Nordic Concrete Research – Publ. No. NCR 71 – ISSUE 2/ 2024 – Article 5, pp. 91-110

sciendo	Nordic Concrete Federation
	ISSN online 2545-2819 ISSN print 0800-6377
DOI: 10.2478/ncr-2024-0015	Received: Sept. 30, 2024 Revision received: Dec. 18, 2024 Accepted: Dec. 19, 2024

Automatic Measurement Techniques for Compositional Properties of Fresh Concrete: Focus on Water/Cement Ratio and Air Content

Teemu Ojala
M.Sc., Doctoral Researcher
Department of Civil Engineering
School of Engineering, Aalto University
P.O. Box 12100, FIN-00076, Espoo, Finland
e-mail: teemu.ojala@aalto.fi

Jouni Punkki
Ph.D., Professor of Practice
Department of Civil Engineering
School of Engineering, Aalto University
P.O. Box 12100, FIN-00076, Espoo, Finland
e-mail: jouni.punkki@aalto.fi

ABSTRACT
Current testing methods for fresh concrete are time-consuming and operator-dependent and, thus, should be replaced with automatic testing methods. This study investigated automated measurement techniques for determining water/cement (*w/c*) ratio and air content in fresh concrete, addressing this need for more efficient and continuous quality control. The research compared microwave absorption (MWA) and time-domain reflectometry (TDR) techniques for *w/c* ratio measurement as well as acoustic wave propagation (AWP) technique for air content measurement, against the reference testing methods. Laboratory investigations were conducted on various concrete mix compositions. Results showed that MWA and TDR techniques demonstrated a good correlation with reference methods for *w/c* ratio (R^2 = 0.808 and 0.858, respectively), but were sensitive to air content variations. The AWP technique for air content

measurement showed a moderate correlation with the pressure method (R^2 = 0.654 for static measurements), with accuracy influenced by concrete consistency. The study highlights the potential of these automated techniques for real-time concrete quality control, while also revealing limitations related to mix composition variations and calibration requirements. These findings contribute to the ongoing development of more precise and reliable automated measurement systems for fresh concrete properties, supporting the move towards advanced quality control methods.

Key words: testing method, measurement, fresh concrete, sensor, automation

1. INTRODUCTION

1.1 Background

Concrete is one of the most widely used construction materials globally, valued for its versatility, durability, and strength. The quality and performance of concrete are heavily influenced by its compositional properties [1]. Particularly, water/cement (*w/c*) ratio and air content both in the fresh and hardened concrete are critical parameters in cold climates. These properties play crucial roles in determining the workability and compactibility of fresh concrete and as well as strength and long-term durability of hardened concrete [2]. The drive for low-carbon concretes also sets challenges for producing concretes with consistent quality with more complex mix compositions. Hence, it must be ensured that all the concrete loads align with compositional requirements as it leaves the ready-mix plant.

European concrete standard EN 206 [3] and its national appendices set requirements for the *w/c* ratio of concrete. While the variation of concrete constituents in a batched concrete should be within ± 3%, the *w/c* ratio should be within ± 0.04 of the specified value. In practice, *w/c* ratio of a concrete batch is determined by weighing the constituents to the mixer, which commonly relies on daily estimations for moisture content of aggregate. However, the water content of the batched concrete fluctuates during production since the aggregate can contain up to 10% surface moisture content. The risk is increased when the aggregate is exposed to precipitation in cold climates. Even small variation in the moisture content has a significant impact on the *w/c* ratio. For instance, a change of 15 kg/m³ in water content may cause noticeable changes in strength, durability, and cohesiveness in production of ready-mix concrete [4], also increasing the slump class of the mixture [5]. As such, Hover [6] notes that the moisture content must be controlled to attain the target properties of concrete.

Various measurement techniques have been proposed to measure the water content as summarised by Mardmomen et al. [7]. For example, automated techniques such as time-domain reflectometry [8], electromagnetic sorption [9] techniques, nuclear gauges [10] and ground-penetrating radar [11] has been researched in order to measure the water content in fresh concrete. Many of these techniques are based on measuring the dielectric properties of fresh concrete [12]. Nevertheless, the weight loss due to the heating with microwave oven remains to be believed the most effective method to determine the moisture content in the fresh concrete [7, 8, 13, 14]. These real-time measurement systems for water content can be also used to evaluate the effectiveness of the mixing process [15]. Regardless of the past studies, little knowledge about their sensitivity or applicability can be found in more recent literature.

Concrete is often air-entrained to improve the freeze-thaw resistance of concrete by adding air-entraining agent (AEA) to the mixture during the mixing process. To reach a sufficient quality of air-entrainment, a target air content is set to approximately 4–7% by volume as typically required by the national appendices. A proper air entrainment provides protective spaces for water to expand when it freezes, significantly reduces internal stresses and subsequent cracking in hardened concrete [16]. However, controlling the amount of air content is a delicate process, which is affected by multiple factors during the production. While insufficient air content can lead to poor freeze-thaw resistance, excessive air can greatly reduce compressive strength of the concrete [2]. For instance, it has been shown that an increase of 1% in air content per volume often decreases compressive strength approximately by 5% [16]. Al-Neshawy et al. [17] observed that combination of superplasticisers (SPs) and AEAs may cause unstable air-void system. Recently, X. Wang et al. [18] demonstrated further that the unstable air-void system, caused by unreacted AEA, may also increase the air content of concrete during excessive high-frequency compaction with poker vibrators. These challenges in air-entraining underscore the importance for continuous and real-time measurement of air content during the concrete production.

