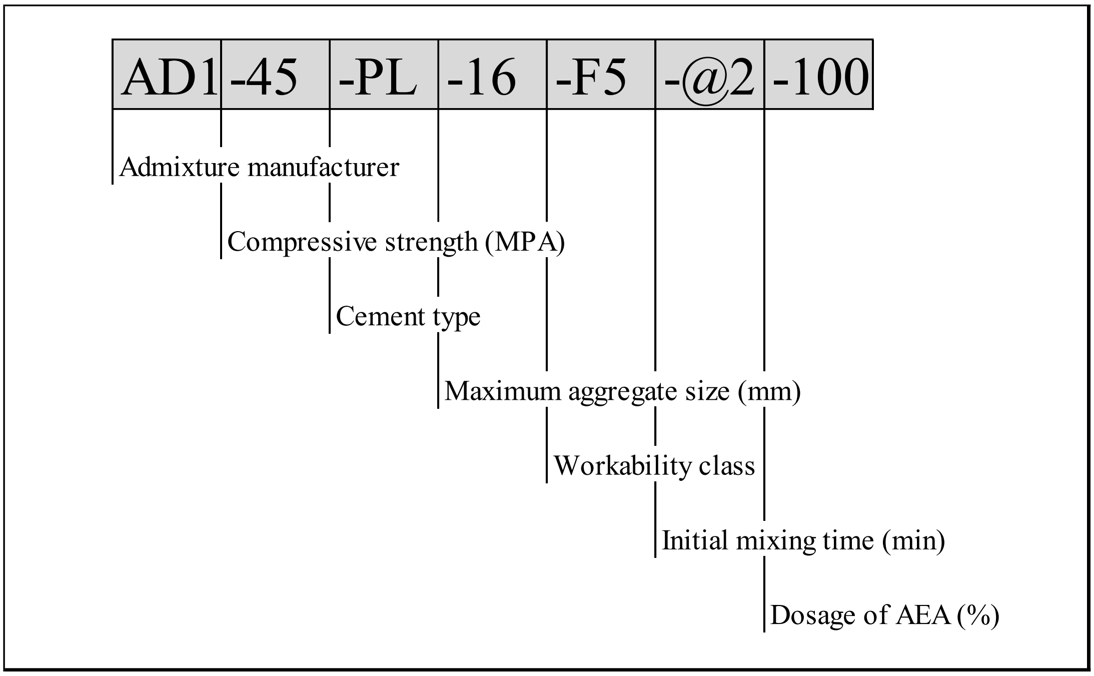


Figure 3. Coding system of the concretes in the experimental work.

All the concretes in this research were designed using the absolute volume equation that can be written in two ways as follows:

$$\begin{aligned}&Absolute\ volume\ of\ the\ concrete\ (m^3)\\&= \frac{Weight\ of\ materials\ (kg)}{Specific\ gravity\ of\ material\ (-)\cdot Unit\ weight\ of\ water\ (\frac{kg}{m^3})}\end{aligned} \tag{1}$$

$$\frac{W_{cement}}{\rho_{cement}} + \frac{W_{aggregate}}{\rho_{aggregate}} + \frac{W_{admixture}}{\rho_{admixture}} + W_{effective\ water} + Air = 1000\ m^3 \tag{2}$$

where W is the weight of the material (kg), ρ is the density of the material (kg/m³) and Air stands for the volume of the air (m³). The absolute volume granular material is a net volume and does not include the voids between the particles.

Achieving the set targets was ensured doing preliminary tests for the target compressive strength, the consistency and the air content for each concrete design.

3.1.4 Admixtures used in the mixes

The experimented concretes used a total of seven type of AEAs and polycarboxylate based SPs produced by different admixture manufacturers. The Table 4 lists all the air-entraining agents and the Table 5 all the superplasticizers respectively. The results are shown using code names AD 1-7 having own assigned to each admixture manufacturer.

Preliminary tests were done using the same AEA and SP by a single manufacturer. The amount of these additives was locked water was changed to reach the target workability classes. For other additives, the w/c ratio was kept constant but the dosages of the admixtures were changes to keep the air amount and slump as constant as possible. The data from the different admixtures where not only used in comparison of the accuracies but also in the periodical mixing simulation.

Table 4. Air-entraining agents used in experimental work.

Admixture code name	Manufacturer	Recommended dosage / binder
MasterAir 100	BASF Oy	0.02 – 0.08 %
ILMA-PARMIX	Finnsementti Oy	0.01 – 0.08 %
PANTAPOR 2020 (LP)	Ha-Be Betonchemie GmbH	0.01 – 0.40 %
Mapeair 50	MAPEI	0.06 – 0.3 %
Master Air 102	Semtu Oy	0.03 – 0.1 %
Sika Air-Pro V5	Oy Sika Finland Ab	0.05 – 1.0 %
Darex AEA T (LP)	GCP Applied Technologies	0.2 – 1.01 %

Table 5. Superplasticizers used in the experimental work.

Admixture code name	Manufacturer	Recommended dosage / binder
MasterGlenium SKY 600	BASF Oy	0.2 – 2.0 %
VB-PARMIX	Finnsementti Oy	0.3 – 3 %
PANTAHIT TB100 (FM)	Ha-Be Betonchemie GmbH	0.2 – 2.20 %
Dynamon SX-23	MAPEI	0.3 – 2.0 %
Sem Flow MC	Semtu Oy	0.2 – 2.5 %
Sikament -RSX (25%)	Oy Sika Finland Ab	0.2 – 2.5 %
ADVA Flow 444-L	GCP Applied Technologies	0.2 – 3.0 %

3.2 *Equipment used in the experiment*

3.2.1 Traditional testing methods

Two types of air measurement methods were chosen to accommodate the real-time air amount measurement of CiDRA AIRtrac which were:

- Pressure method
- Gravimetric method.

The pressure method being the most commonly used test to measure the air amount in the fresh concrete was clear option and was executed following the European standard *SFS-EN 12350-7 "Testing fresh concrete. Part 7: Air content. Pressure methods"*. The gravimetric method was carried out using the *ASTM C 138 "Standard Test Method for Density (Unit Weight), Yield and Air Content (Gravimetric) of Concrete"* standard. The weight of the fresh concrete unit was weighed using the same bowl as in the pressure method. This meant that the precision between the gravimetric and pressure method was minimized since both the methods used the same compacted sample.

Workability was measured using following tests:

- Slump-test
- Flow table test.

The tested concretes were divided into two different workability classes. The S3 represented a stiffer concrete that was measured using the *SFS-EN 12350-2 – "Testing fresh concrete. Part 2: Slump-test"* standard. In turn, the F5 was measured using the *SFS-EN 12350-5 - "Testing fresh concrete. Part 5: Flow table test"* standard. The testing method was kept the same from the first measurement for comparison reasons even though the plasticity of the concrete decreased dramatically over time. The equipment used these tests are shown in the Pictures 5 and 6.

Picture 5. The equipment used in the slump-test.

Picture 6. The equipment used in the flow table test.

3.2.2 Mixer

The CiDRA AIRtrac system requires a mixer that has a stationary drum floor or wall for the installation of the sensor unit. Hence, the system was attached to an older stationary-wall pan mixer (Picture 7) that was available in the concrete laboratory. The one-speed mixer presents a simpler mixer style where the only moving parts are rotating paddles. The paddles rotate about 60 times per minute while the rest of the mixer stays stationary. Because it is important that the basic components are combined as efficiently into homogenous mixture as possible, using another mixer might yield to different results.

The batch size needs to be relatively big so that the sensor probe is covered properly while the concrete is being mixed since the area of the drum is rather large. Moreover, larger batches reduce the risk of improper mixing and have more concrete to testing without losing too much concrete throughout the long experiments. This is because the concrete is contaminated after the procedure of the pressure method and therefore the concrete amount in the mixer decreases from the initial amount over-time if the test procedure contains many testing cycles. In addition, samples for compressive strength decrease the amount in the mixer significantly if they are a part of the experiment protocol.

Picture 7. The pan-type mixer that was used in the concrete batches.

3.2.3 CiDRA AIRtrac

The CiDRA AIRtrac system was used to measure the air amount in fresh concrete in real-time while the concrete is being mixed. The system consists of a sensor, a transmitter and a PC for operation and collecting the data. The sensor probe that holds all the measuring probes was installed directly to a stationary wall pan-mixer. The sensor was attached to the bottom of the mixer bowl as shown in Pictures 8 and 9.

While mixer is running, the sensor will be uncovered a certain amount depending on the batch amount, the workability of the concrete and the mixer type. Because the changes in the depth of the concrete on top of the sensor may have a significant impact on the accuracy of the system it is recommended at least a 15-cm concrete layer on top of the sensor unit at most times. The AIRtrac technology has some minor limitation on measurement quality. For example, very low slump (< 3.8 cm) or w/c ratio (< 0.30) of the concrete can limit measurement quality. If either of these two parameter limits are met, getting a proper measurement can be problematic.

Furthermore, the AIRtrac measures the air amount of uncompacted concrete. This air volume is usually a 1–2 percentage points larger than the compacted concrete that is used on traditional testing methods. The optimal conditions for the measurement are a slow mixing speed where a new concrete sample is introduced continuously, the face of the sensor probe is adequately covered and the mixing motion does not create “bad air”. This bad air is created during fast mixing in combination of admixtures in that mix design and the mixer type. This phenomenon can skew the readings so that the measurements seem to be bigger and add variability to the other test method comparisons.

Picture 8. The CiDRA AIRtrac sensor probe installed to the mixer floor.

Picture 9. The surface of the AIRtrac sensor probe can be seen from the above.

The AIRtrac system measures the air amount acoustically directly in a mixer. The system determines the speed of sound that propagates through the plastic concrete between a sound source and receiver in the sensor probe. The sound source is made of a baffled piston that is driven on a relatively low-frequency. The sound receiver can be put at the same plane because the sound propagates nearly equally to every direction. This makes possible both the source and the receiver to be packaged to a single probe and to be installed to the floor or side wall of the mixer possible. In other words, the system measures the time-of-fight between the source and receiver using a single probe and a known distance. Furthermore, the probe is designed mechanically so that it can withstand the abrasive environment caused by the direct contact of the concrete. (Tregger, et al., 2013)

The speed of sound in bubbly liquids, like concrete, can be described using Wood's model (Wood, 1930). The accuracy of the speed of sound model is shown in slurries and gas-bearing sediment, which makes is applicable to plastic aerated concrete (Wilson, et al., 2008). Because the concrete is mixed in a static pressure and having always some air bubbles, the Wood's model can be reduced to the Equation 4 when the frequency is notably lower that the lowest resonance of the air bubbles (Tregger, et al., 2013).

$$c = \sqrt{\frac{P_a}{\varphi(1-\varphi)\rho}} \tag{4}$$

where, c is the speed of sound (m/s), P_a is the absolute static pressure (Pa), φ is the volumetric fraction of air, and ρ is the density of the concrete slurry (kg/m³).

This reduced Wood's model is dependent only on the static pressure and slurry density making it suitable for most concrete mixing applications. The small variations between the concrete mixes can be generally be ignored. The Figure 4 illustrates how the speed of sound changes as the air content increases. The measured speed of sound is then used to calculate the volumetric fraction of the air in the concrete. A correcting factor can be used to shift the display value closer to the true value or measurements from the other test methods. (Tregger, et al., 2013)

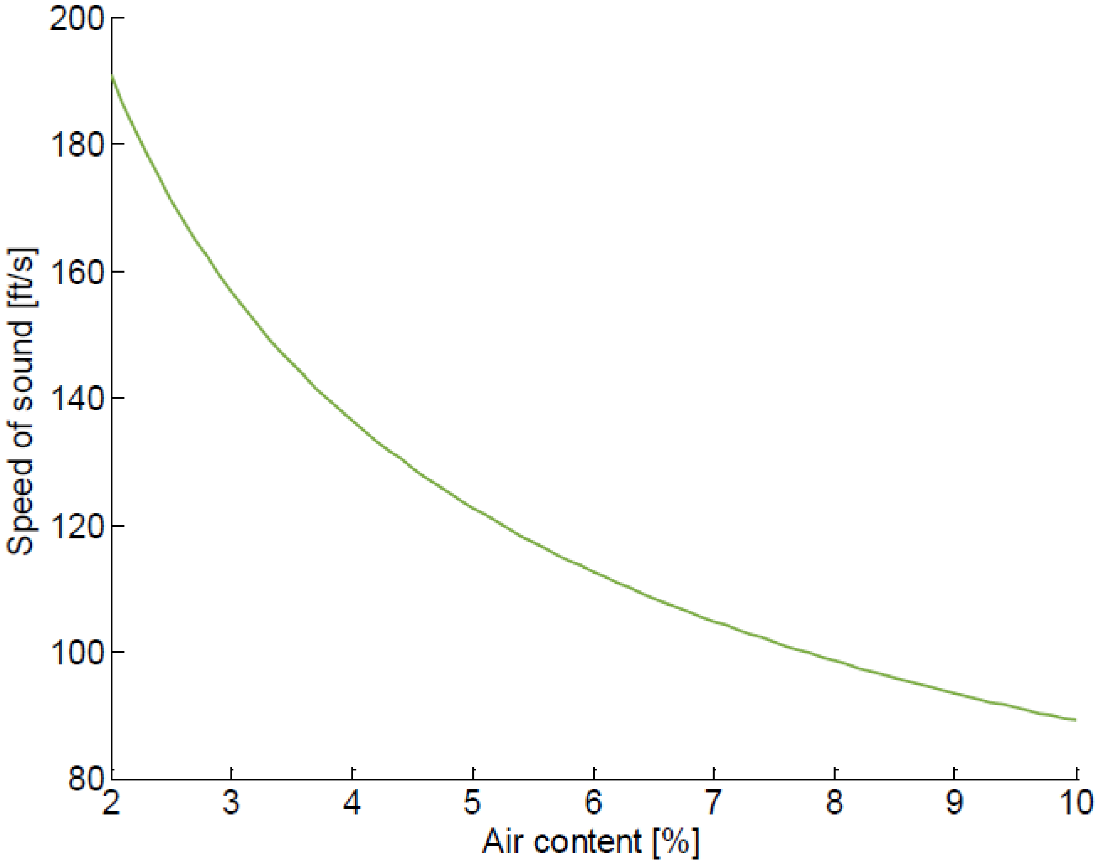


Figure 4. Wood's simplified model for plastic concrete. (Tregger, et al., 2013)

The CiDRA AIRtrac is designed for industrial use where the volume of the production is large and it is important to keep track on the out-going concrete batch by batch. This emphasizes the monitoring of the final air amount with each batch before it is dumped for transportation. On the other hand, the goals can be significantly different in laboratory environment and analysis of air-entrainment. In this research, the main purpose was to compare the measurement accuracy between the AIRtrac and the traditional air measurement methods for fresh concrete. The secondary goal was to analyze the air-entrainment process of concrete using the continuous measurement of the AIRtrac.

In previous research, two types of measurements that are shown in the Figure 5, were used to calculate measurement readings from the collected continuous data. Firstly, dynamic measurements were done representing the air content in the concrete during high speed mixing. These measurements were taken as an average over 10 seconds before the speed of the mixer was changed. Secondly, semi-static measurements were taken presenting the air content in the concrete without mixing. The reading was taken also as an average over 10 seconds but before dumping the concrete from the mixer. Furthermore, a series of repeatability tests were also performed that showed the sensor readings to be quite repeatable as illustrated in the Figure 6. (Tregger, et al., 2013)

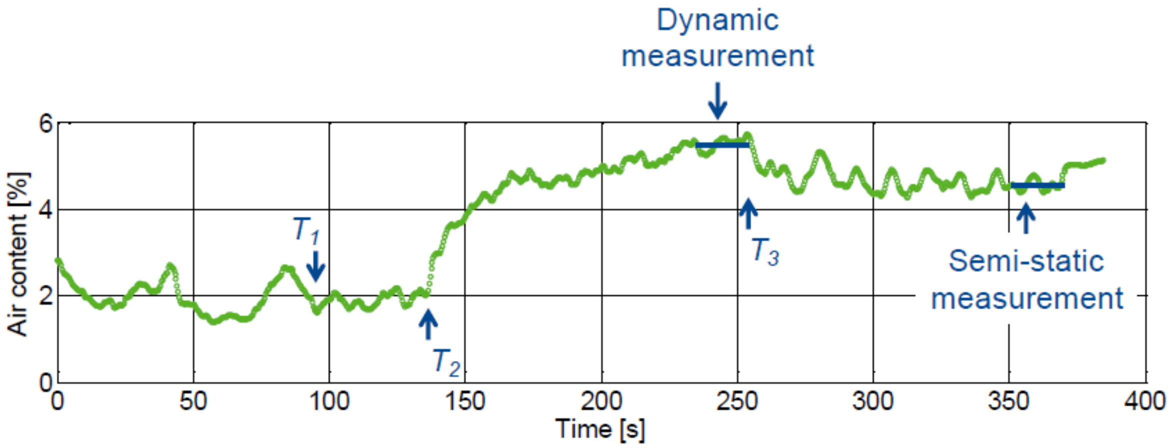


Figure 5. A real-time output from the novel air measurement system (Tregger, et al., 2013).

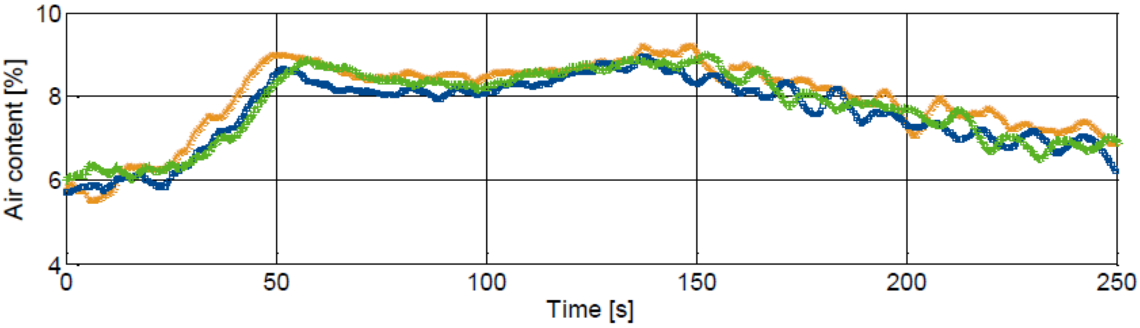


Figure 6**.** Repeatability tests using the air measurement system (Tregger, et al., 2013).

The AIRtrac software provides output files where all the measurement readings during the mixing are collected. Having these consecutive measurement points offers new possibilities in analysis of air-entrainment process when compared to the traditional methods. The AIRtrac was operated through a PC software that was provided with the other equipment included in the CiDRA AIRtrac. The PC (Picture 10) was connected to a transmitter box during the tests and the data was analysed afterwards in Microsoft Excel and IBM SPSS.

Picture 10**.** Operating PC connected to the transmitter box of CiDRA AIRtrac.

During preliminary tests, it was noted that the air amount of the fresh concrete increased rapidly while it was mixed. Because the main purpose of this research was to analyze the accuracy and precision of the AIRtrac by comparing the measurement results, a few calculation measurements types were considered in this research. The fast growth of the air amount led to choosing a shorter dynamic measurement time of 5 seconds that presented more closely the final value before stopping the mixer. In addition, the other measurement type was limited by the mixer that was available to use. Having no choice to change the speed of the mixer resulted in a static measurement where the mixer has just has been turned off. Preliminary tests also indicated that calculating an average over 30 seconds just after the mixer was stopped gave consistent measurement values when compared to the traditional methods.

As a result, two types of air content measurements were done in this research:

1. **Dynamic measurement**, representing the air content in the concrete during high speed mixing. The measurement reading is calculated as a median over 5 seconds before the mixing speed is changed or the mixer is stopped.
2. **Static measurement**, representing the air content in the concrete while the mixer is totally stopped. The measurement reading is calculated as an average over 30 seconds just after the mixer is stopped.

An illustration of the measurements can be seen from the Figure 7. The graph shows the air amount as a function of time when the concrete was initially mixed a total time of 3.5 minutes. The AIRtrac started to collect the data about after two minutes when the concrete was sufficiently homogenous for a good quality measurement. It should be noted that the air amount might not be increasing the whole time during the mixing. Hence, the shape of the graph can vary but the timing principals of the two measurements types stay the same.