Even though achieving the correct air content is essential, few measurement methods exist for concrete. The standardised pressure method (EN 12350-7 [19]) is the most used method to quantify the air content, but it is time-consuming and user-dependent to perform. For more qualitative analysis, an air-void analysis, such as the standard EN 480-11 [20], can be used to verify the frost resistance for freeze-thaw cycles. Evaluating hardened concrete causes even more delays for the quality control. Fortunately, a good correlation exists between the fresh concrete and the hardened concrete [21], which is necessary for measuring air content of fresh concrete. Automated measurements for air content have seen little innovation, except the introduction of acoustic measurement technique, which uses the speed of sound to estimate the volumetric air content [22]. However, little peer-reviewed literature can be found for the technique.

The advent of automated measurement techniques represents a significant advancement in concrete quality control where they potentially offer automated adjustments in real-time and reduced reliance on manual testing and human interpretation. These advanced methods show great promise and alternative to traditional methods, but their reliability is not fully studied under controlled settings.

1.2 Scope of the paper

This study aims to evaluate the most prominent automated measurement methods to determine *w/c* ratio and air content that can be used during the mixing process of concrete. The scope of this paper comprises the following key elements:

- The objective of this paper is to assess the reliability and practical applicability of the selected measurement techniques. The study involves a combination of literature review, laboratory testing, and comparative analysis.
- The experimental investigation focuses on three automated measurement techniques: two dielectric-based techniques for determining *w/c* ratio and an acoustic technique for estimating air content in fresh concrete. The results of these automated techniques are compared to reference testing methods.

2. EXPERIMENTAL PROGRAM

The experimental program in the following subsections is divided into two sections where two laboratory investigations are described in parallel. In the first subsection, the investigation for determining the *w/c* ratio is discussed. In the second subsection, the investigation for determining air content is discussed.

2.1 Materials and mix composition

Water/cement ratio

For the investigation of *w/c* ratio, nine different mix compositions were designed (Table 1). The mix compositions consisted of three *w/c* ratios (0.40, 0.50, and 0.60) where in each *w/c* ratio three air content levels were targeted (2%, 5%, and 10%). The dosage of AEA varied between 0.009 and 0.200 kg/m³ depending on the targeted air content values. The cement type was CEM II/B-M (S-LL) 42.5 N and the amount of cement ranged between 300 and 400 kg/m³. For each *w/c* ratio, seven different aggregate fractions were portioned to ensure cohesiveness of the mixture. The combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixtures are presented in Tables A.1–A.3 of Appendix A. Since the air content was radically different among same *w/c* ratio, the aggregate amount in the mix compositions varied between 1631 and 1911 kg/m³. The aggregate fractions, except the filler, were granitic gravel that were washed and sieved by the manufacturer. The water absorption of the aggregate was 0.8% by mass, which was considered in calculations regarding the effective water content. The water content was 160 kg/m³ for the mix compositions with *w/c* ratios of 0.40 and 0.50 and 180 kg/m³ for the mix compositions with *w/c* ratio of 0.60. The workability was adjusted using SP to achieve the desired consistency. As seen in the table, the slump values of the concrete mixtures were 140–230 mm and the air content values were 2.1–11.0% by following the standards EN 12350-2 [23] and EN 12350-7 [19], respectively.

Table 1 – The mix compositions and fresh concrete results for w/c ratio investigation.

Concrete code	Cement (kg/m³)	Water (kg/m³)	Aggregate (kg/m³)	AEA (kg/m³)	SP (kg/m³)	Slump (mm)	Air content (%)
A-0.40-A2	400	160	1838	-	4.8	190	2.8
B-0.40-A5	400	160	1761	0.016	3.6	150	5.8
C-0.40-A10	400	160	1631	0.200	2.0	140	9.2
D-0.50-A2	320	160	1911	-	2.8	160	2.1
E-0.50-A5	320	160	1833	0.011	1.9	170	7.3
F-0.50-A10	320	160	1720	0.160	1.6	170	11.0
G-0.60-A2	300	180	1877	-	1.8	170	4.0
H-0.60-A5	300	180	1801	0.009	0.4	190	5.9
I-0.60-A10	300	180	1668	0.162	-	230	9.1

Air content

For the investigation of air content, eight concrete mixtures were batched (Table 2). The *w/c* ratio of these concretes varied between 0.33 and 0.35. The water content in all mixtures was set to 140 kg/m³ and cement content was 425 kg/m³, except for the mixture A-S120 that had cement content of 400 kg/m³. The cement type was CEM II/B-M (S-LL) 42.5 N. The investigation of air content used the same aggregate fractions as the investigation of *w/c* ratio, but the gradation of the aggregates was the same in all the mix compositions. The combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixture is presented in Table A.4 of

Appendix A. As such, the amount of aggregate only varied between 1766 and 1805 kg/m³. The dosage of AEA ranged between 0.140 and 0.850 kg/m³, which was influenced by the relatively high dosage of SP (3.613–9.290 kg/m³). For the mix concrete mixtures, the fresh concrete testing showed slumps of 80–170 mm and air contents of 4.1–11.0%, as shown in the table.

Table 2 – The mix compositions and fresh concrete results for air content investigation.

Concrete code	Cement (kg/m³)	Water (kg/m³)	Aggregate (kg/m³)	AEA (kg/m³)	SP (kg/m³)	Slump (mm)	Air content (%)
A-S120	400	140	1805	0.140	4.8	120	5.7
B-S130	425	140	1770	0.149	5.1	130	5.4
C-S80	425	140	1766	0.149	6.3	80	6.0
D-S150	425	140	1770	0.808	4.1	150	5.3
E-S120	425	140	1767	0.136	6.0	120	6.2
F-S160	425	140	1770	0.196	4.8	160	4.3
G-S110	425	140	1768	0.323	5.4	110	4.1
H-S170	425	140	1772	0.850	3.6	170	11.0

2.2 Methods for experimental investigation

The reference testing methods for determining of the *w/c* ratio and the air content are the calculation based on the batching information and the pressure method, respectively. In this subsection, the selected automated techniques are described for the experimental program.

Water/cement ratio
A microwave absorption (MWA) technique was used to estimate the *w/c* ratio directly in the mixer based on the measured moisture ratio and known cement content of the mixture. The MWA system consists of a sensor and a computer software to collect the data in real-time. The sensor can be installed inside a mixer, a conveyer belt, or a hopper based on the need of the application. For this investigation, an in-mixer sensor was selected as all the aggregates are oven dry.

The sensor radiates a low power field of microwave energy above the sensor. The amount of energy absorbed is affected by the dielectric properties of the material adjacent to the sensor. According to the manufacturer, increasing the moisture ratio also shifts the detected frequency component, which causes amplitude of the response to decrease. As this lowers the apparent response, using a fixed measurement frequency can be challenging. Thus, the experimented MWA system uses multi-frequency measurements levels to sense a wide variety of moisture ratios.

The MWA system needs to be calibrated for different materials. Thus, a calibration was carried out for one of the concrete mixtures (concrete code of D-0.50-A2). During the calibration process, the water was added into the mixer in four steps to obtain the final *w/c* ratio of 0.50. After each addition, the mixing was continued until the mixture was homogenous, the mixer was stopped, and an uncalibrated reading was collected. Afterwards, a calibration curve was fitted to the data based on the uncalibrated readings and the theoretical moisture ratios in each step using the equation:

$$R_{\text{moisture}} = a \cdot (D_{\text{uncalibrated}}) - b - SSD \quad (1)$$

where R_{moisture} is the moisture ratio, $D_{\text{uncalibrated}}$ is the unscaled value, and a as well as b are coefficients determined during the calibration. An offset value called saturated surface dry (*SSD*) can be used to correct for absorption of aggregates, which was set to zero. The calibration resulted in the coefficients of $a = 0.192$ and $b = 4.804$ with a coefficient of determination (R^2) of 0.976. The polling rate of the MWA system was 25 data entries per second. Due to noisy signal caused by the blades and the movement of the concrete, a strong noise removal was applied to the raw signal in real-time as suggested by the manufacturer. Since the MWA sensor did not agitate the concrete, reading remained unchanged after stopping the mixer. Thus, a static measurement reading was taken immediately after the mixer was stopped.

In addition to the MWA technique, a time-domain reflectometry (TDR) technique was used to estimate the *w/c* ratio based on the measured water content and known cement content of the mixture. Similar to the MWA technique, the TDR sensor can be installed inside a mixer, a conveyer belt, or a hopper but it also can be used as a handheld probe. For this paper, a handheld probe was selected as the neighbouring sensors would interfere with the other. The MWA and TDR sensors can also be used to measure the moisture ratio of the aggregate in addition to the concrete mixture.

Yu et al. [24] describe that the TDR system commonly consists of a pulse generator and a sampler, a connection cable, and a measurement probe. While the pulse generator sends a pulse, the sampler records a response. Typically, the response consists of a first reflection peak when the pulse crosses the interface of the materials, and a second reflection valley when the electromagnetic pulse meets the end of the probe. Dielectric constant of the material determines the electromagnetic wave speed which is determined from the travel time of the pulse. Based on the manufacturer, the velocity of the TDR pulse can be computed from the following equation:

$$c = \frac{c_0}{\sqrt{\varepsilon_r \mu_r}} \tag{2}$$

where c is the pulse velocity, c_0 is the speed of light, ε_r is the dielectric constant, and μ_r is the magnetic parameter set to one. The velocity measurement can be transformed into a transit time t based on the known transit distance L_a ($c = \frac{2L_a}{t}$). Yu et al. [24] summarise that the apparent dielectric constant, that represents the real part of the frequency dependent dielectric permittivity, can be calculated from the pulse respond with the following equation:

$$K_a = \left(\frac{L_a}{L_p}\right)^2 \tag{3}$$

where K_a is the apparent dielectric constant, L_a is the scaled horizontal distance between the two reflections, and L_p is the length of the probe in the material. Since the dielectric constant of free water is higher in multiple magnitudes when compared to the air and other solids, TDR measured dielectric constant can be used to measure moisture content in many materials. A relationship for the gravimetric water content and soil dry densities to soil dielectric constant has been established using the equation:

$$\sqrt{K_a}\frac{\rho_w}{\rho_d} = a + bw \tag{4}$$

where K_a is the apparent dielectric constant, ρ_w is the density of water, ρ_d is the density of dry soil, w is the gravimetric water content, and a and b are material specific constants from the calibration tests [25, 26]. To calculate the water content of a concrete sample, the concrete sample can be place into a cylindrical container with a known volume, from which the total density of concrete can be determined. Defined by the relationship between total density and dry density, the water content can be computed from the equation:

$$\rho_d = \frac{\rho_t}{1 + w} \tag{5}$$

where ρ_d is the dry density of concrete, ρ_t is the total density of concrete in the mould, and w is the free water content. By substituting Equation (4) into Equation (5), and solving for the water content, we can calculate the water content with the following equation:

$$w = \frac{\sqrt{K_a}\frac{\rho_w}{\rho_t} - a}{b - \sqrt{K_a}\frac{\rho_w}{\rho_t}} \tag{6}$$

where w is the free water content, K_a is the apparent dielectric constant, ρ_w is the density of water, ρ_t is the total density of concrete, and a and b are material specific constants. The measurement probe investigated in this study detects the amount of free water content in the concrete, as well as the water absorbed by the aggregates and the amount chemical admixture added into the concrete mixture. As specified by the manufacturer, the probe can sense only a 1/3 of the absorbed water, and hence, should be removed from the measured value. Thus, the following equation to calculate the effective water content:

$$W_{\text{effective}} = W_{\text{measured}} - \frac{1}{3}W_{\text{absorbed}} - W_{\text{chemical}} \tag{7}$$

where $W_{\text{effective}}$ is the effective water content, W_{measured} is the measured water content from the device, W_{absorbed} is the absorbed amount of the water by the aggregates, and W_{chemical} is the amount of chemical admixture. The TDR probe was set to measure concretes with normal gradation of aggregates. No bias was set in the probe during the measurement to compensate for the absorbed water, but it was taken into account during the conversion to the effective *w/c* ratio. While the amount of absorbed water was relatively small with the used aggregates, the absorption can be significant error source for different aggregate types.

The measurement procedure for the TDR technique was dissimilar to the in-mixer sensors. For the handheld TDR probe (Figure 1c), a 5-litre plastic bucket was filled with concrete immediately after the mixing. This density from the pressure vessel was set in the TDR probe while other parameters were set to default, reflecting the normal concrete with a typical gradation of the aggregates. The probe was inserted to the bucket filled with concrete a total of five times in different locations, and the mean of these readings were calculated in-device. Each time the probe was inserted to the bucket, it was knocked three times to verify a good connection between the probe surface and the concrete mixture. The TDR system gave the estimation of water content in L/m³ that was converted into the effective *w/c* ratio based on the cement amount and absorption of the aggregate.

Air content
An acoustic wave propagation (AWP) technique was used to estimate the air content directly in a concrete mixer or truck where the sensor is in-contact with moving concrete. Tregger et al. [22] describe that the AWP system measures speed of sound that propagates through the concrete mixture between the sound source and the receiver. The sound source is a baffled piston that is driven on a relatively low, audible frequency. The sound receiver can be located close to the sound source within a known distance in the same plane because the sound propagates nearly equally to every direction. Since the concrete is mixed in a static pressure, always containing some air bubbles, and the frequency of the sound source is notably lower that the lowest resonance of the air bubbles, Tregger et al. [22] reduced an equation, originally presented by Wood [27], for the relationship of the speed of sound and air content to the following equation:

$$c = \sqrt{\frac{P_a}{\varphi(1-\varphi)\rho}} \tag{8}$$

where, c is the speed of sound, P_a is the absolute static pressure, φ is the volumetric fraction of air, and ρ is the density of the concrete mixture. Furthermore, Tregger et al. [22] stated that since the reduced Wood's model is dependent only on the static pressure and concrete mixture density, the equation is suitable for most concrete mixing applications. The measured speed of sound is then used to calculate the volumetric fraction of the air in concrete where the speed of sound decreases as the air content increases.