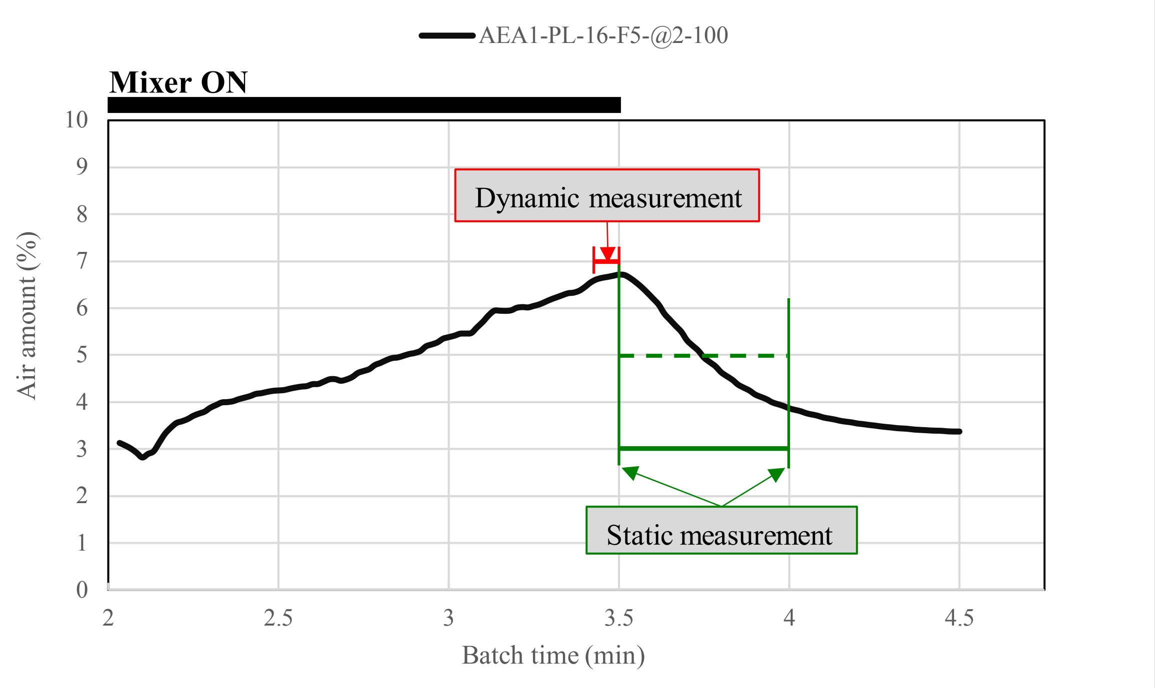


Figure 7. An illustration of the two AIRtrac measurements done after the initial mixing on this research.

3.3 *Experimental work*

3.3.1 Test series in the experimental work

The experiments were divided into three different series as shown in the Table 6. Series A consisted of concretes that had a workability class of S3 having the slump-test measurements vary mostly between 100–150 millimeters. Series B had workability class of F5 and therefore the design target for the flow table test target was between 590–620 millimeters. Series C had larger batch size of 75 liters (+ 25 %) while keeping the workability the same as the series B. In addition, two types of mixing times were used in the analysis of the effects of the mixing time in the series C. This was done to accommodate for the secondary purpose of this work.

The series A was done using only concretes having a workability class of S3. The series B and C focused on the concretes that had notably better workability of class F5. The A and B series contained three cement types and had two maximum aggregate size concretes. The specific amounts of concrete and water for each cement type were chosen so that the strength and workability targets were achieved. The AEA dosage was designed so that the target air amount was achieved after the concretes were mixed 3.5 minutes.

Furthermore, the series C consisted of concretes that had two AEA dosages. It included concretes that had the normal AEA dosage, notated as 100 percent, and concretes having only a 50 percent of the normal dosage. The water amount was kept also constant depending on the workability class and the cement type used even though the AEA dosage differed from each other. Finally, an additional concrete was designed without any air-entrainment for low air amount measurements to accommodate the measurement range better.

Table 6. The test series in the experimental work.

Name of the Series	A	B	C
Workability class	S3	F5	F5
No. of Batches (N)	14	20	29
Batch size (liters)	60	60	75
Target air amount (%)	5.0 – 6.0	5.0 – 6.5	5.5
Cement amount (kg/m³)	400 – 440	400 – 440	425
Effective water amount (kg/m³)	140 – 160	155 – 175	153 – 160
W/C ratio (%)	0.33 – 0.38	0.36 – 0.40	0.36 – 0.38
Dosage of AEA (-)	normal	normal	normal & 50 % of normal

3.3.2 Mixing procedure

To ensure a similar basis for the air-entrainment, it is important to keep the mixing conditions the same. Hence, the same mix protocol was used on every batch during the experimental work. Before the aggregates and the cement were added, the drum was cleaned and wetted if needed so that the starting moisture content of the mixer stayed constant and did not have to dry completely before a new batch. Furthermore, the aggregates were added in the specific order shown in the Table 7. The purpose of this is to maximize the chance for a proper mixing before the liquids are added.

Table 7. The mixing procedure of the ingredients in the experimental work.

Added Material	Mixing time
R 2 - 5	Filling up the mixer
R 5 - 10	
R 8 - 16	
Cement	
R 1 - 2	
R 0,5 - 1,2	
R 0.1 - 0.6	
Filler	Dry mixing 30 seconds
80 % of the total water	Wet mixing 30 seconds
AEA and 10 % of the total water	Wet mixing additional 30 seconds
SP and 10 % of the total water	Wet mixing additional 2 minutes or 5 minutes

After the initial mixing, the concrete was mixed every 30 minutes. The series A and B included an addition of superplasticizer just before the final fourth mixing cycle that was done exceptionally after 15 minutes from the third measurement cycle at 75 minutes. The purpose of this addition was to return the workability of the concrete back to origin. The series C was more focused on the different admixtures and controlled measurements over one-hour experiments.

3.3.3 Measurement protocol

The test experiments were divided into three different series. Series one and two followed the same measurement protocol that lasted 75 minutes. The third series was 15 minutes shorter lasting an hour because the fourth measurement cycle was left out that included the extra SP dosage on the final cycle. The Table 8 demonstrates when the measurements were taken in the series A and B and the Table 9 in the series C. The CiDRA AIRtrac measured the air-entrainment process continuously throughout the whole experiment and the measurement values were calculated afterwards using the measurement types mentioned in the chapter 3.2.3. The AIRtrac started to collect the data when the concrete was homogenous enough for sufficient measurement quality. Usually this happened one minute after the SP was added into the mixer.

The pressure method was not used at 30-minute mark in the series A and B to conserve the concrete in the mixer since the concrete was considered contaminated after the measurement protocol of the pressure method. Therefore, the maximum amount of the observations that included the pressure method in series of A and B was three times the amount of the concretes totaling of 102 observations. However, in the series C all the measurements were taken every 30 minutes making a maximum of 87 observation points. Some of the AIRtrac measurements had to be rejected because they were in the top limit of the measurement range. The slump-test or flow table test was selected according to the initial workability class of the concrete and kept at the same until the end of the experiment.

Table 8. Measurement protocol for the series A & B in the experimental work.

Series A & B					
Time after the initial mix	Traditional methods			CiDRA AIRtrac	
	Gravimetric	Pressure	Slump/Flow	Dynamic	Static
0 min	X	X	X	X	X
30 min	X		X	X	X
60 min	X	X	X	X	X
75 min	X	X	X	X	X

Table 9. Measurement protocol for the series C in the experimental work.

Series C					
Time after the initial mix	Traditional methods			CiDRA AIRtrac	
	Gravimetric	Pressure	Slump/Flow	Dynamic	Static
0 min	X	X	X	X	X
30 min	X	X	X	X	X
60 min	X	X	X	X	X

3.4 Analyzing accuracy and precision statistically

3.4.1 Accuracy and precision of measurement systems

The concrete is quite heterogeneous material in a microstructural level. This leads to relatively large deviations in its measured properties. The deviation consists of many sources that include the both the materialistic and production technology components. However, the measured parameters behave like a sum of these individual factors and sub-components. For example, the level of compaction has an effect on the properties of the concrete. This is especially emphasized on concretes that have an abnormal plasticity. (Punkki, 1994)

Correlation analysis of the concrete requires an adequate sample size and the observations should be evenly distributed around the measurement range. The correlation method is useful statistical approach when the effects of the possible factors are not certain. The coefficient of the correlation is also important tool for building a mathematical model of the phenomenon. (Punkki, 1994)

The purpose of the research was to analyze the air-entrainment of the fresh concrete by comparing the measurement values from different measurement instruments. Therefore, it is important to know the accuracy and precision of the instruments while they are ideally the measurements are tightly clustered around the true value. According to the *ISO 5725-1:1994 "Accuracy (trueness and precision) of measurement methods and results -- Part 1: General principles and definitions"* standard when the term is used to sets of measurements of the same measurand, the accuracy involves the component of a random and a systematic error and a term of trueness instead. To clarify, in this work these terms specified as the following:

- Precision is a measure of repeatability, description of random errors and a measure of statistical variability.
- Accuracy is a proximity of measured results to the true value and a description of systematic errors.

Getting a true value by measuring the concrete is challenging since all the measurement methods have systematic error caused by the measurement equipment or the user. Because of this error, increasing the sample size and the amount of the observations increases the precision but does not increases the accuracy or, in other words, the closeness to the true value. Moreover, eliminating the systematic error does not change the precision of the measurement equipment. (Taylor, 1997)

In addition, many traditional methods rely on reading the scales of the measurement equipment. These measurements contain uncertainties and their magnitude should be known. However, estimating magnitudes of these certainties can be fairly complicated. Figuring a value between the markings on the measurement scale is called interpolation which can be improved with practice. (Taylor, 1997) For example, the scales can have variable intervals where the difference of the markings increases towards the end of the scale making the reading even more imprecise. The Picture 11 illustrates the problem of the reading of the scale using the pressure method.

Picture 11. A reading scale of the pressure method instrument.

For the measurement of the accuracy the difference between the mean of the observations and the reference value can be used. This difference is necessary for calibration of the measurement equipment. Both the accuracy and the precision can be analyzed using a regression model that is based on the observations from the test methods.

3.4.2 Regression analysis

Analysis used to find the best equation to describe relationship between the regressand Y and one or more regressors X. Analysis can be executed to any variable where the target is to find the right explanatory variables giving the best regression equation. The model should not include regressands that correlate strongly with each other or through some other factor. (Milton & Arnold, 1987)

Regression coefficient R^2 describes the compatibility of thee regression equation and observations. The size of the coefficient represents how big portion of the variation of the Y can be explained by the variation in X. The rest of coefficient are pure deviation or the lack of the model. (Milton & Arnold, 1987)

With one variable, the linear regression can be represented in form of Equation 1.

$$Y_i = b_0 + b_1 \cdot X_i + e_i \tag{1}$$

where b_0 and b_1 are the constant term and the slope of the linear equation.

The constants b_0 and b_1 can be solved using the method of the least squares where the square sum is created from the residuals of the square sums. This sum of the squares of the errors (SSE) can be seen is calculated as seen in the Equation 2.

$$SSE = \sum e_i^2 = \sum (Y_i - b_0 - b_1 \cdot X_i)^2 \tag{2}$$

The constants can be calculated from the Equations 3 and 4.

$$b_1 = \frac{n \cdot \sum X_i Y_i - [(\sum X_i) \cdot (\sum Y_i)]}{n \cdot \sum X_i^2 - (\sum X_i)^2}, \tag{3}$$

$$b_0 = \bar{Y} - b_1 \cdot \bar{X} \tag{4}$$

The Coefficient of Determination (R^2) is calculated from the Equation 5.

$$R^2 = \frac{S_{yy} - SSE}{S_{yy}} = 1 - \frac{SSE}{S_{yy}} \tag{5}$$

where the Error Sum of the Squares is the following Equation 6.

$$S_{yy} = \frac{n \sum Y_i^2 - \left(\sum Y_i\right)^2}{n} = \sum Y_i^2 - \frac{\left(\sum Y_i\right)^2}{n} \tag{6}$$

This linear regression model was used in the statistical analysis of the results. The regression model was calculated automatically in Microsoft Excel as the results were plotted to the graph. The variables were selected so that the regression models would give desired information about the relationship of the variables in the data set.

3.4.3 Descriptive statistical analysis

Descriptive statistics can be used to analyze the precision of a measurement system. These estimates can be used to compare the differences between data sets. A mean was used to compare the magnitudes between the measurements. The mean that is close to zero indicates that the compared methods are giving the same measurement values on average. The standard deviation was calculated to compare the amount of the error between two different methods. The smaller the standard deviation, the greater the precision of the measurement method on average. The descriptive statistics were calculated automatically in the IBM SPSS software.

The mean is defined as the Equations 7 (Taylor, 1997).

$$\bar{x} = \frac{\sum x_i}{n} \tag{7}$$

The standard deviation is defined as the Equation 8 (Taylor, 1997).

$$\sigma_x = \sqrt{\frac{1}{n-1} \sum {d_i}^2} = \sqrt{\frac{1}{n-1} \sum (x_i - \bar{x})^2} \tag{8}$$

4 Results and analysis of the experiments

4.1 *Results of the experiments*

The combined results from the experiments can be seen in the Appendix 3. The table shows all the air amount measurements and the corresponding plasticities of the concrete at the time of the tests. The CiDRA AIRtrac was configured so that the measurement quality had to be adequate for a five second period before the software started to collect the data. In addition, the AIRtrac was set to measure the air amount in the range of 2–15 percent. To avoid any direct error caused by these measurement limits, observations larger than 14.5 percent of air were discarded. Furthermore, the smallest air amount that was measured by the AIRtrac was 3.7 percent that was achieved using a normal concrete.

In analysis of the accuracy, the air amount measurements from the pressure or gravimetric were listed next to the AIRtrac measurements and compared in the analysis. The workability measurements were used to find correlation between the air measurements and the plasticity or the amount of the concrete. In precision analysis, the same results were used to plot the differences between the testing methods into histograms and calculating descriptive statistics from the corresponding data series. The difference between the two methods is described as an error of pressure, dynamic and static method on this research.

4.2 *Analysis of the accuracy*

4.2.1 Comparison of combined results

This chapter combines all the series A, B C that were done during in the experimental phase. The series contained a total of 63 different concretes that had varying attributes shown in the Chapter 3.3.1. The number of concretes gave a total of 200 observations that were in the limits for the CiDRA AIRtrac. Since the pressure method was not done on the second cycle in the series A and B, a total of 183 pressure method measurement points was collected on combined results.

The Figures 8 and 9 show the results from all the observations during the experiments. Firstly, a correlation between pressure and gravimetric method was calculated that represented only the traditional methods in the experimental work. This functioned as a reference point for all the following comparison as these are the most commonly used methods for measurement of air content in fresh concrete. Because the gravimetric method was assumed to have the least amount of error during the experiments, it was chosen to function as a reference point for other methods. Secondly, the measurements calculated from the CiDRA AIRtrac data were compared to the gravimetric method being the reference.

The Determination of Coefficient (COD) for the pressure method and gravimetric method was calculated to be as high as 0.9374. With a couple of exceptions, the observations are located closely to the linear regression line that was calculated in Microsoft Excel (ME). It can be noted though that as the air amount increases the observation disperse more from the line indicating more error when measuring high air mounts. Moreover, the error of the pressure method could be shown in the increased dispersion of the observations.

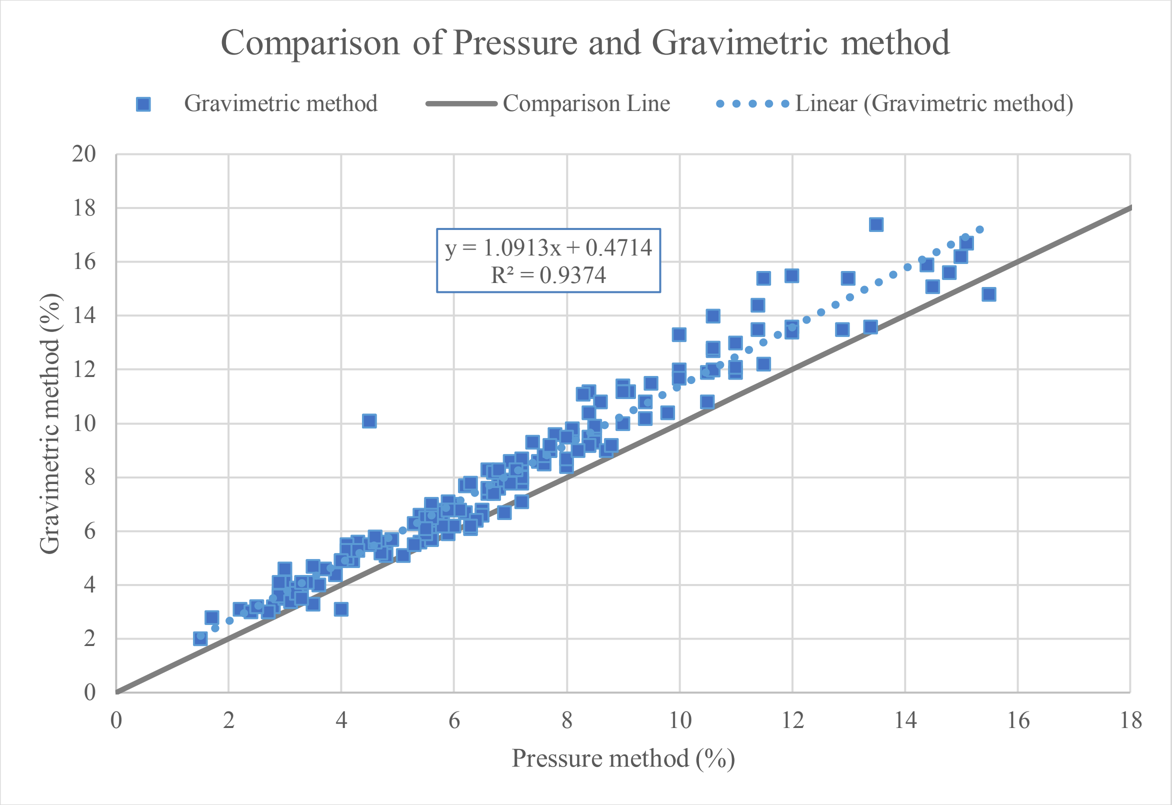


Figure 8. Comparison of pressure and gravimetric method.

The observations and their regression lines of the AIRtrac measurements are shown in the Figure 9. The CODs for the dynamic and static measurements are 0.7342 and 0.6875 giving a slight edge for the dynamic AIRtrac measurements while the concrete was being mixed. The difference of these AIRtrac measurements is roughly two percent in average as it can be seen from the coefficients of the regression lines. This is expected because the measured air amount using the AIRtrac starts to decrease rapidly after the motion in the mixer stops. The rapid decrease is caused by the compacting motion of the piston of the AIRtrac sensor unit and not having a new sample to measure.

Although the number of the observations points is large on the combined results, these comparisons do not unveil the possible factors that might affect the accuracy of the AIRtrac measurements. Hence, the concretes of this research were divided into three series that had specific properties that could influence the measurement accuracy and precision. These series are analyzed separately on the following chapters.