Two measurement types for AWP technique were calculated from the collected data, which were compared to the standard pressure method. Firstly, a dynamic measurement was calculated during the mixing where it was calculated as a median of last 5 seconds of mixing. Secondly, a semi-static measurement was calculated immediately after the mixing as an average over 30 seconds. The polling rate of the AWP sensor was one data entry per second. In contrast to the MWA sensor, the AWP sensor agitates the concrete with the baffled piston, which causes the concrete to compact near the piston, causing the reading to decrease over-time. The rotating blades also sweep over the sensor, causing the dynamic measurement to fluctuate cyclically. Hence, the static measurements are lower when compared to the dynamic measurements.

2.3 Testing procedure

For both the laboratory investigations, the same pan-style concrete mixer was used that allowed the installation of the in-mixer sensors on the opposing sides of the stationary floor (Figure 1). The paddles of the mixer rotated over its axis 60 times per minute. All the constituents were at a constant room temperature of 20°C in the beginning of the mixing. The initial mixing process was divided into the following steps:

1. The coarse aggregates from fractions 2–5 mm to 8–16 mm were added in the mixer. Immediately after, the cement, fine aggregates, and filler were added in the mixer. Afterwards, the mixer was turned on.
2. After 30 seconds, 80% of water was added without stopping the mixer.
3. After another 30 seconds, a pre-mixed solution of 10% of water and AEA was added without stopping the mixer.
4. After another 30 seconds, a pre-mixed solution of 10% of water and SP was added without stopping the mixer.

5. Finally, the mixture was mixed another 2 min.

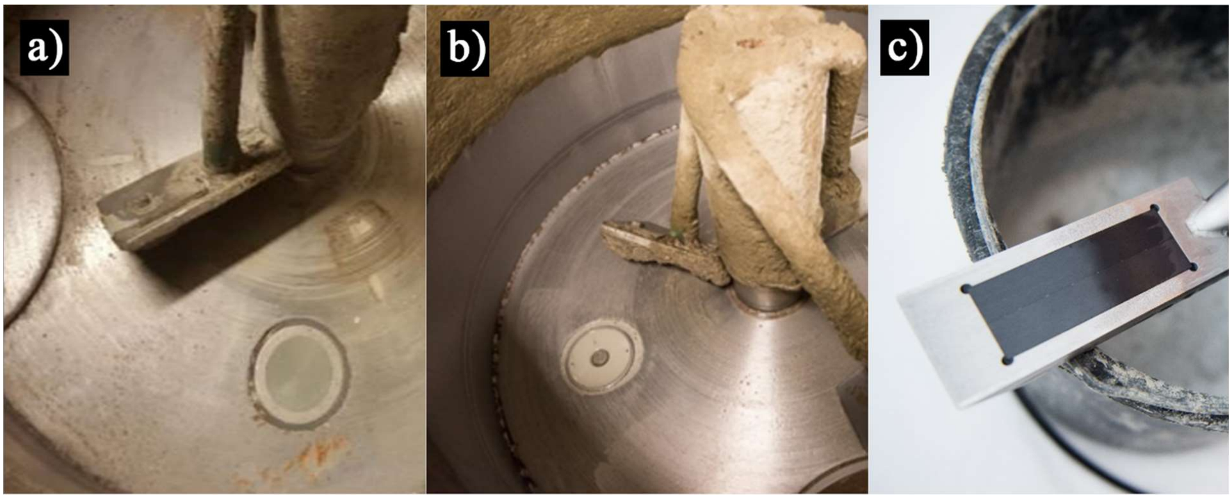

*Figure 1. The sensors for **a)** the MWA and **b)** the AWP systems were installed on the opposing sides of the planetary mixer floor, and sensor for **c)** TDR system was used as a handheld probe inserted to a concrete-filled bucket.*

Water/cement ratio

For the laboratory investigation of the *w/c* ratio, the nine concrete mixtures were prepared and tested. The batched volume of the concrete was 70 litres. During the mixing, the MWA system measured and collected the moisture ratio of concrete. After mixing, the slump test was performed using the standard EN 12350-2 [23] and the air content was measured using the standard EN 12350-7 [19]. The density of the compacted concrete was determined by weighing the 8-litre pressure method vessel. After the pressure method, the density of the concrete was set in the TDR probe and water content of the concrete mixture was measured from the concrete-filled bucket. In practice, the theoretical density could be used for pre-calibration of the probe, assuming that the target air content has been achieved. The tests were carried out by two operators so that the total time of the testing could be limited to 15 min. In addition, the operators always performed the same tests.

Air content

The laboratory investigation of the air content followed the same initial mixing and testing procedures. However, a total of eight concrete mixtures were mixed in four testing cycles to collect observation points. The batched volume of the concrete was 60 litres. During the mixing, it was noticed that the AWP system started to record the measurements when the concrete reached a certain consistency after both the water and the SP were added. It was assumed that the pressure method contaminated the concrete by introducing extra water to the concrete sample, which prevented the concrete to be returned to the mixer, resulting in smaller volume of concrete in the following testing cycles. Because of limiting factors, the pressure method was excluded from the 2nd testing cycle. Hence, only the 1st, 3rd and 4th testing cycles were utilised in the analysis. The additional testing cycles were started at 30 min, 60 min, and 75 min after the initial mixing finished. The concrete mixture was mixed for 2 min in the beginning of each cycle to ensure the cohesiveness of the mixture. After mixing, both the slump and air content fresh concrete tests were performed following the same procedure as with the first laboratory investigation.

3. RESULTS AND DISCUSSION

The results and discussion of the laboratory investigations are discussed in parallel in the following subsections. In the first subsection, the investigation for determining the *w/c* ratio is discussed. In the second subsection, the investigation for determining air content is discussed. Subsequently, a general discussion of automated measurements is presented.

3.1 Laboratory investigation

Water/cement ratio

Comparison of the true (effective) *w/c* ratio and the corresponding measurements with the automated techniques are presented in Figure 2. Since the MWA system measures the moisture ratio and TDR system measures the water content, the measurements were converted to the equivalent effective *w/c* ratios by excluding the water from absorbed water and chemical admixtures in the calculations. The figure reveals that the measurements were consistent although they did not achieve the same *w/c* ratios as the true *w/c* ratios, based on the weighing of the constituents. The R^2 of 0.808 and 0.858 were reached for MWA and TDR techniques, respectively. This suggests that the correlation between the reference method and the automatic methods is promising.

On closer inspection, the automatic measurement techniques seemed to measure higher *w/c* ratios in general. The over-estimation happened clearly with *w/c* ratios of 0.40 and 0.50 and less with *w/c* ratio of 0.60 where the mean of the measurements was close to the true value. The variation between the measurements within the same *w/c* ratio appears higher. In addition, the air content of the mix compositions clearly affected the measurements with the experimented techniques. The authors believe that the over-estimation might be caused by the inadequate calibration for each mix composition and highly varied air content. For the MWA technique, having more air content decreased the automatically measured *w/c* ratio. Contrarily, the higher air content increased the measured *w/c* ratios with the TDR technique. Thus, the results suggest that mix composition may heavily influence the measured *w/c* ratio with both the automatic techniques.

As discussed, the MWA and TDR techniques do not directly measure the *w/c* ratio. In fact, they measure the dielectric properties of the concrete mixture. Hence, they can only detect the presence of the water content that increases the apparent dielectric constant of the concrete, affecting the response signal. In practice, a higher *w/c* ratio does not always reflect in moisture ratio of the concrete mixture. For instance, with the highest *w/c* ratio the moisture ratio had a mean of 8.7% where concretes with *w/c* ratio of 0.5 and 0.4 had mean moisture ratios of 7.6% and 7.5%, respectively. On the other hand, the change in air content modifies the relationship between the moisture content and the dry constituents of the mix design. Therefore, concrete with a high air content has a lower moisture ratio as concrete with a low air content even with higher *w/c* ratio. These changes in moisture ratio suggest that calibrations should be carried out for different mix compositions.

To explain the over-estimation of automatic measurement techniques, the calibration procedures must be evaluated. Even though the calibration of the MWA system was performed for concrete D-0.50-A2, the measurement error seems significant. On the other hand, the TDR system was calibrated in real-time by setting the density of the concrete mixture before the measurements. Even with this calibration, higher air contents appeared the probe to greatly over-estimate the *w/c* ratios. The results show that only the mix compositions with *w/c* ratio of 0.60 and moderate air content can give similar results to the theoretical *w/c* ratio (Figure 2). To reduce the risk of segregation with the highest *w/c* ratio of 0.60, the aggregate gradation was adjusted to contain more fine aggregate. This change in gradation may be reflected in the lower measurement values of both techniques.