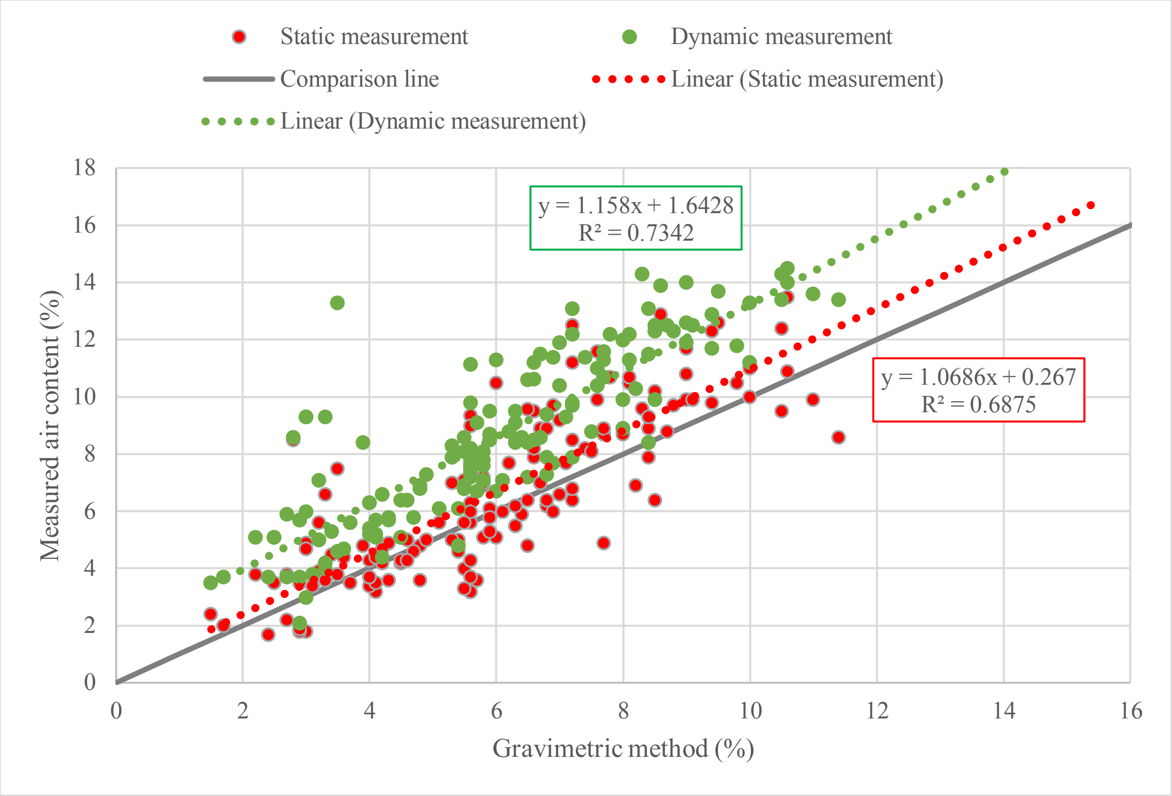


Figure 9. Comparison of gravimetric method and CiDRA AIRtrac measurements.

4.2.2 Results of series A

The Series A consisted of the concrete having a workability class S3 and had an initial batch amount of 60 liters. The tests were 75 minutes long that included four measurement cycles for each concrete. Because the concrete lost workability during the experiment, the measurements were more difficult to execute consistently. The slump-test showed initial values of 75–226 mm and went down as far as 0 mm as the experiment progressed. This caused difficulties in compacting the concrete properly in traditional methods. Moreover, the measurement quality of the AIRtrac can be problematic.

Without a doubt, the level of the compaction was user-dependent and the differences in the measurements from the pressure and gravimetric methods might have been affected from the inconsistency. Nevertheless, the gravimetric method was held the most accurate measurement method since it requires the least user-dependent steps including the compaction and weighing of the concrete in the pot. Furthermore, as the experiment progressed the amount of the concrete decreased since some of the concrete was contaminated or put into molds. This caused a significant decrease of the concrete layer over-time in the mixer. In combination with the small workability, the time that the sensor had no concrete cover increased notably.

The Figure 10 shows the 44 observations in series A where pressure method was used. The COD is 0.8397 which is good as the observations are distributed evenly along the linear regression line. However, one observation clearly stands out, which could be explained by a measurement error when using pressure pot. It can be noted that pressure method gave smaller values than the gravimetric method. The coefficient for the slope of the curve is pretty close to one, meaning that the pressure method measures consistently about 1–2 percent less air than the gravimetric method in the concrete.

The regression line has a constant of 0.7379 indicating that the gravimetric method gives larger values than the pressure method on the whole measurement range.

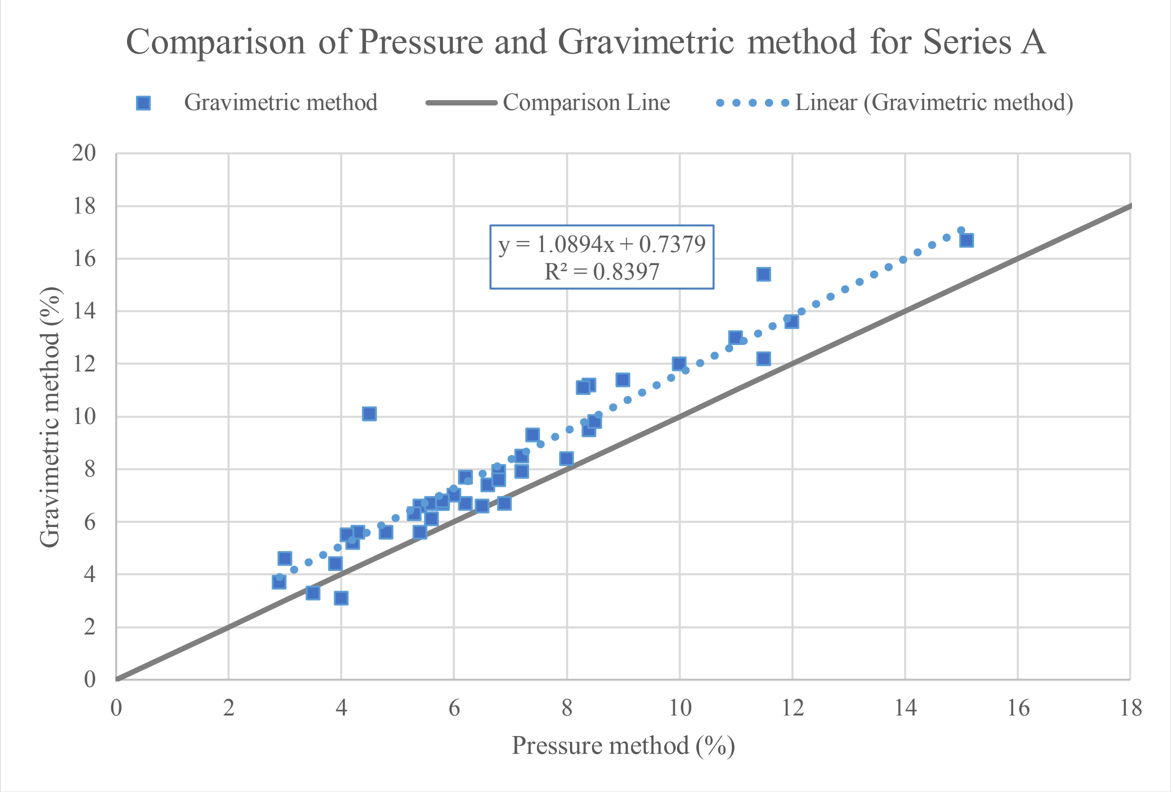


Figure 10. Comparison of pressure and gravimetric method in series A.

The low workability and the amount of the concrete in the mixer caused difficulties when measuring the air amount with AIRtrac. During the mixing, the sensor was covered properly only a fraction of the second per rotation of the mixer during the two last mixing cycles. This can be explained, as said in the previous chapter, the combination of the loss of the concrete from and workability over-time. Taking observations only from the first cycles or mixing bigger concrete batches could increases the accuracy significantly.

The Figure 11 shows the 48 observations that were calculated from the collected AIRtrac data using the dynamic and static measurements methods. As it can be seen from the regression lines, the dynamic measurement suffered the most from the measurement conditions in the mixer. When the mixer was stopped, the sensor was covered manually to maximize the coverage of the sensor for more repeatable condition.

The CODs for the dynamic and static measurements are respectively 0.4677 and 0.6229. These mediocre coefficients suggest how important is to keep the sensor covered as much as possible of the time. The CODs differ 25 percent, which indicates that the static measurement is not as dependent as the dynamic measurement when the amount of the concrete decreases. On the other hand, this could be explained by the manual coverage of the sensor after the mixer has stopped. In addition, the regression lines of the static and dynamic measurements have a difference of two percentage points. The constant of the static regression line has a value of 0.1408 meaning that the observations between this method and gravimetric method give measurement values of the same magnitude.

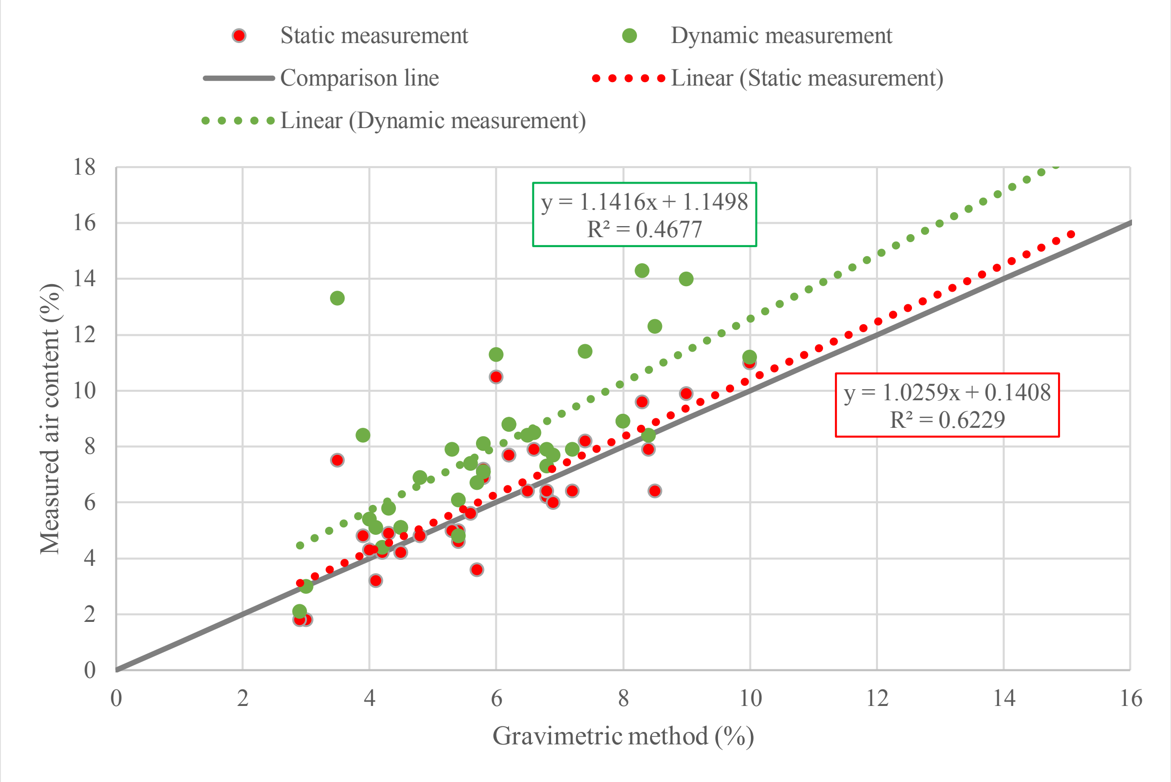


Figure 11. Comparison of gravimetric method and CiDRA AIRtrac measurements in series A.

To explain the differences in the measurement methods, the difference of the air amount is plotted a function of the slump as shown in the Figure 12. The figure shows that if the slump get lower than 55 mm, the dynamic error increases greatly while having less deviation on higher slumps. Before this mark, most of the observations are ± 2 percentage points from each other having most of the differences positive. This means that the dynamic measurement tends to give slightly larger air amounts as seen also in the regression line constant in the Figure 11.

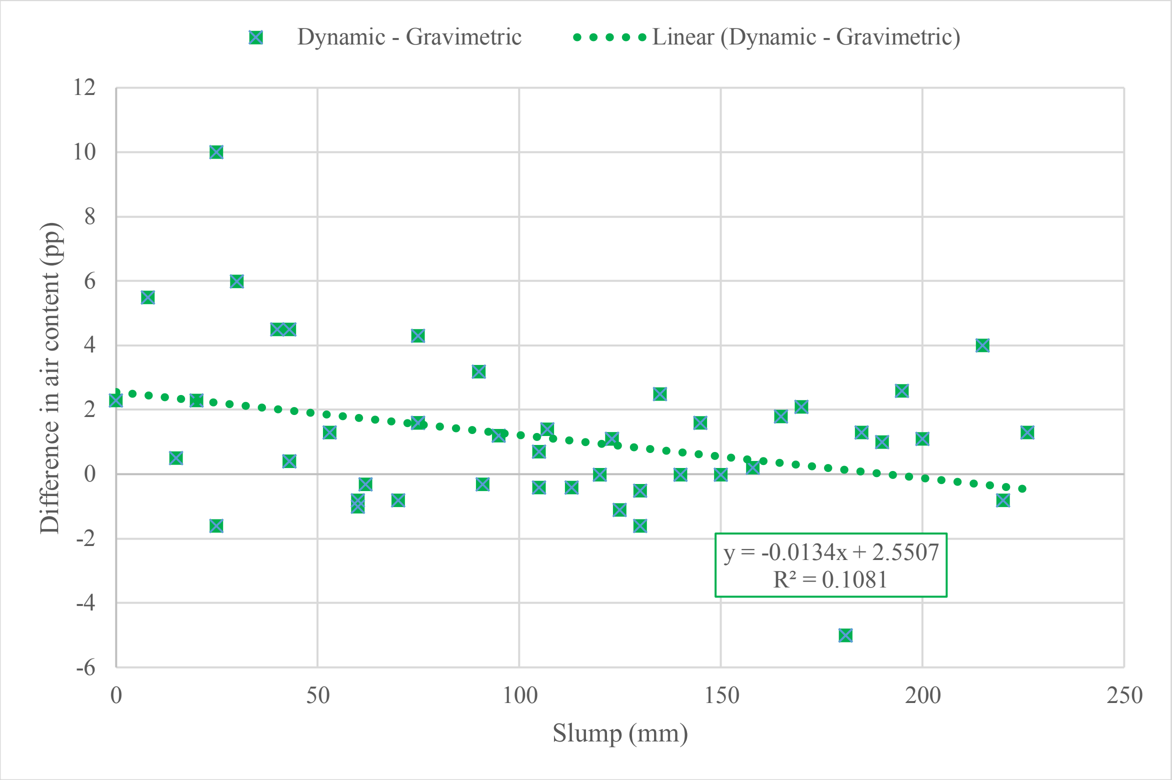


Figure 12. The effect of slump to the difference between dynamic measurement and gravimetric method in percentage points in series A.

On the contrary, as seen in the Figure 13, the static error stayed pretty similar as the concrete got lost workability meaning that the static measurements are less dependent on the plasticity of the concrete. On the other hand, the slope of the regression line indicates that the static measurements gave bigger values compared to the gravimetric method when the concrete lost workability. The difference of the methods stays mainly at four percent on average that is only about a fourth of the difference between the dynamic and gravimetric method.

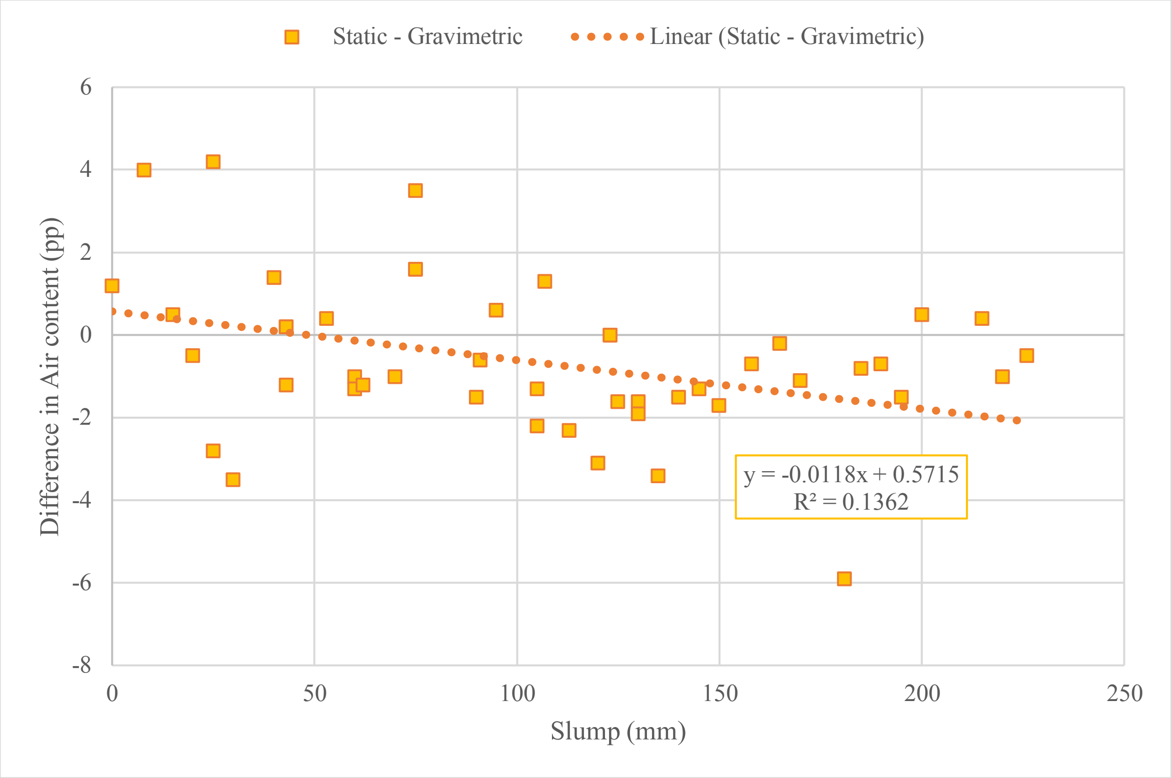


Figure 13. The effect of slump to the difference between the static and gravimetric method in percentage points in series A.

4.2.3 Results of series B

The measurement protocol of the series B was the same as with the series A. The size of the series was larger having a total of 65 observations for AIRtrac measurements and 63 observations for the pressure method. The workability class was increased to F5 but the batch size was kept the same as earlier. The better workability made the measurements easier since the plasticity of the concrete stays moderate throughout the whole experiment. This increased the time that the sensor unit of the AIRtrac was covered and made the compaction of the traditional methods easier and more consistent.

The workability tests were done on the flow table and the values varied between 340–700 millimeters. The biggest flow measurement values were taken after an additional SP dosage just before the final mixing cycle. Because the ratio of the additional dosage calculated from the initial SP amount was kept the same for all the SP products, some of the flow-tests showed some evidence of segregation and over-flow (> 700 mm). This in turn was one of the reason why the air amount to dropped suddenly. The most notable factor in the accuracy of the measurements was the decreasing amount of the concrete as the experiment progressed.

The results from the pressure and gravimetric method were plotted first (Figure 14) as done with the series A. The amount of observations increased to value of 63. The COD increased from the previous series significantly to a value of 0.9627. It can be seen that the observations start to diverge from the regression line as the air amount increases. The coefficient of the slope has a value of 1.0635 meaning that the pressure method gives consistently smaller measurement values as the gravimetric method in the whole measurement range. Towards the highest measured air amounts, the observations start to disperse more while the pressure method starts to give smaller measurement values. The pressure method gives about the one percent less air than the gravimetric method on average.

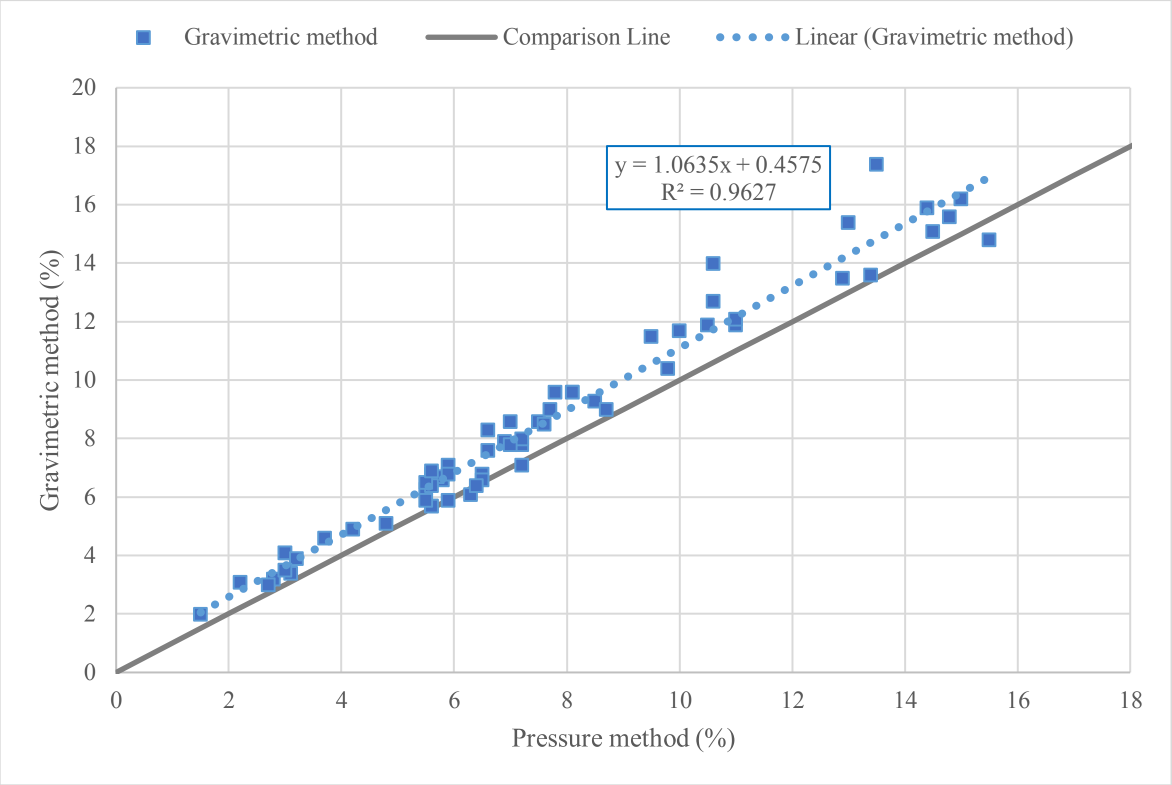


Figure 14**.** Comparison of pressure and gravimetric method in series B.