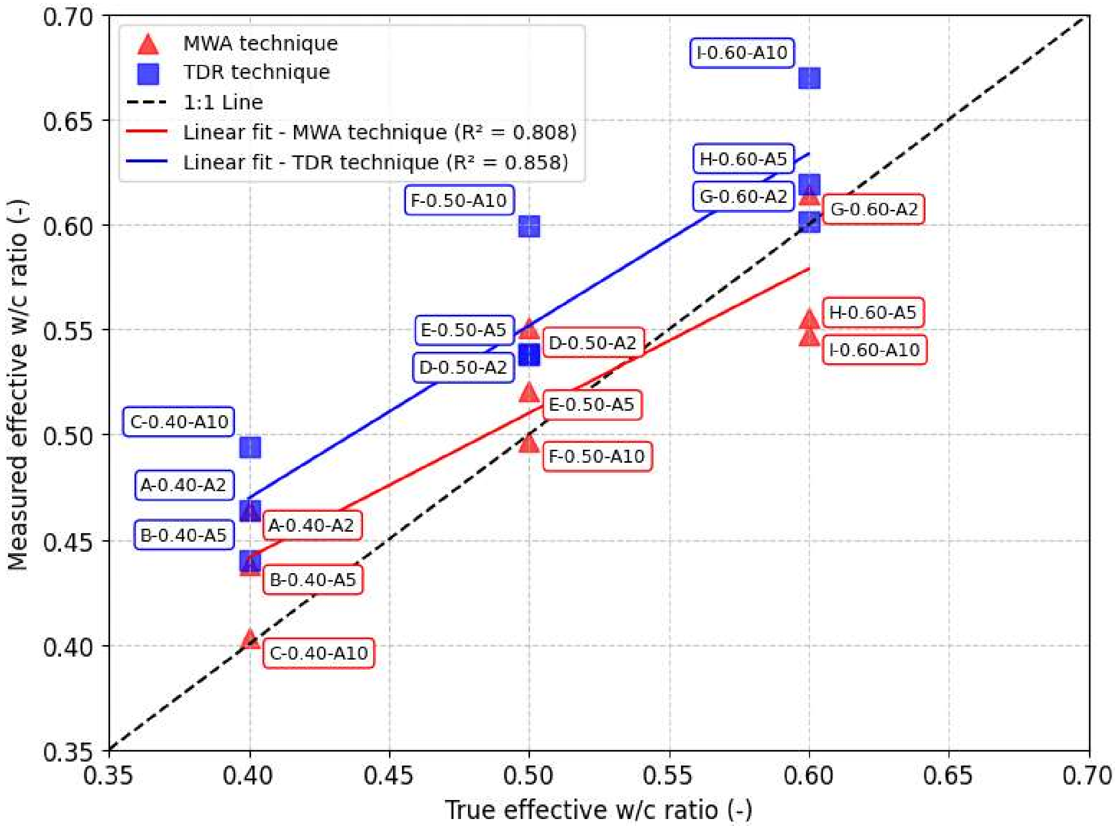

Figure 2 – Comparison of the reference method and the two automated measurement techniques (MWA and TDR) for the effective w/c ratio. The reference method is presented by the true w/c ratio, calculated from the batching information.

Since the air content of the concrete affected the measurements of the *w/c* ratio, the difference between the theoretical (true) and the automatic measurement techniques was plotted as a function of air content (Figure 3). A contrasting effect of the air content is clearly visible, where moderate linear correlations were found for the MWA and the TDR techniques (R^2 of 0.390 and 0.440, respectively). The statistical analysis also confirmed that the air content has marginally significant correlation to the MWA and TDR techniques with *p*-values of 0.0513 and 0.0722, respectively. This finding highlights the effect of air entrainment on the measurement accuracy. However, air content alone cannot fully explain the observed variation. Unfortunately, the amount of experimented mix compositions limits the investigation of other compositional parameters, which are reflected in the calculated moisture ratios of the mixtures. It should be noted that limited calibration was intentionally done in this paper to study the possible error sources.

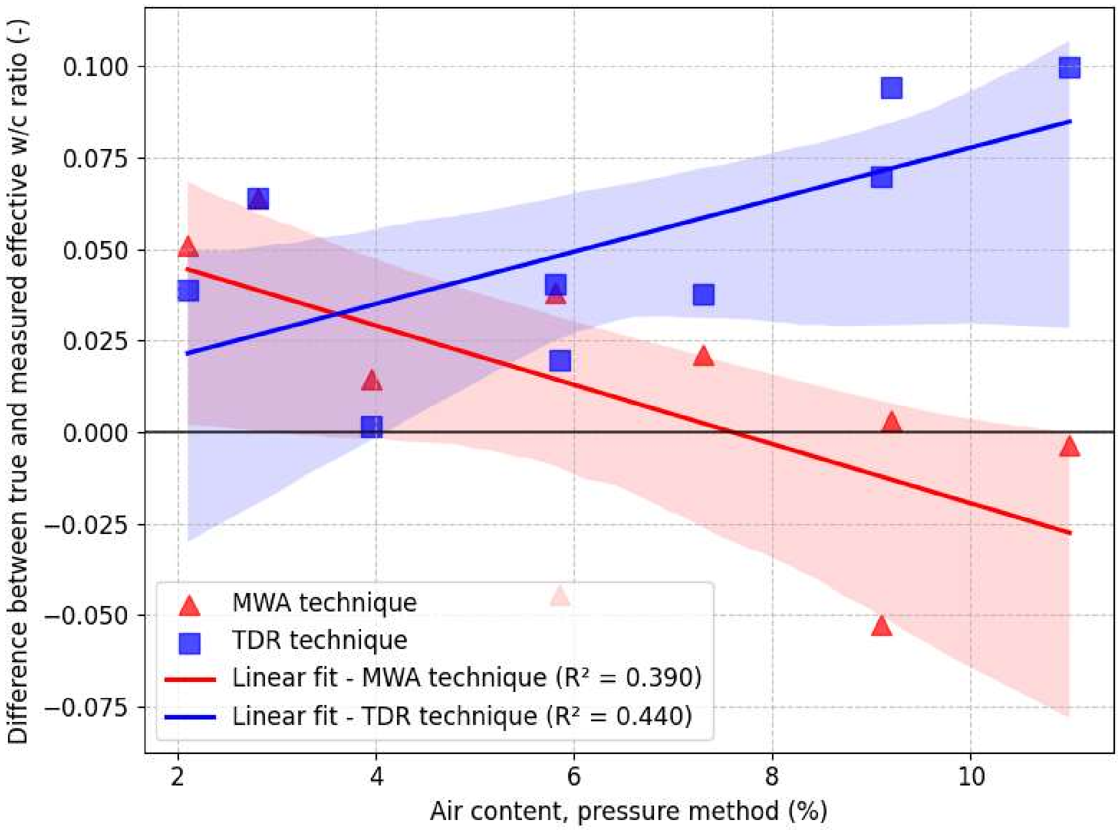

Figure 3 – Effect of air content on the difference between effective true w/c ratio and measured w/c ratio with the two automated measurement techniques (MWA and TDR). The coloured areas represent the 95% confidence intervals.