The Figure 15 shows the 65 observations from the dynamic and static measurements in similar fashion as before. The COD for the dynamic method increased to a value of 0.7697 meaning an increase of about 65 percent. The observations are distributed evenly along the desired measurement range. On the other hand, the calculated COD value of 0.5543 for static measurement meant a decrease of about 12 percent when compared to series A.

The observations seem to be dispersed significantly more than on the traditional methods along the regression lines on the both AIRtrac measurement methods. On the other hand, the dispersion is more controlled on the dynamic method that can be seen more important type of measurement. The notable decrease of the concrete workability might have caused differences especially in the static measurements as the concrete comes more compactable skewing the results. Therefore, comparing the method using a certain workability might decreases the deviation between the observations and improve the precision.

The coefficient of the slope for the dynamic method is 0.9230 indicating similar measurement values at high air amounts with gravimetric method. Respectively, the coefficient for the static method is 0.8288 meaning that the measurements tends to be lower on high air amounts and higher on low air amounts. The constant of the regression line for the dynamic measurement shows that the values are at least 2.5 percent bigger than the measurements from the gravimetric method. The static measurement values are about two percent lower than the values from the dynamic method and about the same as the measured values from the gravimetric method.

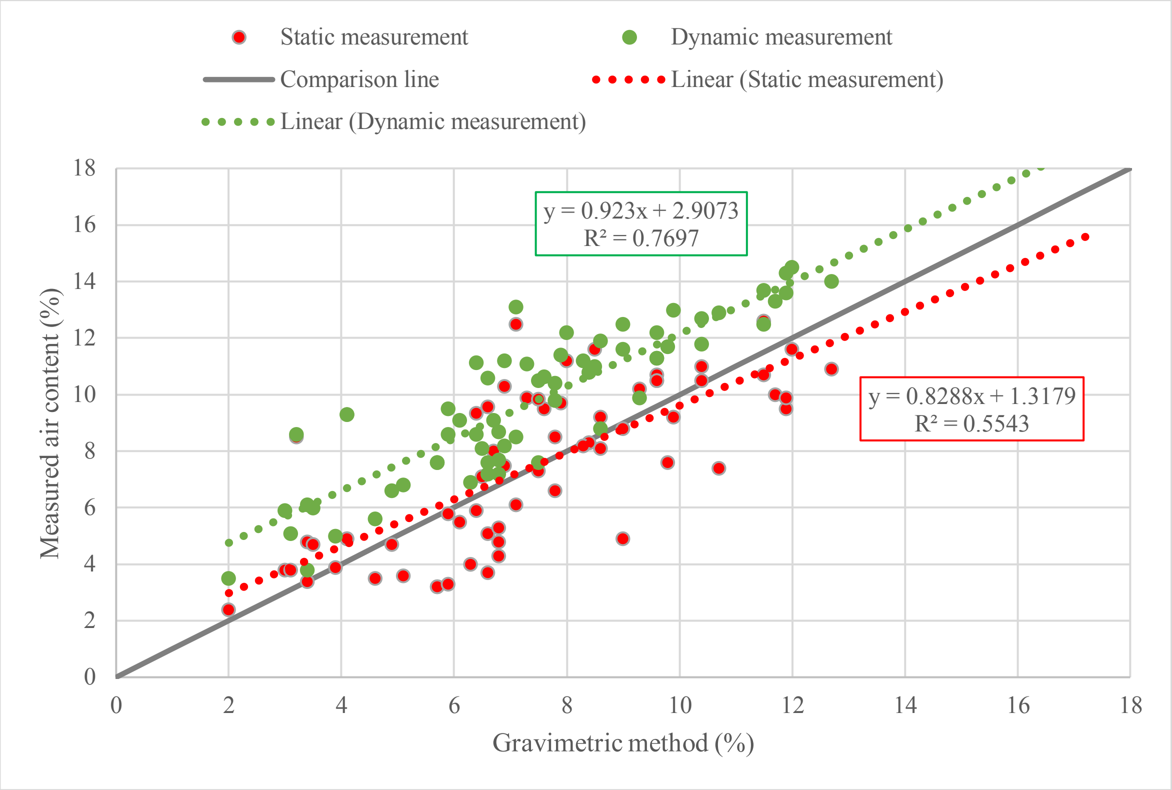


Figure 15. Comparisons of gravimetric method and CiDRA AIRtrac measurements in series B.

The S3 concrete showed an evidence on the correlation with the loss of the workability as it lowered below the certain point. However, as it be seen from the Figure 16 the difference between the dynamic and gravimetric method is barely notable as the workability decreases. This suggests a minimum workability for a specific batch size to keep the precision of the measurements sufficient.

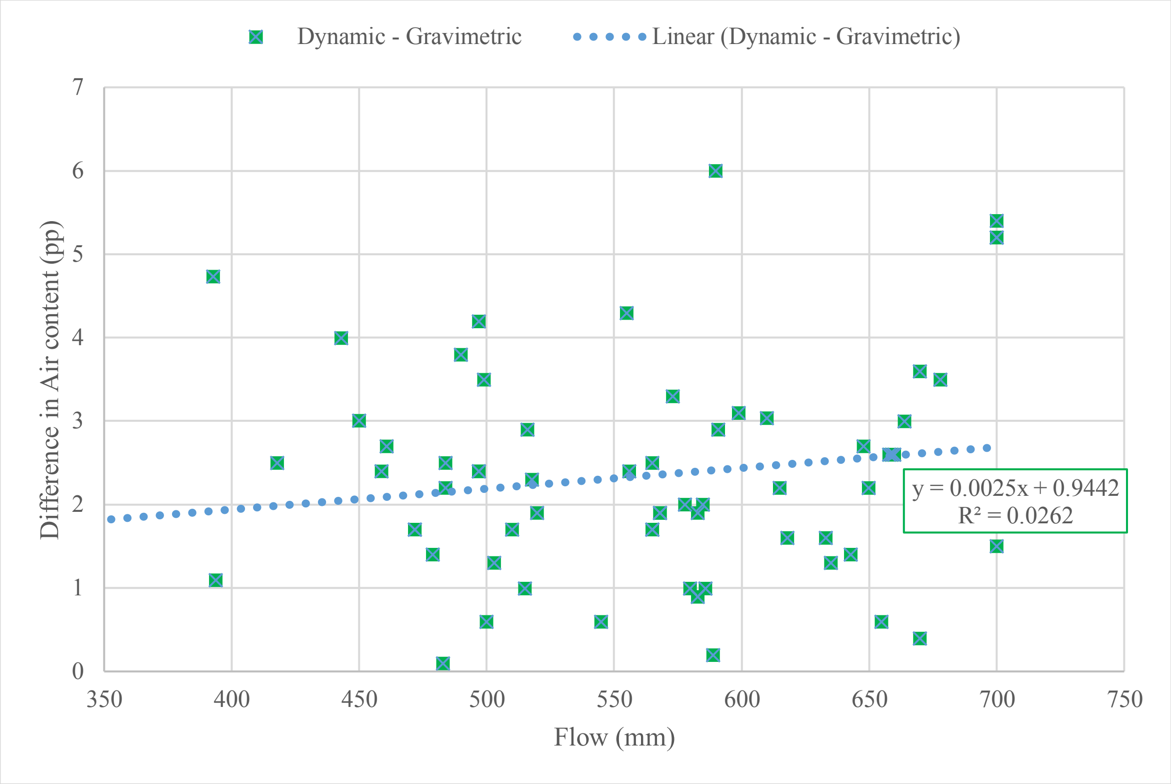


Figure 16. The effect of flow to the difference between the dynamic and gravimetric method in percentage points in series B.

The Figure 17 shows the difference between the static and gravimetric method as a function of consistency in the series B. As the workability gets higher the difference seems to increase. The effects of the extremely high workability, as described previous, could accentuate the measurement time of 30 seconds in the static measurement. For example, shorter measurement times for more fluidly concretes could be considered. Moreover, because after the addition of the SP on the final cycle, some of the concretes started to lose the air over-time. Therefore, the static measurement could have been measuring the air while it was still leaving from the concrete. Minutes later, the gravimetric method could have measured the final air amount from more stable mix.

Moreover, the Figure 17 shows that the difference of the measurements values tends to give lower values and even to negative as the flow increases. This means that the static method gives lower measurement values as the flow increases. This might be because the compacting effect of the piston in the AIRtrac sensor unit. In overall, the static and gravimetric values seem to give very similar values initially because the difference is near zero on average.

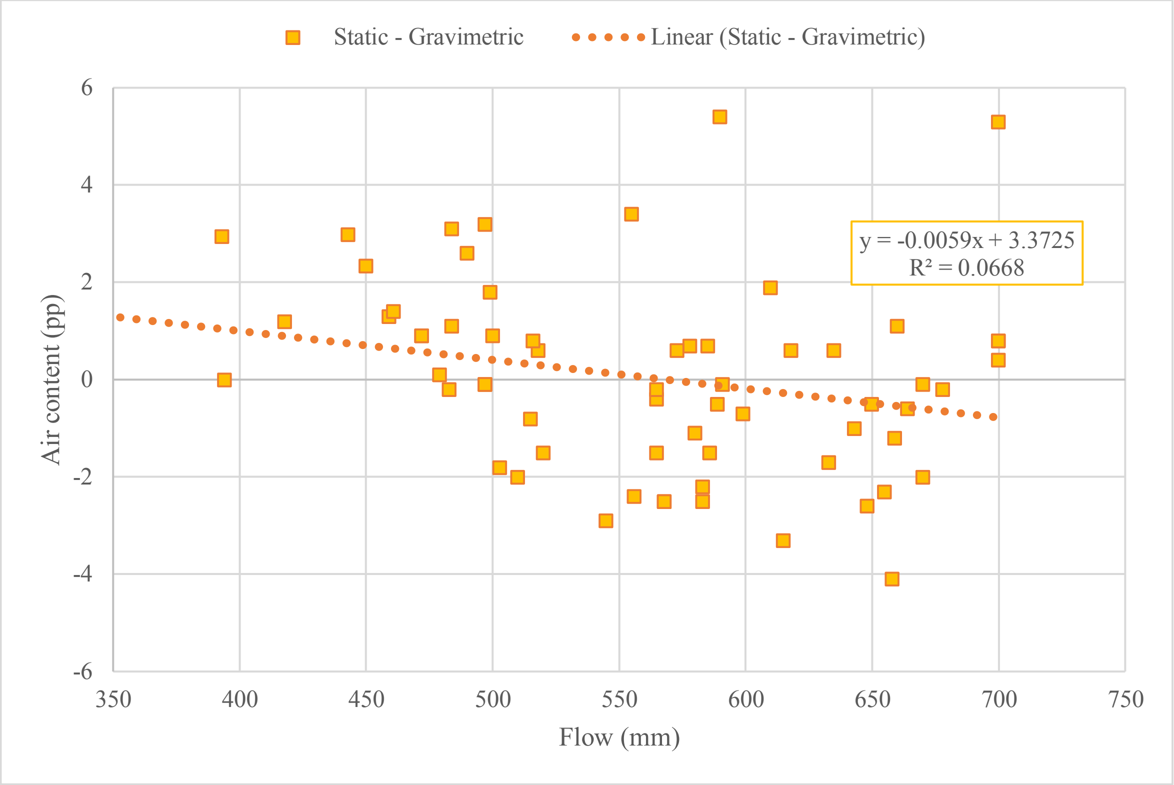


Figure 17. The effect of flow to the difference between the static and gravimetric method in percentage points in series B.

4.2.4 Results of series C

The target of the series C was to optimize the measurement conditions in the mixer. The workability of the concrete was kept the same F5 and the batch size was increased to 75 liters. In addition, the test program had three measurement cycles losing only eight liters of concrete due to the contamination per cycle. This maximized the time that the concrete covered the sensor while keeping an adequate layer of concrete on top of the sensor throughout the experiment. Furthermore, in this series the amount of concretes batches was increased to 29 that yielded to 76 observations using pressure method and 87 observations with AIRtrac.

The Figure 18 represents these 76 measurement points using the pressure and gravimetric methods. The COD value of 0.9695 confirms the good correlation between these methods. The observations are closely distributed along the regression line. However, as previously the dispersion of the points start to disperse after the air amount has passed a value of 10 percent. Moreover, the pressure method gives slightly lower measurement values as the air amount increases.

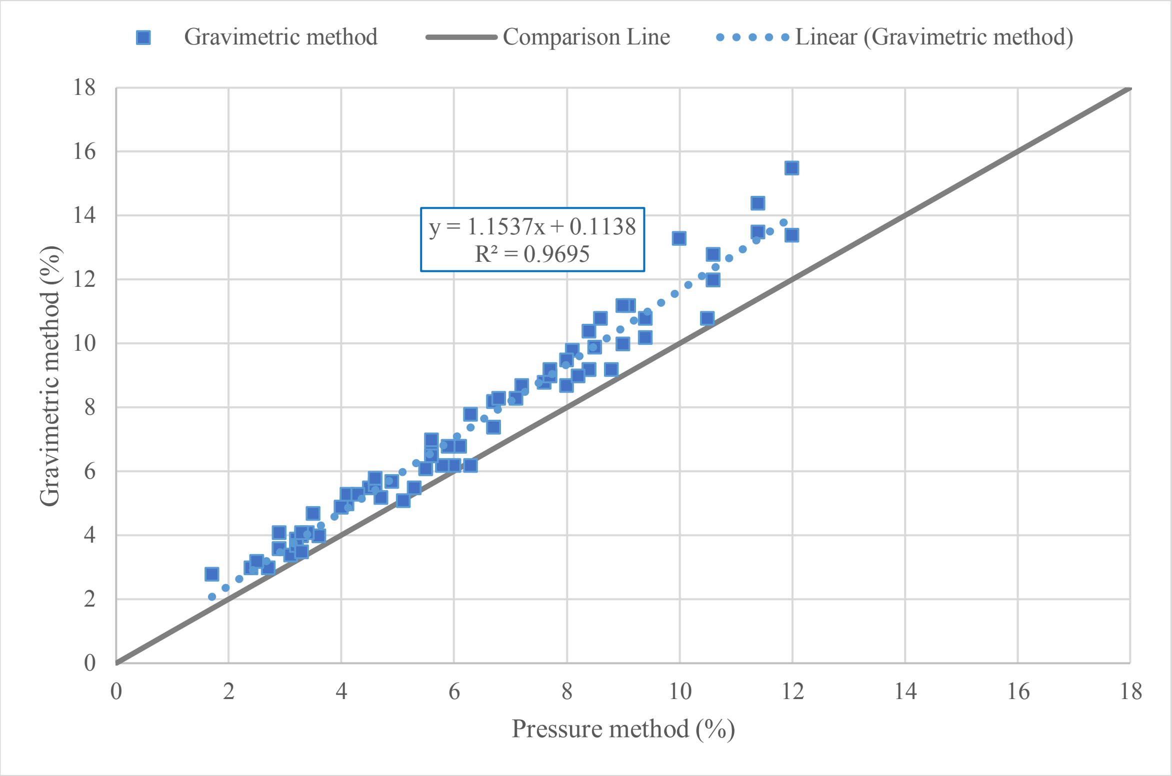


Figure 18. Comparison of pressure and gravimetric method in series C.

The 87 AIRtrac measurements in series C were plotted in the Figure 19 as done with the previous series. The CODs for the dynamic and static methods increased considerably. The COD for the dynamic increased from 0.7697 to 0.8745 which meant a 13.6 percent increase. The coefficient for the static measurement went up from the value of 0.5543 to 0.7996 meaning an increase of 44 percent. In addition, the observation points along the regression line seem to be less dispersed.

Furthermore, the regression lines are almost parallel to each other as the coefficients of the regression line slopes also indicate. Because of this and similar values of the CODs, the both measurement methods are very comparable in accuracy and precision giving a slight edge for the dynamic measurement method. Furthermore, the static method gives about the same measurement values as the gravimetric method on average while dynamic method gives about two percent higher measurement values.

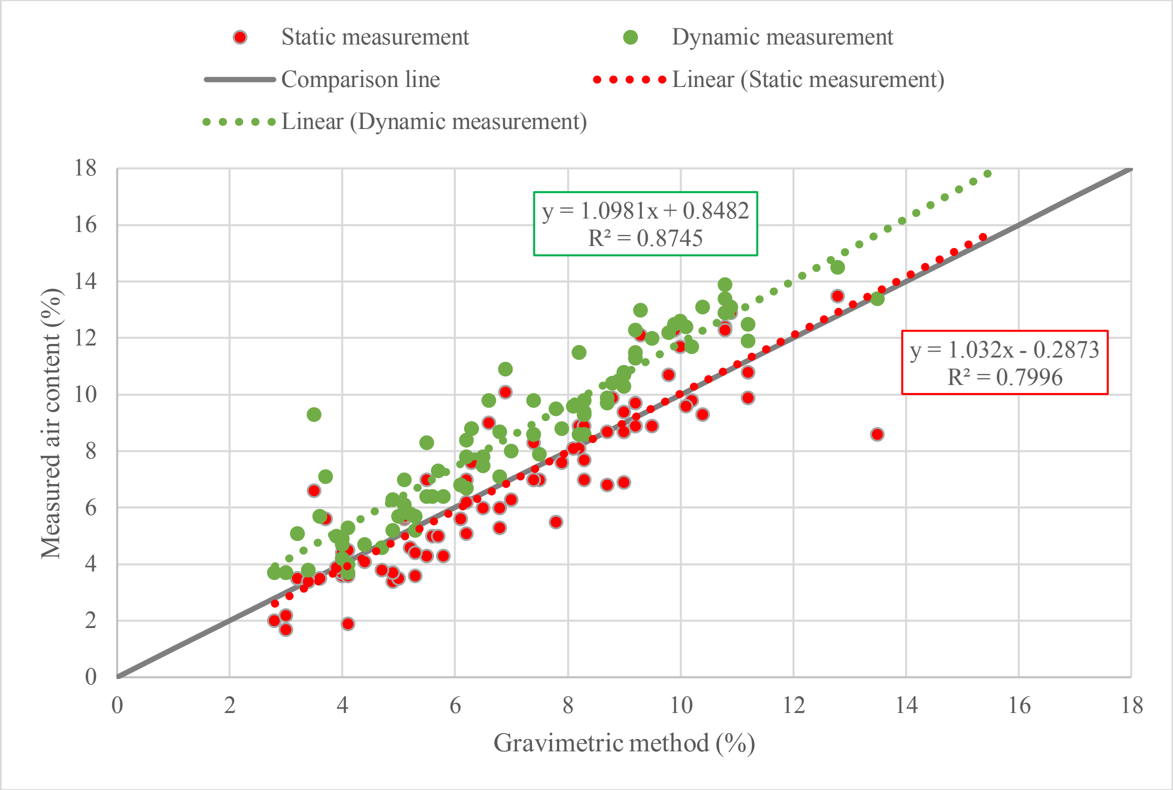


Figure 19. Comparisons of gravimetric method and CiDRA AIRtrac measurements in series C.

In the Figure 20 the relationships of the dynamic and static measurement methods were inspected more closely. The COD value of 0.9039 affirms a good correlation between these methods but shows still some dispersion of the observation along the regression line. This dispersion could be explained by the amount and plasticity of the concrete in the mixer. For example, the static method seems to be affected more by the workability the concrete.

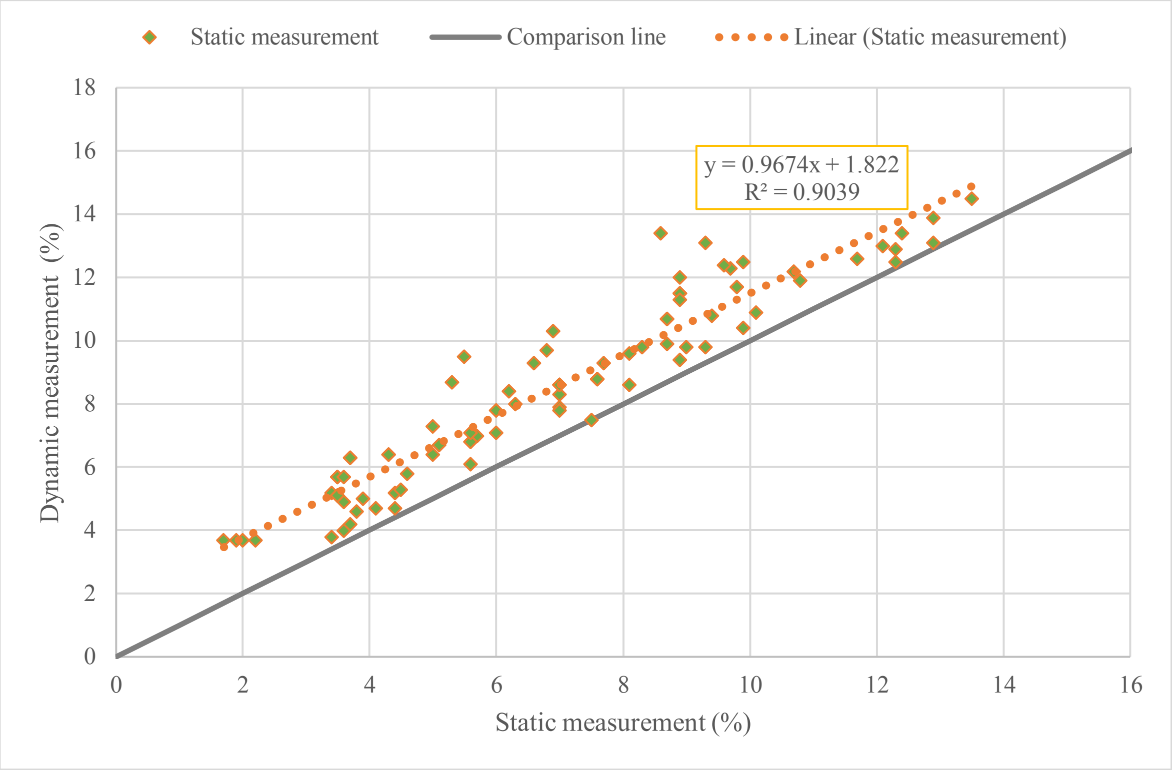


Figure 20. Comparison of dynamic and static measurement methods in series C.

The Figures 21 and 22 below represent the differences between the CiDRA measurements and the gravimetric method as a function of flow. The both figures indicate that the difference between the AIRtrac measurement methods and the gravimetric method slightly increases as the workability decreases. In the previous series, the smaller concrete batch sizes of the concrete might have concealed the effect of the workability. However, as it can be seen from the figures, the trends are similar than before. Furthermore, the both regression lines are decline meaning that the CiDRA gives slightly bigger results as the concrete loses its plasticity.

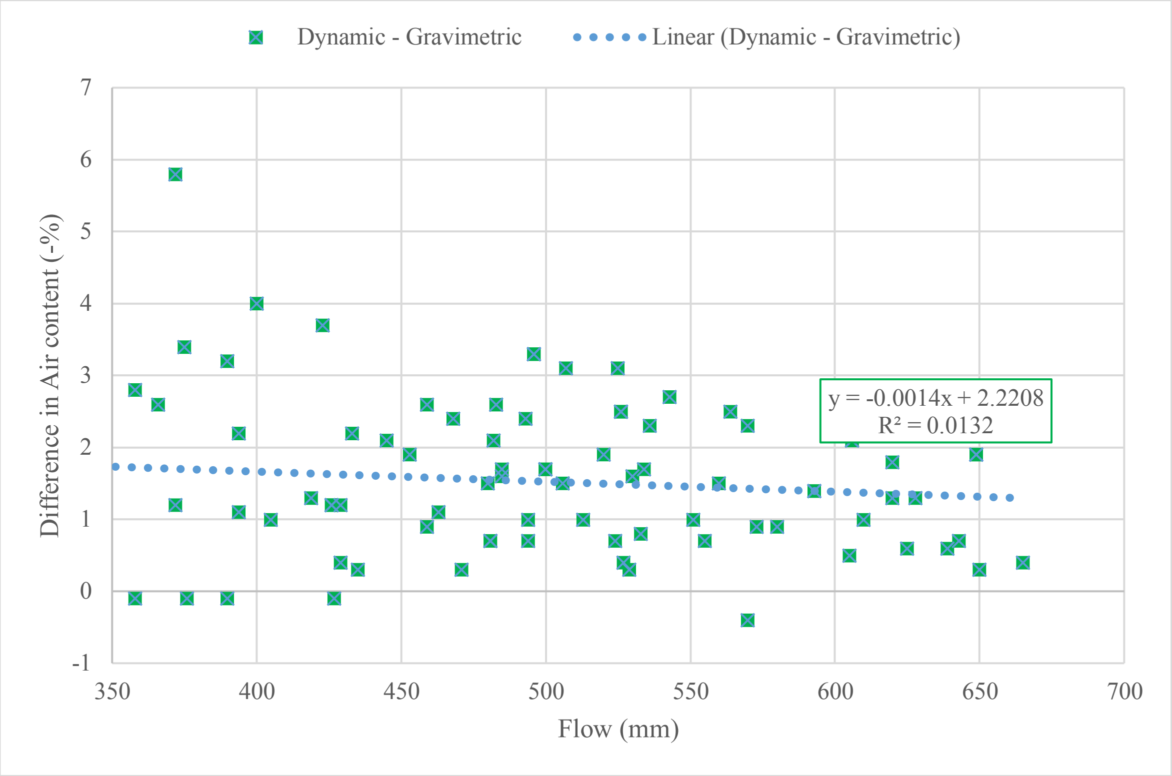


Figure 21. Effect of flow to the difference between the dynamic and gravimetric method in percentage points in series C.

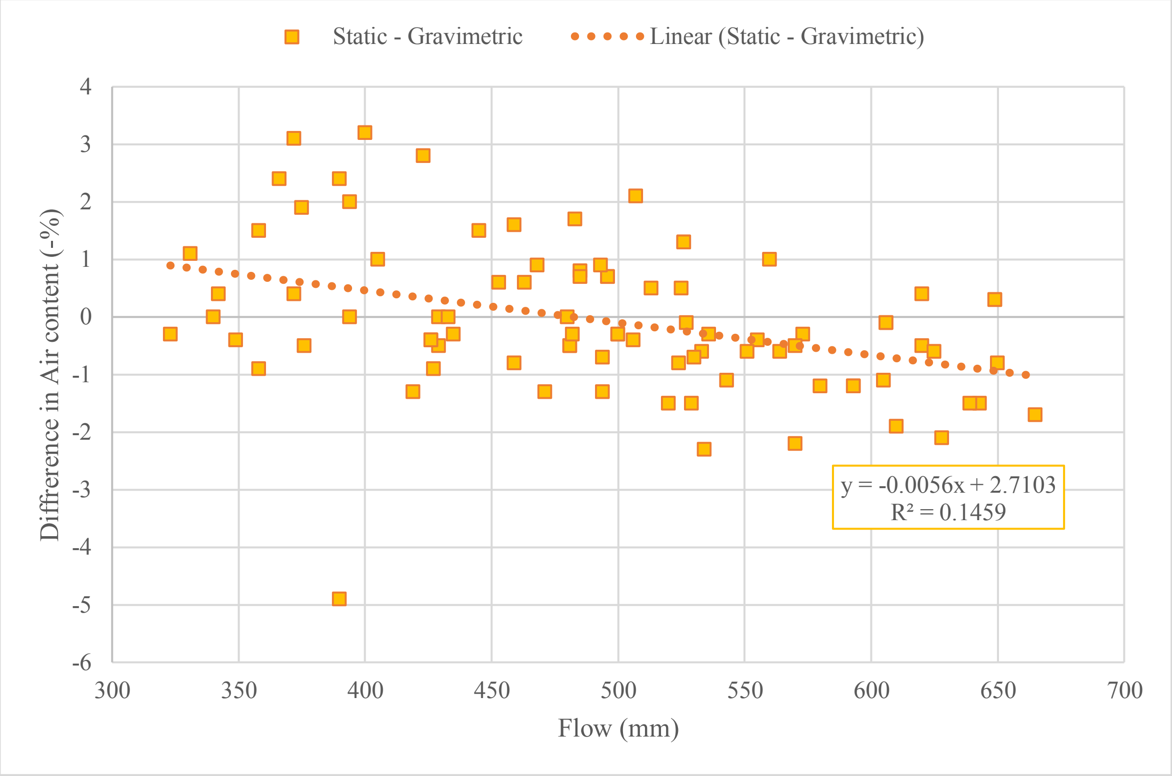


Figure 22. Effect of flow to the difference between the static and gravimetric method in percentage points in series C.

4.3 Analysis of the precision

4.3.1 Combined results

The precision of the AIRtrac was analyzed more carefully by inspecting the differences between two different methods. These differences between two different methods are called errors of the method on this research. Furthermore, descriptive statistics (Appendix 4) and histograms were created using IBM SPSS software to support the regression line models.

The combined results of all the concretes were first investigated. The regression models of the previous chapter showed that the best correlation was between the pressure and the gravimetric method. The Figure 23 shows the combined pressure method errors plotted into a histogram. The mean of pressure method error was calculated to have a value of -1.09 and the standard deviation a value of 0.89. Because the regression analysis showed the best correlation between the pressure and gravimetric method, these values for the pressure method error act as a good baseline for the following comparisons.

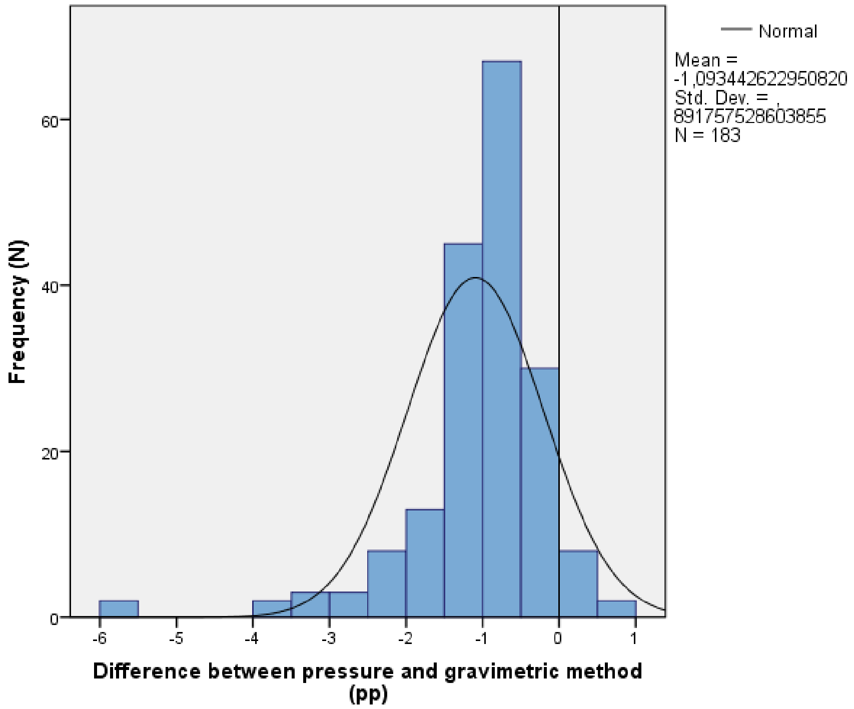


Figure 23. The difference between the pressure and the gravimetric method shown in histogram.

The difference between the dynamic and static measurement and the gravimetric method were plotted into the histograms shown in Figures 24 and 25. The mean of the static error has a value of -0.18 meaning that the values from the static method are very close to the values acquired from the gravimetric method. On the other hand, the dynamic error has a positive value of 1.70 indicating about two percent greater measurement values on average than the gravimetric method. In addition, the standard deviations of these methods were increased to 1.68 (+89 %) and 1.73 (+94 %) respectively. This tells that the measurements of the AIRtrac are about two times more dispersed than the traditional methods.

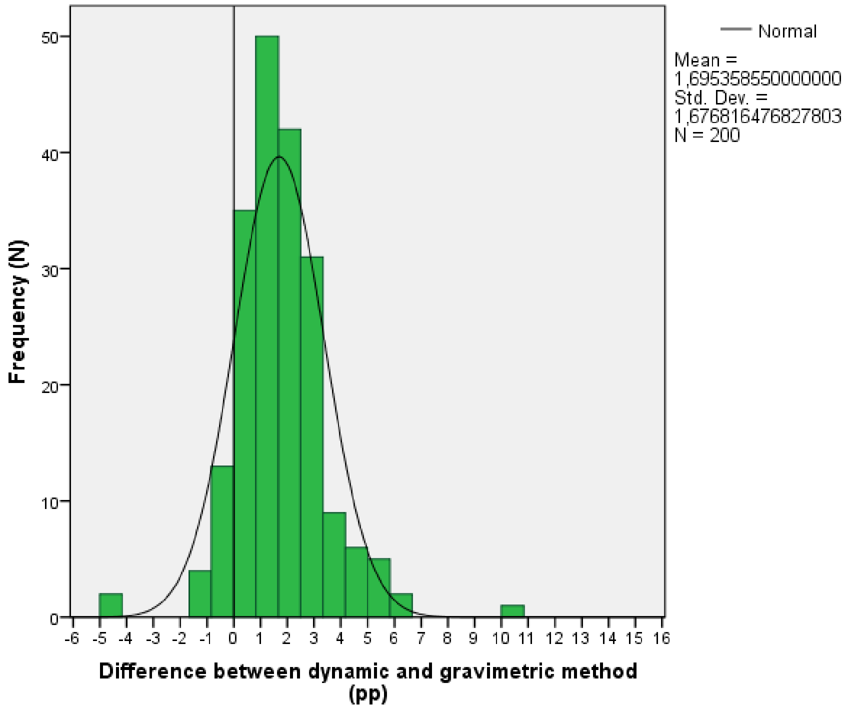


Figure 24. The difference between the dynamic and the gravimetric method shown in histogram.

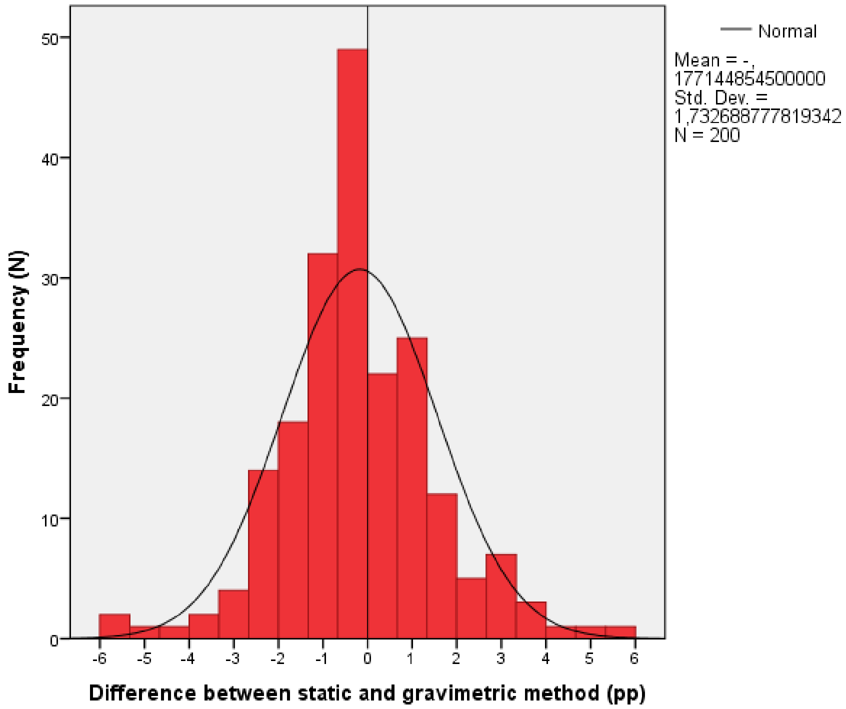


Figure 25. The difference between the static and the gravimetric method shown in histogram.

4.3.2 Results of series C

The combined results indicated that if the measurement conditions are not appropriate, AIRtrac system could be notably less precise than the traditional methods. However, the previous chapter included all the concrete where some of measurement were executed on disadvantageous conditions. Furthermore, the correlation using the regression modes was greatly increased as the conditions improved. Therefore, the precision of the AIRtrac was analyzed also in the series C where the amount of the concrete was high throughout the whole experiment and the workability class of the concrete was initially F5.

The Figure 26 represents the results of the series C. The mean (-1.08) is almost identical to the previous comparison of the combined results indicating that the pressure method gives about one percent less air than the gravimetric method. In addition, the standard deviation decreased to a value of 0.69 (-22 %) when the workability of the concrete was reasonably high.

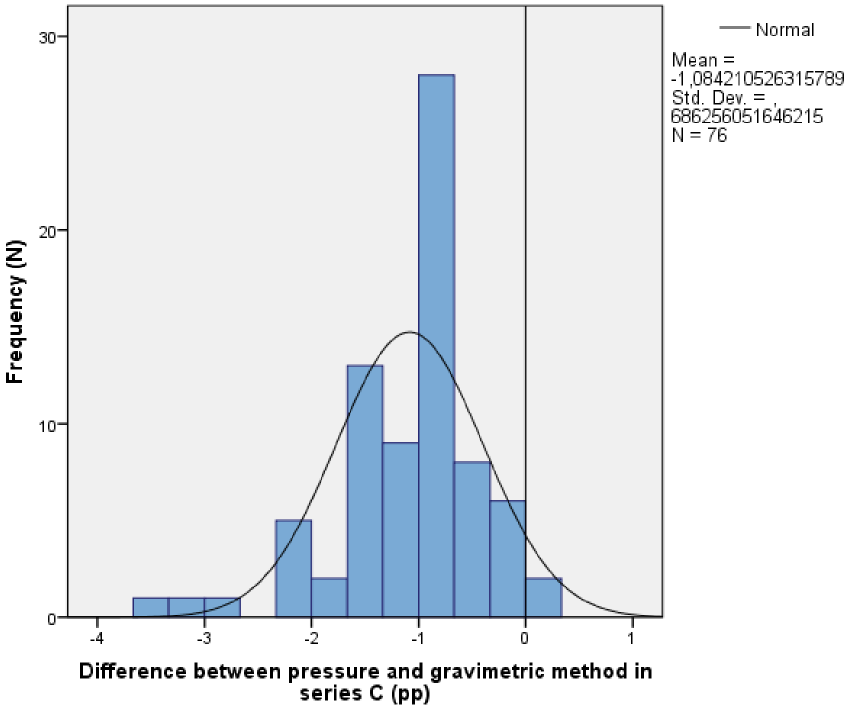


Figure 26. The difference between the pressure and the gravimetric method shown in histogram in series C.

The Figures 27 and Figure 28 show the results from the AIRtrac measurements using the series C. It was noted previously that the CODs of the regression lines were improved when the measurement conditions were better. The dynamic and static errors were calculated to be 1.53 and -0.06 staying close to the original values from the combined results. However, the standard deviations of the errors are decreased to 1.08 (-56 %) and 1.31 (-24 %) respectively. This notable increase of the precision suggests a strong relationship between the measurement conditions and the precision of the AIRtrac.

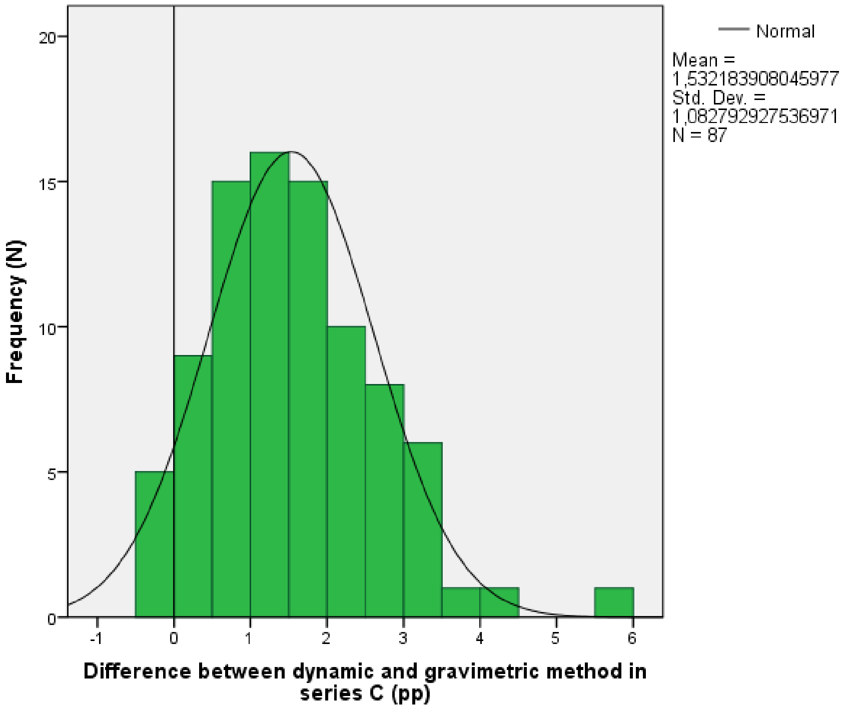


Figure 27. The difference between the dynamic and the gravimetric method shown in histogram in series C.

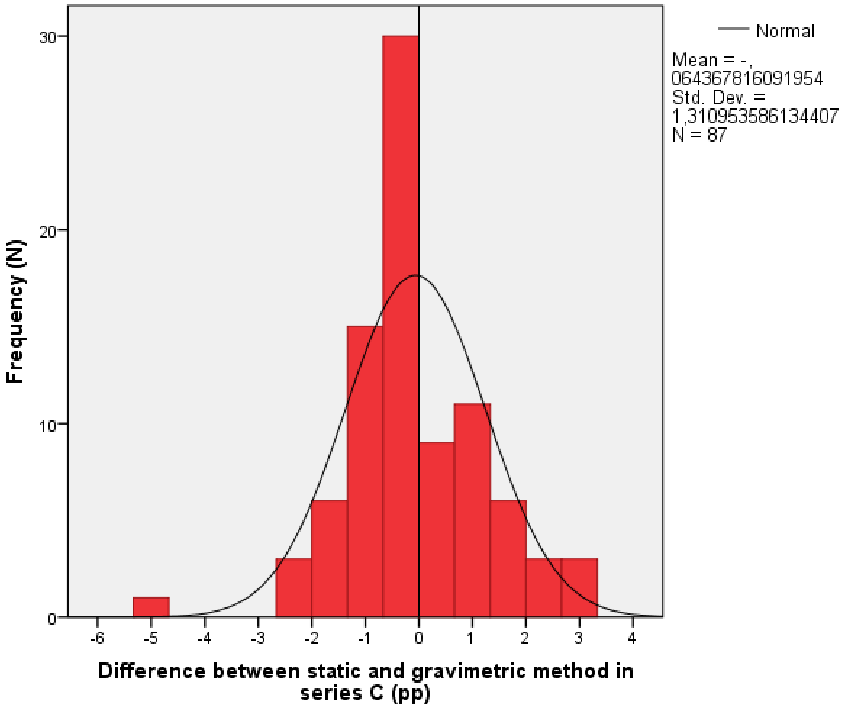


Figure 28. The difference between the static and the gravimetric method shown in histogram in series C.

4.4 Measurement of air content while mixing

The secondary goal of the research was to analyze the air-entrainment process using the CiDRA AIRtrac. The continuous measurement allows better understanding of the development of the air content in the fresh concrete. These measurements were taken during the series C when multiple admixture products were tested. The AIRtrac measured the air amount every second in the mixer throughout the whole experiment, which would be impossible to do with traditional methods that require manual labor and a specific amount of time for each measurement. These AIRtrac measurement points can be used to show the air amount a function of time.

The software was configured to collect the data as soon as the quality of the measurement exceeded the given limits. This happened about 30 to 45 seconds after the superplasticizer was added to the mixer, in the total batch time of 2–2.5 minutes. Each product combination was tested using two mixing time and AEA dosage combinations, which resulted in four batches per manufacturer.

All the concretes were first designed so that the target air was reached after two minutes of mixing with a certain dosage that was written as in 100 percent of the normal dosage on this research. Secondly, the same concretes were tested using the same recipe but the mixing time was increased to five minutes. Finally, the recipe was change so that the dosage of the AEA was cut half (50 % of the normal dosage) while keeping the w/c ratio the same.

The Figure 29 shows an example of air-entrainment development in four different concrete batches during the initial mixing. The figure shows the air measurement values that were collected during the first mixing cycle. When the mixer stopped, the measured air amount started to decrease rapidly as the vibrations from the sensor caused the air bubbles to leave the measurement area above the piston. The curves illustrate the differences in air development caused by the mixing time and dosage, which are in this case:

- The largest air amounts are seen usually just before the mixing stops.
- The smaller dosage gives the same final air amount when the concrete is mixed longer.
- The air amount increases the same speed when using a certain dosage.

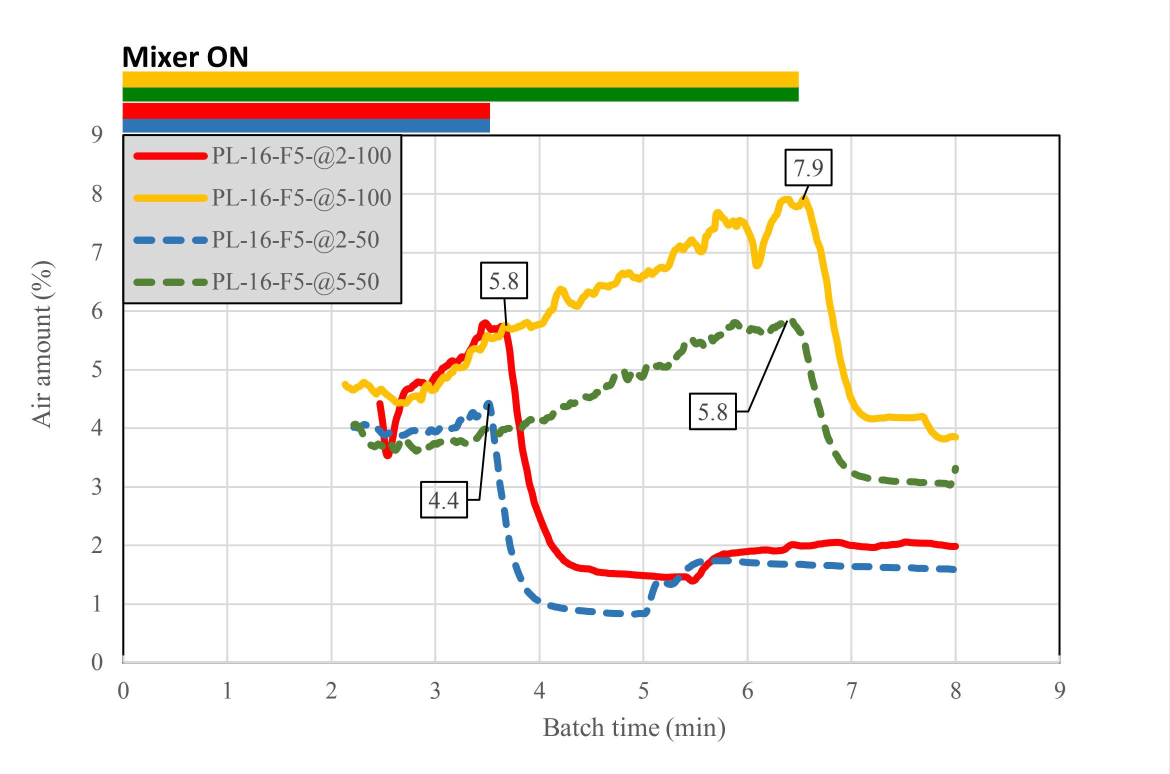


Figure 29. An example of the air-entrainment development during the initial mixing.

Differences between the admixtures products were found as seen in the Figure 30. When the dosage of the AEA was lowered to 50 percent, the development of the air in the concrete was nonexistent. This can be explained by the fact that the dosage of the AEA was decreased below the minimum recommended dosage given by the product company. Therefore, the optimal dosage is different for each product and should be analyzed for each combination separately.

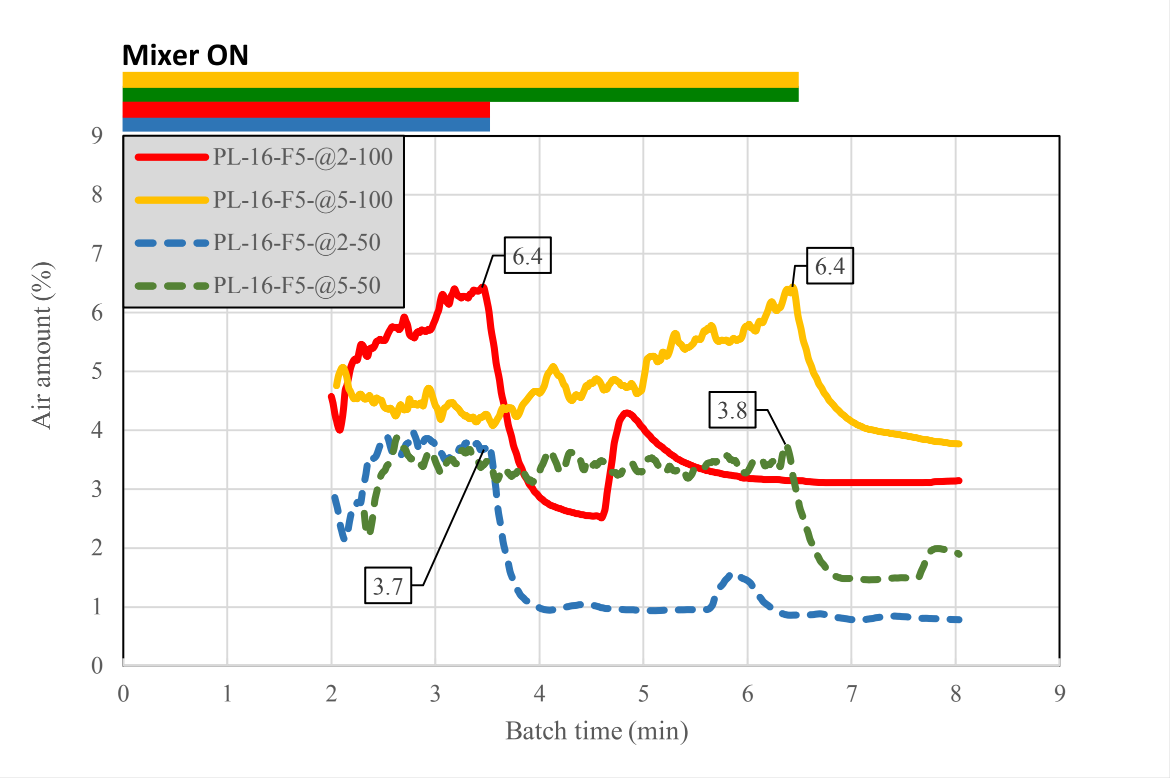


Figure 30. Example 2 of development of air-entrainment process during the initial mixing.

The Figure 31 illustrates how the air-entrainment develops during the first five minutes of mixing. All the seven concretes in the figure used had different AEA and SP combination that had the dosages adjusted so that the target air amount was reached after a total time of 3.5 minutes mixing. In addition, the dosage of SP was designed so that the set workability during that time and amount of air-entrainment. The air amount increased after 3.5 minutes linearly on most of the concretes. On many concretes, the air development seemed to continue even after five minutes of wet mixing. One of the concretes showed large air amounts after the initial mixing even though the dosage was set to recommended minimum. In concrete industry, the batch time seldom exceeds a mixing time of 2.5 minutes. Therefore, it could be questioned whether the mixing time is appropriate for the used mixer and admixtures. Ideally, the air amount development should stop by the end of the initial mixing. Furthermore, the air amount should stay stable even the concrete might get adjugated later in the supply chain.

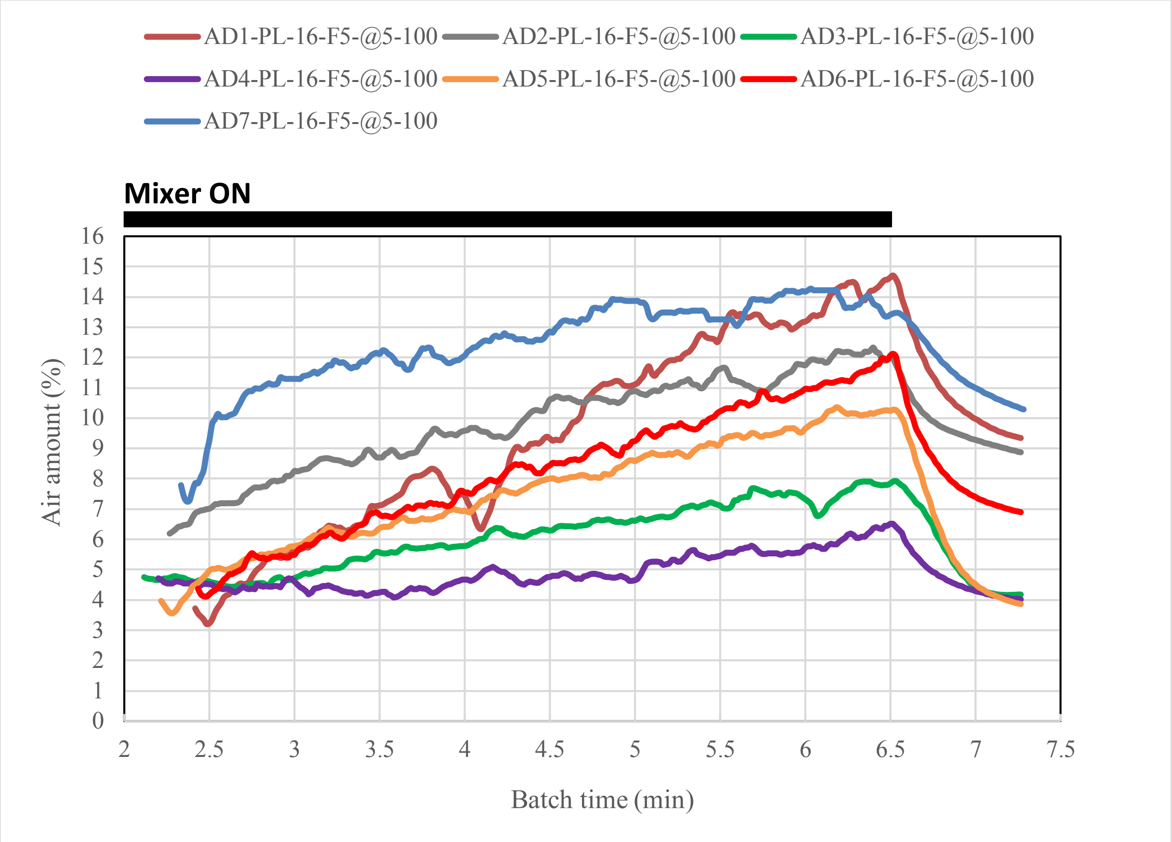


Figure 31. Comparison of air-entrainment development during 5 min mixing.

4.5 *Discussion of the experiments*

4.5.1 Discussion of the limitations

The limiting factors that might have affected the results originated from the mixer used in the experimental work. Because the mixer was plain by features, the analysis of the precision of the AIRtrac and the development of the admixture had to be simplified to on-off operation using a single rotation speed. Even though the batch sizes were relatively big for typical laboratory work, the 15-cm layer was impossible to maintain throughout the whole experiment because the material consumptions and labor intensity would have been too great. For example, the precision could have been better especially in the final cycles of the experiment if the batches were larger since the sensor unit would have been covered quicker. However, in the series C the amount of the concrete stayed adequate all the three cycles, which resulted in faster sensor coverage and therefore better precision.

In addition, the long execution time and the labor intensity of traditional methods limited the number of the measurements per concrete during the tests. To avoid fatigue from the tests, the workload was divided between the laboratory personnel each having a main task to execute. Furthermore, the division of the tasks minimized the imprecision caused by repeatability reducing the error even though the methods were executed according to the standards. On the other hand, while the mixing conditions might not represent the industrial environment exactly, the approach of this research allowed more accurate analysis of the limiting factors for the AIRtrac. The analysis between the different methods as a function of the workability showed how the precision is affected by these regressors found in this work.

The unfavorable conditions in the laboratory might have been accentuated the obtained the imprecision of the AIRtrac. Especially the combination of the loss of the material in the mixer and the large fluctuation in the plasticity of the concrete over-time could have emphasized the effects of the workability. This is because the workability lowered at the same time as the concrete amount decreased in the mixer during the measurement cycles. However, these limitations could be avoided in concrete industry since the mixers are run on higher fill ratio while having better efficiency at the same time.

4.5.2 Discussion of analysis

In all the series, the CiDRA AIRtrac seemed to give consistent accuracy and precision. However, the precision depended greatly on the amount and workability of the concrete in the mixer. The static and dynamic measurement values were calculated afterwards from the continuously collected data provided by the AIRtrac software. These measurement types were compared to the measurements taken with the traditional method. Because none of the measurement methods gave the true value of the specific property of the concrete, the measurement values from the different methods were compared to each other by regression analysis. The error amount and descriptive statistics were also calculated using the relationship between of the observations.

When all the concretes were combined, the precision of the AIRtrac was moderate in comparison to the traditional methods. The correlation between the gravimetric and pressure method was high and the dispersion of the observations was noticeable only in the relatively high air amounts. The accuracy, as in the distance to the true value, was fairly constant throughout all the concretes in all the series. The observations from the concretes were divided into three series called A, B and C. In regression analysis of these series, it was shown that the workability and the amount of the concrete in relation with the size of the mixer had most effect on the precision of the measurements. Under the conditions on this research, the size of the concrete batch was the most limiting factor in the analysis. When the concrete had better workability, the sensor was covered quicker giving more time for better measurement. The same phenomenon could be also noticed if the batch size were increased.

Series A demonstrated the reduction of the precision in the disadvantageous conditions. While the AIRtrac measurement quality was poor due to the condition in the mixer, the static measurement method gave reasonable measurement values (COD 0.6229) when compared to the dynamic and gravimetric measurement methods. The sensor just had to be covered right after the motion of the mixer stopped to take the static measurements. Moreover, the traditional methods were more difficult to execute because the compaction of the concrete came very user-dependent and thus affected both the gravimetric and pressure method.

In series B, the workability of the concrete was increased from S3 to F5 while keeping other parameters of the concrete the same. The COD for dynamic measurement increased greatly but the static measurement got even worse. Because the plasticity of the concrete was increased, the sensor was covered more quickly, which the AIRtrac more time for proper measurements. On the other hand, the extreme workability (> 600 mm) affected the static measurements negatively especially on the last measurement cycle when the additional SP dosage was put into the mixer. The worse static measurement precision could be explained by the fact that the concrete comes more easily compactable by the piston of the AIRtrac probe as the plasticity increases, which results in a lower measurement value during the measurement time of 30 seconds.

The improved conditions in the series C increased the precision of the AIRtrac. All the concretes had workability class of F5 and the batch size of 75 liters. The more focused testing protocol allowed for a minimum concrete loss throughout the experiment, which increased the measurement precision especially on the last measurement cycles. The standard deviation for the dynamic error decreased to a value of 1.08 while the standard deviation for the pressure method was calculated to have a value 0.69. Even though the error for the pressure method was calculated to be 36 percent smaller, the AIRtrac seemed to be more than adequate for industrial applications and reasonable at laboratory environment. In addition, in quality monitoring it is typically important to find defected batches that exceed the given error limits. On the other hand, the laboratory tests might need more precise measurement values in more challenging conditions.

The graphs that were created using the continuous data showed promising results in the analysis of the air-entrainment development. The dosage of the AEA was set so that the target air amount was achieved during the normal mixing time. In all the tested concretes, the air amount increased linearly during the typical time of 2 minutes of wet mixing. On most cases, the air development continued even after a wet mixing time of five minutes. Furthermore, the set of concretes were designed to have only the half of the normal AEA dosage. On some of the concretes, the target air amount was reached even on these halved dosage amounts. Because the efficiency of the used mixer in the experimental work was assumed to be below average, the air development results might have showed the exaggerated versions that could happen in the industrial mixers in practice.

5 Conclusion and aspects for the future

5.1 *Conclusion of the analysis*

It is shown that the air-entrained bubbles in the concrete are very sensitive and many factors throughout the whole supply chain affect the final air amount in the finished concrete structure. Since many factors influence the air-entrainment, all the components in the production line should be monitored to guarantee the best possible concrete quality. The quality control is currently based on measuring methods that are laborious and time-consuming. This means that the quality checking is user-dependent and highly manual, which leads inevitably to errors and even to negligence if the tests are not supervised properly. By improving the quality control these possible defects could be noticed sooner and the additional expenses avoided.

This thesis used the acoustic measurement system called CiDRA AIRtrac to analyze the air-entrainment of the concrete directly in the mixer. The system allows continuous measurements in real-time and automatically. Furthermore, it can monitor the final air amount and temperature batch by each batch making any deviations easily noticeable. The accuracy and precision of the AIRtrac measurements were analyzed by comparing the air amount of the concrete using different testing methods alongside. The experiment consisted of the total of 63 concretes that were mixed in the laboratory. They were divided into three different series that were analyzed separately to find out the viability of the AIRtrac technology in laboratory and industrial environment. In addition, the experiments revealed the effects of the limiting factors that influence the measurement precision.

The main purpose of this research was to analyze the accuracy and the precision of the new measurement system. The AIRtrac showed promising results when analyzing the concrete in the laboratory experiments. Even though the measurement conditions in the laboratory were limited, the accuracy was consistent throughout the experiments and the precision was accurate when the minimum requirements were met. The most notable limitations for the precision were found to be the batch size and the workability of the concrete. On the other hand, in the industrial applications these limitations are usually avoided because of the higher usage capacity of the mixers and in more efficient mixer types. Compared to the traditional methods, the precision was of the measurements was slightly lower. Because the systems like the AIRtrac allow operation and measurement digitally without any additional effort, they would be much more suitable for digital measurement control systems in the future.

The secondary goal of the work was to find the viability of the continuous measurement in the analysis of the air amount development. Because many of the present concretes utilize one or more additives, it is important to know exactly how the different substances work in combination. For example, the newer AEAs that are commonly used in Finland seem to be unstable over-time and might lead to elevated air contents in finished constructions. Furthermore, the many of the additives might affect the final air content undesirably especially if they are added afterwards in the construction site. Analyzing the effects of the different mixing energies and sequences using variety of additives would give leading information about the stability of the air-entrainment.

5.2 *Further studies*

The AIRtrac seems promising method to measure the air amount directly in the mixer fulfilling the requirements in the concrete station. The precision of the digitalized measurement systems could be improved by measuring the consistency of the concrete at the same time. In addition, having more information about the concrete materials themselves could increase the precision of the measurement system. However, all these factors concern just the concrete itself in the whole production line. Therefore, information about the other components in the production technology should be included also in automated quality control systems such as compaction, strength development and dehydration process of concrete.

The increased air amounts in the finished structures indicate that the current quality control of the concrete production might be inadequate. This is probably caused by multiple factors in the whole supply chain. For example, most of the quality control are done in the concrete station. Additional point measurements are done on-site manually, which makes the final steps of the quality control user-dependent and hard to monitor efficiently. Digitalization of the measurement equipment would aid the quality control and remove the human error at the same time. In practice, the digitalized control system should operate in a network called Internet of things (IoT) where many objects collect and exchange data remotely across the existing network infrastructure, which would improve the efficiency, accuracy and even economic benefit.

Moreover, the air-entrainment of concrete using different admixture with different mixers should be investigated using continuous measurement. Measuring the air amount during the mixing process allows better understanding on how the air-entrainment develops in real-time. Even though the AIRtrac could be used in replacement of traditional methods for pure air measurements, the beneficial feature of continuous measurement should be utilized in the development of admixtures and the mixers themselves. This could guarantee that the full potential of the admixtures would be used using certain mixers as efficiently as possible.

Digitalized measurement systems like the CiDRA AIRtrac will be in important role in modernizing the quality control of concrete. The future needs comprehensive means to measure the most important properties of the concrete such as air amount, workability and w/c ratio in all phases of concrete production. These measures should be done in real-time and automatically with minimum effort needed. For example, having a measurement system close to the nozzle of the concrete pump would give real-time information about the air amount and the plasticity of the concrete. In together, they would give accurate representation of the present concrete.

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List of Appendices

Appendix 1. Combined aggregates for concrete mix designs.

Table A- 1 Combined aggregates for C30/37 16 mm concrete mix design.

Fraction	Aggregate 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 1-2	15	0	1	2	7	79	100	100	100	100	100
R 2-5	15	0	0	1	1	1	47	100	100	100	100
R 5-10	18	0	0	0	0	0	3	82	100	100	100
R 8-16	20	0	0	0	0	0	0	5	99	100	100
Combined aggregates (%)	100	4	9	18	29	44	55	78	100	100	100

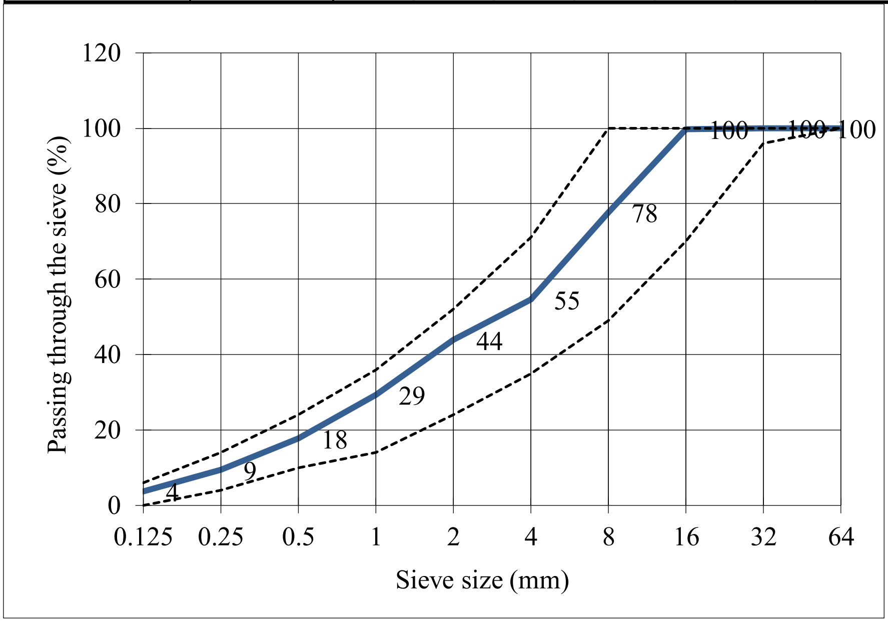


Table A- 2 Combined aggregates for C30/37 8 mm concrete mix design.

Fraction	Aggregate 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 1-2	20	0	1	2	7	79	100	100	100	100	100
R 2-5	22	0	0	1	1	1	47	100	100	100	100
R 5-10	22	0	0	0	0	0	3	82	100	100	100
R 8-16	0	0	0	0	0	0	0	5	99	100	100
Combined aggregates (%)	100	5	12	20	33	52	67	96	100	100	100

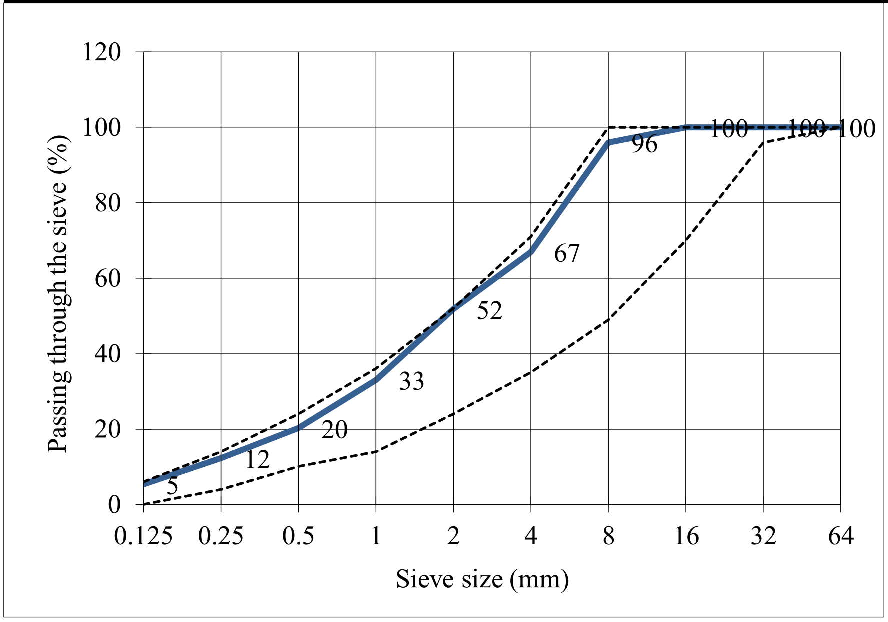


Table A- 3 Combined aggregates for C35/45 16 mm concrete mix design

Fraction	Aggregate 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 1-2	15	0	1	2	7	79	100	100	100	100	100
R 2-5	15	0	0	1	1	1	47	100	100	100	100
R 5-10	12	0	0	0	0	0	3	82	100	100	100
R 8-16	32	0	0	0	0	0	0	5	99	100	100
Combined aggregates (%)	100.00	4	9	15	24	38	48	67	100	100	100

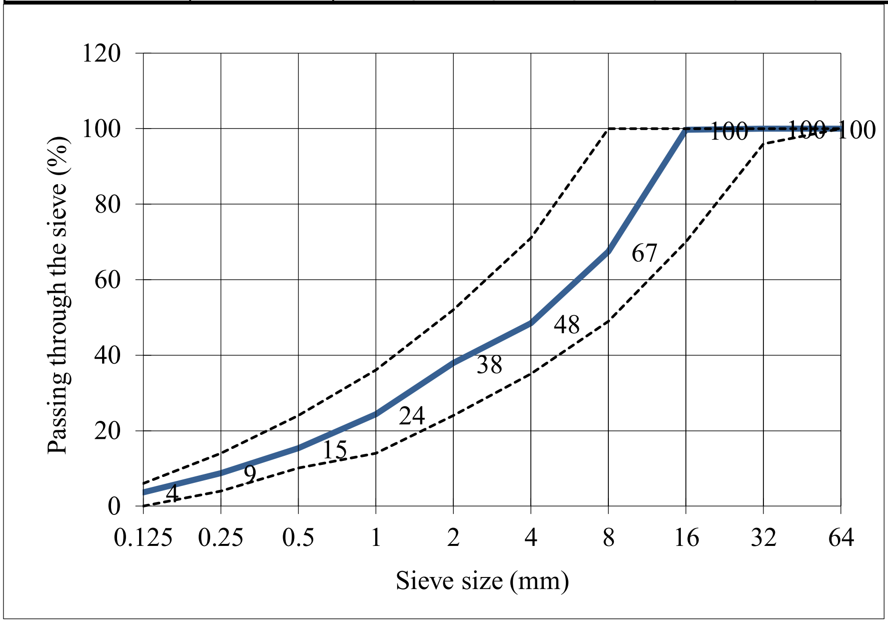
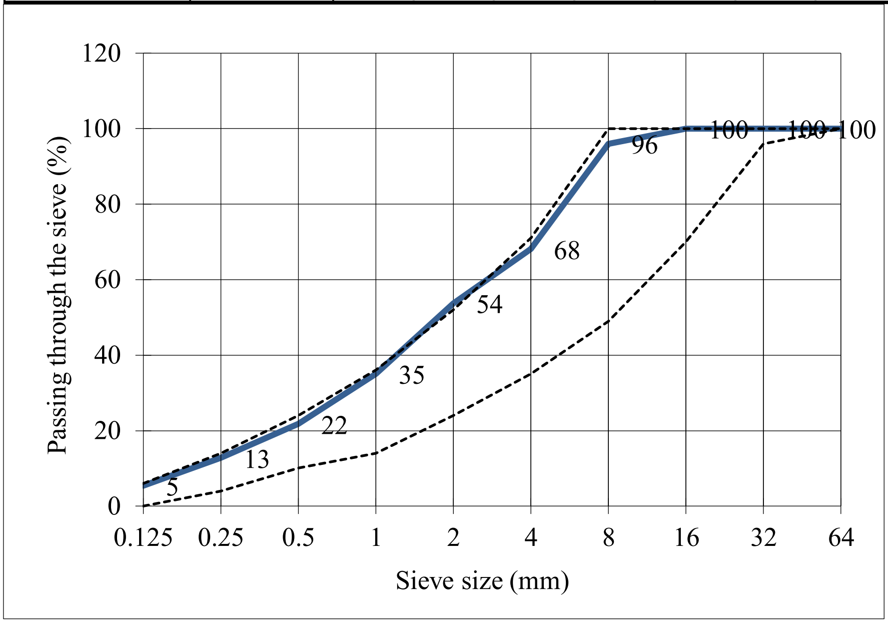


Table A- 4 Combined aggregates for C35/45 8 mm concrete mix design

Fraction	Aggregate 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 1-2	20	0	1	2	7	79	100	100	100	100	100
R 2-5	20	0	0	1	1	1	47	100	100	100	100
R 5-10	22	0	0	0	0	0	3	82	100	100	100
R 8-16	0	0	0	0	0	0	0	5	99	100	100
Combined aggregates (%)	100.00	5	13	22	35	54	68	96	100	100	100



Appendix 2. Mix design of the concretes.

Series	Concrete mix	Cement (kg)	Effective Water (kg)	Aggregate (kg)	Air-entraining agent (kg)	Superlasticizer (kg)	Target Air content (%)
A	AD1-37-BR-16-F5	400	155	1752	0.268	4.800	5.5
	AD1-37-BR-16-S3	400	140	1806	0.268	4.400	5.0
	AD1-37-PL-08-F5	420	170	1694	0.147	5.040	5.5
	AD1-37-PL-08-S3	420	160	1721	0.147	5.040	5.5
	AD1-37-PL-16-F5	400	155	1765	0.140	4.800	5.0
	AD1-37-PL-16-S3	400	140	1805	0.140	4.800	5.0
	AD1-37-SR-16-F5	400	155	1752	0.200	4.800	5.5
	AD1-37-SR-16-S3	400	140	1805	0.240	4.800	5.0
	AD1-45-BR-16-F5	425	155	1729	0.340	5.100	5.5
	AD1-45-BR-16-S3	425	140	1772	0.179	4.250	5.5
	AD1-45-PL-08-F5	440	175	1636	0.145	5.280	6.5
	AD1-45-PL-08-S3	440	155	1689	0.154	5.280	6.5
	AD1-45-PL-16-F5	425	160	1716	0.149	5.100	5.5
	AD1-45-PL-16-S3	425	140	1770	0.149	5.100	5.5
	AD1-45-SR-16-F5	425	155	1729	0.231	5.100	5.5
	AD1-45-SR-16-S3	425	140	1769	0.234	5.100	5.5
B	AD1-45-PL-16-S3	425	140	1770	0.149	5.100	5.5
	AD1-45-PL-16-F5	425	160	1716	0.149	5.100	5.5
	AD1-45-BR-16-F5	425	155	1729	0.231	5.100	5.5
	AD2-45-PL-16-S3	425	140	1766	0.234	5.100	5.5
	AD2-45-PL-16-F5	425	160	1716	0.149	6.290	5.5
	AD2-45-BR-16-F5	425	155	1729	0.140	5.313	5.5
	AD3-45-PL-16-S3	425	140	1770	0.808	3.825	5.5
	AD3-45-PL-16-F5	425	160	1717	0.323	5.440	5.5
	AD3-45-BR-16-F5	425	155	1731	0.786	4.250	5.5
	AD4-45-PL-16-S3	425	140	1767	0.264	5.653	5.5
	AD4-45-PL-16-F5	425	160	1715	0.808	4.123	5.5
	AD4-45-BR-16-F5	425	155	1728	0.145	5.738	5.5
	AD5-45-PL-16-S3	425	140	1770	0.340	4.845	5.5
	AD5-45-PL-16-F5	425	160	1716	0.850	3.613	5.5
	AD5-45-BR-16-F5	425	155	1730	0.230	5.100	5.5
	AD6-45-PL-16-S3	425	140	1768	0.417	4.335	5.5
	AD6-45-PL-16-F5	425	160	1718	0.196	4.760	5.5
	AD6-45-BR-16-F5	425	155	1731	0.230	4.420	5.5
	AD7-45-PL-16-S3	425	140	1772	0.383	3.400	5.5
	AD7-45-PL-16-F5	425	160	1720	0.213	5.185	5.5
	AD7-45-BR-16-F5	425	155	1733	0.850	2.975	5.5

Series	Concrete mix	Cement (kg)	Effective Water (kg)	Aggregate (kg)	Air-entraining agent (kg)	Superlasticizer (kg)	Target Air content (%)
C	AD1-PL-16-F5-@2-100	425	160	1716	0.074	5.1	5.5
	AD1-PL-16-F5-@2-50	425	160	1716	0.074	5.1	5.5
	AD1-PL-16-F5-@5-100	425	160	1716	0.149	5.1	5.5
	AD1-PL-16-F5-@5-50	425	160	1716	0.074	5.1	5.5
	AD1-PL-16-F5-@2-0	425	153	1736	0	4.76	5.5
	AD2-PL-16-F5-@2-100	425	160	1716	0.14	5.313	5.5
	AD2-PL-16-F5-@5-100	425	160	1716	0.14	5.313	5.5
	AD2-PL-16-F5-@2-50	425	160	1716	0.07	5.313	5.5
	AD2-PL-16-F5-@5-50	425	160	1716	0.07	5.313	5.5
	AD3-PL-16-F5-@2-100	425	160	1717	0.786	4.25	5.5
	AD3-PL-16-F5-@2-50	425	160	1718	0.393	4.25	5.5
	AD3-PL-16-F5-@5-100	425	160	1717	0.786	4.25	5.5
	AD3-PL-16-F5-@5-50	425	160	1718	0.393	4.25	5.5
	AD4-PL-16-F5-@2-100	425	160	1714	0.136	5.823	5.5
	AD4-PL-16-F5-@2-50	425	160	1715	0.068	5.823	5.5
	AD4-PL-16-F5-@5-100	425	160	1714	0.136	5.823	5.5
	AD4-PL-16-F5-@5-50	425	160	1715	0.068	5.823	5.5
	AD5-PL-16-F5-@2-100	425	160	1717	0.255	4.871	5.5
	AD5-PL-16-F5-@2-50	425	160	1717	0.128	4.781	5.5
	AD5-PL-16-F5-@5-100	425	160	1717	0.255	4.781	5.5
	AD5-PL-16-F5-@5-50	425	160	1717	0.128	4.781	5.5
	AD6-PL-16-F5-@2-100	425	160	1718	0.315	4.42	5.5
	AD6-PL-16-F5-@2-50	425	160	1718	0.157	4.42	5.5
	AD6-PL-16-F5-@5-100	425	160	1718	0.315	4.42	5.5
	AD6-PL-16-F5-@5-50	425	160	1718	0.157	4.42	5.5
	AD7-PL-16-F5-@2-100	425	160	1720	0.85	2.975	5.5
	AD7-PL-16-F5-@2-50	425	160	1721	0.425	2.975	5.5
	AD7-PL-16-F5-@5-100	425	160	1720	0.85	2.975	5.5
	AD7-PL-16-F5-@5-50	425	160	1721	0.425	2.975	5.5

Appendix 3. Table of air and workability measurements.

Series	Concrete Code	Air amount after X amount of first mixing				Testing method
		0 min	30 min	60 min	75 min	
A	AD1-45-PL-08-S3	6.8			6.9	Pressure method
		7.9	10.7	8.4	6.7	Gravimetric method
		7.9	14.9	14.4	7.7	Dynamic CiDRA AIRtrac
		6.2	11.2	4.9	6.0	Static CiDRA AIRtrac
		150	70	30	190	Slump
	AD1-37-PL-16-S3	5.7		8.0	7.2	Pressure method
		6.7	9.9	8.4	8.5	Gravimetric method
		6.7	14.4	8.9	14.8	Dynamic CiDRA AIRtrac
		3.6	11.3	8.9	8.2	Static CiDRA AIRtrac
		120	40	15	60	Slump
	AD1-37-PL-08-S3	7.2		10.0	8.4	Pressure method
		7.9	12.8	12.0	9.5	Gravimetric method
		7.9	13.5	11.2	8.4	Dynamic CiDRA AIRtrac
		6.4	10.6	11.0	7.9	Static CiDRA AIRtrac
		140	105	60	125	Slump
	AD1-45-PL-16-S3	5.4		6.2	5.6	Pressure method
		6.6	8.0	6.7	6.7	Gravimetric method
		6.1	10.3	15.0	15.1	Dynamic CiDRA AIRtrac
		5.0	7.5	5.5	9.7	Static CiDRA AIRtrac
		130	20	10	60	Slump
	AD1-45-SR-16-S3	6.5		11.5	8.5	Pressure method
		6.6	12.2	12.2	9.8	Gravimetric method
		8.4	15.1	15.0	12.3	Dynamic CiDRA AIRtrac
		6.4	12.4	12.3	6.4	Static CiDRA AIRtrac
		165	70	40	135	Slump
	AD1-37-SR-16-S3	7.4		11.5	9	Pressure method
		9.3	14.8	15.4	11.4	Gravimetric method
		11.4	14.4	15.1	14	Dynamic CiDRA AIRtrac
		8.2	13.5	13.4	9.9	Static CiDRA AIRtrac
		170	105	75	195	Slump
	AD1-45-BR-16-S3	6.6		8.4	8.3	Pressure method
		7.4	12.5	11.2	11.1	Gravimetric method
		8.5	13.7	14.8	14.3	Dynamic CiDRA AIRtrac
		7.9	13.1	12.6	9.6	Static CiDRA AIRtrac
		200	95	38	90	Slump

A	AD1-37-BR-16-S3	5.6		15.1	12	Pressure method
		6.1	14.1	16.7	13.6	Gravimetric method
		7.4	15.1	15	15	Dynamic CiDRA AIRtrac
		5.6	13.9	15.1	13.5	Static CiDRA AIRtrac
		226	188	130	215	Slump
	AD2-AEA5-45-PL-16-S3	6		4	3.5	Pressure method
		7	2.5	3.1	3.3	Gravimetric method
		11.3	8	5.4	13.3	Dynamic CiDRA AIRtrac
		10.5	6.5	4.3	7.5	Static CiDRA AIRtrac
		75	8	0	25	Slump
	AD3-45-PL-16-S3	5.3		5.4	4.2	Pressure method
		6.3	6.3	5.6	5.2	Gravimetric method
		7.9	5.3	4.8	4.4	Dynamic CiDRA AIRtrac
		5	5	4.6	4.2	Static CiDRA AIRtrac
		145	60	70	220	Slump
	AD4-45-PL-16-S3	6.2		5.8	4.5	Pressure method
		7.7	6.5	6.7	10.1	Gravimetric method
		8.8	8.1	7.1	5.1	Dynamic CiDRA AIRtrac
		7.7	8.1	6.9	4.2	Static CiDRA AIRtrac
		123	75	43	181	Slump
	AD5-45-PL-16-S3	4.3		5.8	4.8	Pressure method
		5.6	5.4	6.8	5.6	Gravimetric method
		5.8	6.8	8.1	6.9	Dynamic CiDRA AIRtrac
		4.9	6.7	7.2	4.8	Static CiDRA AIRtrac
		158	107	53	185	Slump
	AD6-45-PL-16-S3	4.1		6.8	3.9	Pressure method
		5.5	6.4	7.6	4.4	Gravimetric method
		5.1	6.1	7.3	8.4	Dynamic CiDRA AIRtrac
		3.2	5.8	6.4	4.8	Static CiDRA AIRtrac
		113	91	62	215	Slump
	AD7-45-PL-16-S3	11		3	2.9	Pressure method
		13	4.3	4.6	3.7	Gravimetric method
		15.1	8.8	3	2.1	Dynamic CiDRA AIRtrac
		13.9	3.1	1.8	1.8	Static CiDRA AIRtrac
		168	43	25	130	Slump

Series	Concrete Code	Air amount after X amount of first mixing				Testing method
		0 min	30 min	60 min	75 min	
B	AD1-45-PL-16-F5	5.8			5.9	Pressure method
		6.6	12.0	13.2	7.1	Gravimetric method
		7.6	15.0	15.1	8.5	Dynamic CiDRA AIRtrac
		5.1	12.9	14.0	6.1	Static CiDRA AIRtrac
		586	445	388	643	Flow
	AD1-45-PL-08-F5	5.5		15.5	7.5	Pressure method
		6.3	13.9	14.8	8.6	Gravimetric method
		6.9	15.0	15.0	8.8	Dynamic CiDRA AIRtrac
		4.0	14.2	13.5	8.1	Static CiDRA AIRtrac
		655	475	425	589	Flow
	AD1-37-PL-16-F5	5.6		13.4	8.5	Pressure method
		6.6	13.8	13.6	9.3	Gravimetric method
		7.2	15.0	14.6	9.9	Dynamic CiDRA AIRtrac
		3.7	13.9	14.3	10.2	Static CiDRA AIRtrac
		545	425	400	500	Flow
	AD1-37-PL-08-F5	4.8		14.4	10.6	Pressure method
		5.1	13.9	15.9	12.7	Gravimetric method
		6.8	14.9	15.0	14.0	Dynamic CiDRA AIRtrac
		3.6	13.9	14.0	10.9	Static CiDRA AIRtrac
		565	445	398	503	Flow
	AD1-45-SR-16-F5	5.6		13.0	7.8	Pressure method
		6.8	15.0	15.4	9.6	Gravimetric method
		7.7	15.1	15.1	12.2	Dynamic CiDRA AIRtrac
		4.3	12.2	10.3	10.7	Static CiDRA AIRtrac
		583	488	445	660	Flow
	AD1-37-SR-16-F5	3.7		14.8	10	Pressure method
		4.6	11.5	15.6	11.7	Gravimetric method
		5.6	12.5	15.1	13.3	Dynamic CiDRA AIRtrac
		3.5	10.7	12.7	10.0	Static CiDRA AIRtrac
		580	515	470	633	Flow
	AD1-45-BR-16-F5	7.2		13.5	10.6	Pressure method
		7.8	14.8	17.4	14	Gravimetric method
		9.8	15	15.1	14.9	Dynamic CiDRA AIRtrac
		8.5	13.8	14.9	14.3	Static CiDRA AIRtrac
		578	485	415	567	Flow

B	AD1-37-BR-16-F5	6.5		15	12.9	Pressure method
		6.8	12	16.2	13.5	Gravimetric method
		7.2	14.5	15	15	Dynamic CiDRA AIRtrac
		4.8	11.6	14.8	8.6	Static CiDRA AIRtrac
		670	565	475	648	Flow
	AD5-45-PL-16-F5	6.9		5.7	7.2	Pressure method
		7.9	7.3	6.7	8	Gravimetric method
		11.4	11.1	9.1	12.2	Dynamic CiDRA AIRtrac
		9.7	9.9	8	11.2	Static CiDRA AIRtrac
		499	490	459	497	Flow
	AD5-45-BR-16-F5	6.6		5.6	6.5	Pressure method
		7.6	7.5	6.4	6.6	Gravimetric method
		10.6	10.5	11.1	10.6	Dynamic CiDRA AIRtrac
		9.5	9.8	9.3	9.6	Static CiDRA AIRtrac
		610	450	393	443	Flow
	AD3-45-PL-16-F5	5.6		8.1	3	Pressure method
		5.7	8.4	9.6	4.1	Gravimetric method
		7.6	10.8	11.3	9.3	Dynamic CiDRA AIRtrac
		3.2	8.3	10.5	4.9	Static CiDRA AIRtrac
		568	497	472	700	Flow
	AD3-45-BR-16-F5	5.5		7.6	5.5	Pressure method
		6.5	6.9	8.5	5.9	Gravimetric method
		8.1	11.2	11.0	8.6	Dynamic CiDRA AIRtrac
		7.1	10.3	11.6	3.3	Static CiDRA AIRtrac
		618	555	484	648	Flow
	AD4-45-PL-16-F5	7		9.5	5.6	Pressure method
		8.6	10.4	11.5	6.9	Gravimetric method
		11.9	12.7	13.7	8.2	Dynamic CiDRA AIRtrac
		9.2	11	12.6	7.5	Static CiDRA AIRtrac
		573	518	484	635	Flow
	AD4-45-BR-16-F5	7		10.5	7.7	Pressure method
		7.8	9.8	11.9	9	Gravimetric method
		10.4	11.7	14.3	11.6	Dynamic CiDRA AIRtrac
		6.6	7.6	9.5	4.9	Static CiDRA AIRtrac
		659	583	556	658	Flow
	AD5-45-PL-16-F5	6.3		11	1.5	Pressure method
		6.1	10.7	11.9	2	Gravimetric method
		9.1	12.9	13.6	3.5	Dynamic CiDRA AIRtrac
		5.5	7.4	9.9	2.4	Static CiDRA AIRtrac
		664	615	510	700	Flow

B	AD5-45-BR-16-F5	6.4		11	7.2	Pressure method
		6.4	9.9	12.1	7.1	Gravimetric method
		8.6	13.0	14.6	13.1	Dynamic CiDRA AIRtrac
		5.9	9.2	12.9	12.5	Static CiDRA AIRtrac
		650	599	488	590	Flow
	AD6-45-PL-16-F5	4.2		9.8	2.8	Pressure method
		4.9	7.5	10.4	3.2	Gravimetric method
		6.6	7.6	11.8	8.6	Dynamic CiDRA AIRtrac
		4.7	7.3	10.5	8.5	Static CiDRA AIRtrac
		565	483	479	700	Flow
	AD6-45-BR-16-F5	5.9		14.5	8.7	Pressure method
		5.9	12.2	15.1	9	Gravimetric method
		9.5	14.8	15.0	12.5	Dynamic CiDRA AIRtrac
		5.8	9.8	13.1	8.8	Static CiDRA AIRtrac
		670	593	540	678	Flow
	AD7-45-PL-16-F5	5.9	3.2	3.1	2.7	Pressure method
		6.8	3.9	3.4	3	Gravimetric method
		8.7	5	3.8	5.9	Dynamic CiDRA AIRtrac
		5.3	3.9	3.4	3.8	Static CiDRA AIRtrac
		520	394	340	516	Flow
	AD7-45-BR-16-F5	6.6		3	2.2	Pressure method
		8.3	3.4	3.5	3.1	Gravimetric method
		11.2	6.1	6.0	5.1	Dynamic CiDRA AIRtrac
		8.2	4.8	4.7	3.8	Static CiDRA AIRtrac
		591	461	418	585	Flow

Series	Concrete Code	Air amount after X amount of first mixing				Testing method
		0 min	30 min	60 min	75 min	
C	AD1-PL-16-F5-@2-100	6	10.4	11.4		Pressure method
		6.2	13.3	14.4		Gravimetric method
		6.7	14.8	14.9		Dynamic CiDRA AIRtrac
		5.1	14.2	14.2		Static CiDRA AIRtrac
		605	430	383		Flow
	AD1-PL-16-F5-@2-50	2.9	6.9	9.1		Pressure method
		4.1	8.3	11.2		Gravimetric method
		3.7	8.6	12.5		Dynamic CiDRA AIRtrac
		1.9	7	9.9		Static CiDRA AIRtrac
		570	471	419		Flow
	AD1-PL-16-F5-@5-100	10	11.7	11.4		Pressure method
		13.3	14.8	13.5		Gravimetric method
		14.6	14.8	13.4		Dynamic CiDRA AIRtrac
		11.6	13.8	8.6		Static CiDRA AIRtrac
		470	408	390		Flow
	AD1-PL-16-F5-@5-50	4	5.9	8		Pressure method
		4.9	7.5	8.7		Gravimetric method
		5.2	7.9	9.9		Dynamic CiDRA AIRtrac
		3.4	7	8.7		Static CiDRA AIRtrac
		529	429	429		Flow
	AD1-PL-16-F5-@2-0	1.7	2.8	3.3		Pressure method
		2.8	4	4		Gravimetric method
		3.7	4.9	4.2		Dynamic CiDRA AIRtrac
		2	3.6	3.7		Static CiDRA AIRtrac
		459	349	323		Flow
	AD2-PL-16-F5-@2-100	5.6	8	8.5		Pressure method
		7	9.3	9.9		Gravimetric method
		8	13	12.5		Dynamic CiDRA AIRtrac
		6.3	12.1	12.3		Static CiDRA AIRtrac
		494	423	366		Flow
	AD2-PL-16-F5-@5-100	8.1	9	7.6		Pressure method
		9.8	10.9	8.8		Gravimetric method
		12.2	13.1	10.4		Dynamic CiDRA AIRtrac
		10.7	12.9	9.9		Static CiDRA AIRtrac
		468	394	331		Flow

C	AD2-PL-16-F5-@2-50	5,1	5,8	5,3	Pressure method
		5,1	6,5	5,5	Gravimetric method
		6,1	7,5	8,3	Dynamic CiDRA AIRtrac
		5,6	7,5	7	Static CiDRA AIRtrac
		513	405	358	Flow
	AD2-PL-16-F5-@5-50	5,8	6,2	5,6	Pressure method
		6,2	6,9	6,6	Gravimetric method
		7,8	10,9	9,8	Dynamic CiDRA AIRtrac
		7	10,1	9	Static CiDRA AIRtrac
		485	400	390	Flow
	AD3-PL-16-F5-@2-100	4,1	6,5	8,4	Pressure method
		5	7,9	9,2	Gravimetric method
		5,7	8,8	11,5	Dynamic CiDRA AIRtrac
		3,5	7,6	8,9	Static CiDRA AIRtrac
		643	573	536	Flow
	AD3-PL-16-F5-@2-50	2,9	5,6	6,7	Pressure method
		3,6	6,3	8,2	Gravimetric method
		5,7	8,8	11,5	Dynamic CiDRA AIRtrac
		3,5	7,6	8,9	Static CiDRA AIRtrac
		606	526	496	Flow
	AD3-PL-16-F5-@5-100	5,6	7,6	8,8	Pressure method
		6,5	8,3	9,2	Gravimetric method
		7,8	9,8	12,3	Dynamic CiDRA AIRtrac
		6	9,3	9,7	Static CiDRA AIRtrac
		620	560	525	Flow
	AD3-PL-16-F5-@5-50	4,7	7,2	9,4	Pressure method
		5,2	8,2	10,2	Gravimetric method
		5,8	8,6	11,7	Dynamic CiDRA AIRtrac
		4,6	8,1	9,8	Static CiDRA AIRtrac
		625	527	506	Flow
	AD4-PL-16-F5-@2-100	4,5	6,8	8,4	Pressure method
		5,5	7,4	9,2	Gravimetric method
		6,4	9,8	15	Dynamic CiDRA AIRtrac
		4,3	8,3	12,1	Static CiDRA AIRtrac
		580	493	467	Flow
	AD4-PL-16-F5-@2-50	2,4	3	4,1	Pressure method
		3	4,4	5,3	Gravimetric method
		3,7	4,7	5,2	Dynamic CiDRA AIRtrac
		1,7	4,1	4,4	Static CiDRA AIRtrac
		494	435	427	Flow

C	AD4-PL-16-F5-@5-100	4.6	7.1	9		Pressure method
		5.6	8.1	10		Gravimetric method
		6.4	9.6	12.6		Dynamic CiDRA AIRtrac
		5	8.1	11.7		Static CiDRA AIRtrac
		533	480	483		Flow
	AD4-PL-16-F5-@5-50	2.7	4.6	6.3		Pressure method
		3	5.1	6.2		Gravimetric method
		3.7	7	8.4		Dynamic CiDRA AIRtrac
		2.2	5.7	6.2		Static CiDRA AIRtrac
		524	453	433		Flow
	AD5-PL-16-F5-@2-100	6.1	7.9	10.5		Pressure method
		6.8	9	10.8		Gravimetric method
		7.1	10.8	13.4		Dynamic CiDRA AIRtrac
		6	9.4	12.4		Static CiDRA AIRtrac
		650	620	459		Flow
	AD5-PL-16-F5-@2-50	4.3	7.2	9		Pressure method
		5.3	8.7	11.2		Gravimetric method
		5.7	9.7	11.9		Dynamic CiDRA AIRtrac
		3.6	6.8	10.8		Static CiDRA AIRtrac
		665	610	555		Flow
	AD5-PL-16-F5-@5-100	8.2	9.8	12		Pressure method
		9	10.1	13.4		Gravimetric method
		10.3	12.4	14.6		Dynamic CiDRA AIRtrac
		6.9	9.6	13.7		Static CiDRA AIRtrac
		628	570	475		Flow
	AD5-PL-16-F5-@5-50	4.6	7.1	9.4		Pressure method
		5.8	8.3	10.8		Gravimetric method
		6.4	9.3	12.9		Dynamic CiDRA AIRtrac
		4.3	7.7	12.3		Static CiDRA AIRtrac
		639	551	445		Flow
	AD6-PL-16-F5-@2-100	4	7.7	10.6		Pressure method
		4.9	9	12		Gravimetric method
		6.3	10.7	14.7		Dynamic CiDRA AIRtrac
		3.7	8.7	13.8		Static CiDRA AIRtrac
		593	500	470		Flow
	AD6-PL-16-F5-@2-50	2.5	5.5	6.7		Pressure method
		3.2	6.1	7.4		Gravimetric method
		5.1	6.8	8.6		Dynamic CiDRA AIRtrac
		3.5	5.6	7		Static CiDRA AIRtrac
		649	481	426		Flow

C	AD6-PL-16-F5-@5-100	8	10.6	12		Pressure method
		9.5	12.8	15.5		Gravimetric method
		12	14.5	15.1		Dynamic CiDRA AIRtrac
		8.9	13.5	15		Static CiDRA AIRtrac
		564	485	462		Flow
	AD6-PL-16-F5-@5-50	4.9	6.8	7.7		Pressure method
		5.7	8.3	9.2		Gravimetric method
		7.3	9.4	11.3		Dynamic CiDRA AIRtrac
		5	8.9	8.9		Static CiDRA AIRtrac
		530	463	482		Flow
	AD7-PL-16-F5-@2-100	5.9	3.2	3.1		Pressure method
		6.8	3.9	3.4		Gravimetric method
		8.7	5	3.8		Dynamic CiDRA AIRtrac
		5.3	3.9	3.4		Static CiDRA AIRtrac
		520	394	340		Flow
	AD7-PL-16-F5-@2-50	6.3	3.2	3.6		Pressure method
		7.8	3.7	4		Gravimetric method
		9.5	7.1	4.7		Dynamic CiDRA AIRtrac
		5.5	5.6	4.4		Static CiDRA AIRtrac
		534	375	342		Flow
	AD7-PL-16-F5-@5-100	8.6	3.3	3.5		Pressure method
		10.8	3.5	4.7		Gravimetric method
		13.9	9.3	4.6		Dynamic CiDRA AIRtrac
		12.9	6.6	3.8		Static CiDRA AIRtrac
		507	372	358		Flow
	AD7-PL-16-F5-@5-50	8.4	3.4	3.3		Pressure method
		10.4	4.1	4.1		Gravimetric method
		13.1	5.3	4		Dynamic CiDRA AIRtrac
		9.3	4.5	3.6		Static CiDRA AIRtrac
		543	372	376		Flow

Appendix 4. Descriptive statistics of the precision analysis.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation	Variance	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
Pressure - Gravimetric	183	-5,6	,9	-1,0934	,8918	,795	-1,990	,180
Dynamic - Gravimetric	200	-5,0	10,0	1,6954	1,6768	2,812	,354	,172
Static - Gravimetric	200	-5,9	5,4	-,1771	1,7327	3,002	,113	,172
A Pressure - Gravimetric	44	-5,6	,9	-1,3386	1,2615	1,591	-1,867	,357
A Dynamic - Gravimetric	48	-5,0	10,0	1,1208	2,5445	6,474	,659	,343
A Static - Gravimetric	48	-5,9	4,2	-,6917	2,0024	4,010	-,028	,343
B Pressure - Gravimetric	63	-3,9	,7	-,9333	,7696	,592	-1,358	,302
B Dynamic - Gravimetric	65	,1	6,0	2,3380	1,3074	1,709	,705	,297
B Static - Gravimetric	65	-4,1	5,4	,0519	1,9524	3,812	,449	,297
C Pressure - Gravimetric	76	-3,5	,1	-1,0842	,6863	,471	-1,315	,276
C Dynamic - Gravimetric	87	-,4	5,8	1,5322	1,0828	1,172	,911	,258
C Static - Gravimetric	87	-4,9	3,2	-,0644	1,3110	1,719	-,016	,258
Valid N (listwise)	0							