Air content

For investigation of the air content, comparison of the pressure method and the AWP technique is presented in Figure 4. The measurements were divided into dynamic and static measurement types where dynamic measurement achieved a poor-to-moderate correlation (R^2 of 0.365), and static measurement achieved a promising correlation (R^2 of 0.654). On average, both the measurement types agreed with the measurement results from the pressure method. A closer inspection indicates that especially the dynamic measurements led to higher air contents when compared to the static measurements. On average, the dynamic measurements were approximately two percentage points (pp) higher than static measurements. This is most probably caused by the measurement of uncompacted concrete during the dynamic measurements. Moreover, dynamic measurement clearly over-estimate some of the observation points, which negatively impacted the correlation.

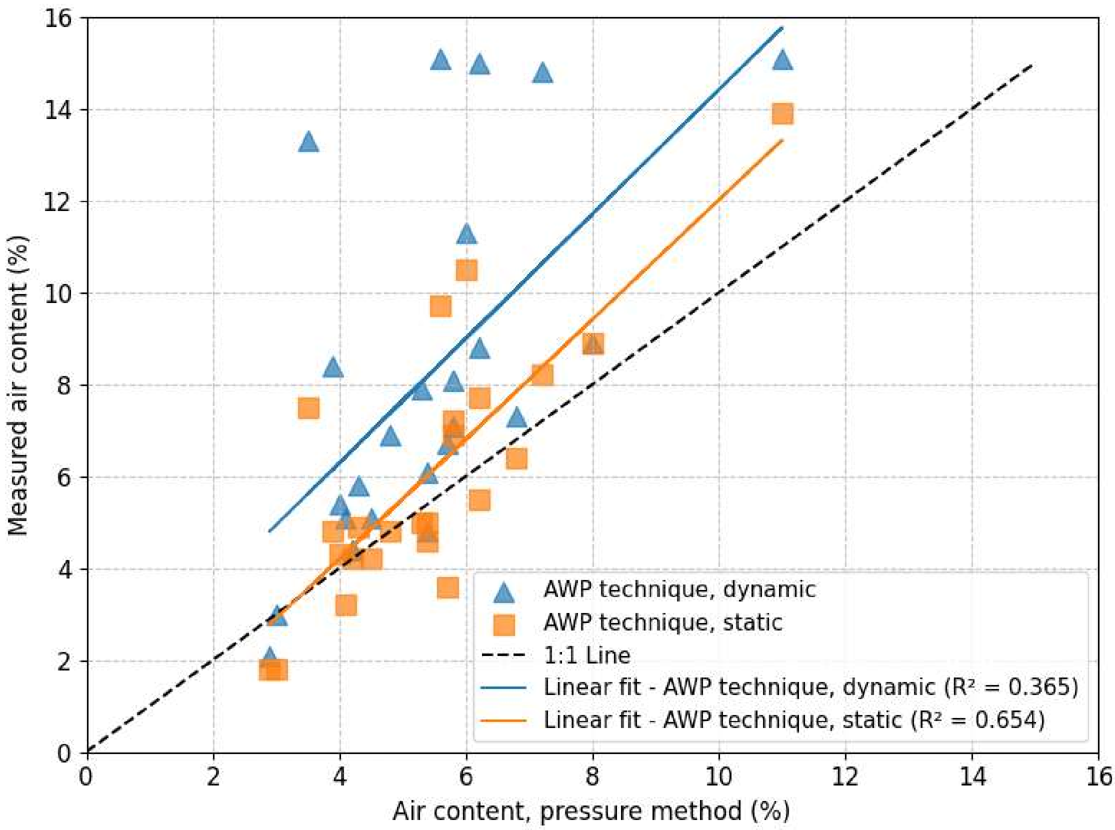

Figure 4 – Comparison of the air content measured with the pressure method and the AWP technique. Both the dynamic and static measurement types were used with the AWP technique.

The effect of concrete slump was further investigated by comparing the difference between the pressure method and the AWP technique (Figure 5). Based on the results, the highest difference between the measurements were with stiff concrete whose slump was less than 100 mm. With higher slumps the measurement error was small, excluding a few outliers. This increased performance can be explained by the greater fluidity of concrete. When the fluidity increases, the time the sensor is properly covered increases during the mixing. Additionally, the improved consistency allows the concrete to have less entrapped air during the measurement. The static measurement type benefitted the measurements for the stiff concrete, giving the concrete time to cover the sensor as the mixer blades were stationary. However, static measurement revealed the compaction effect of the vibrating piston, which caused the measurement to rapidly decrease over-time.

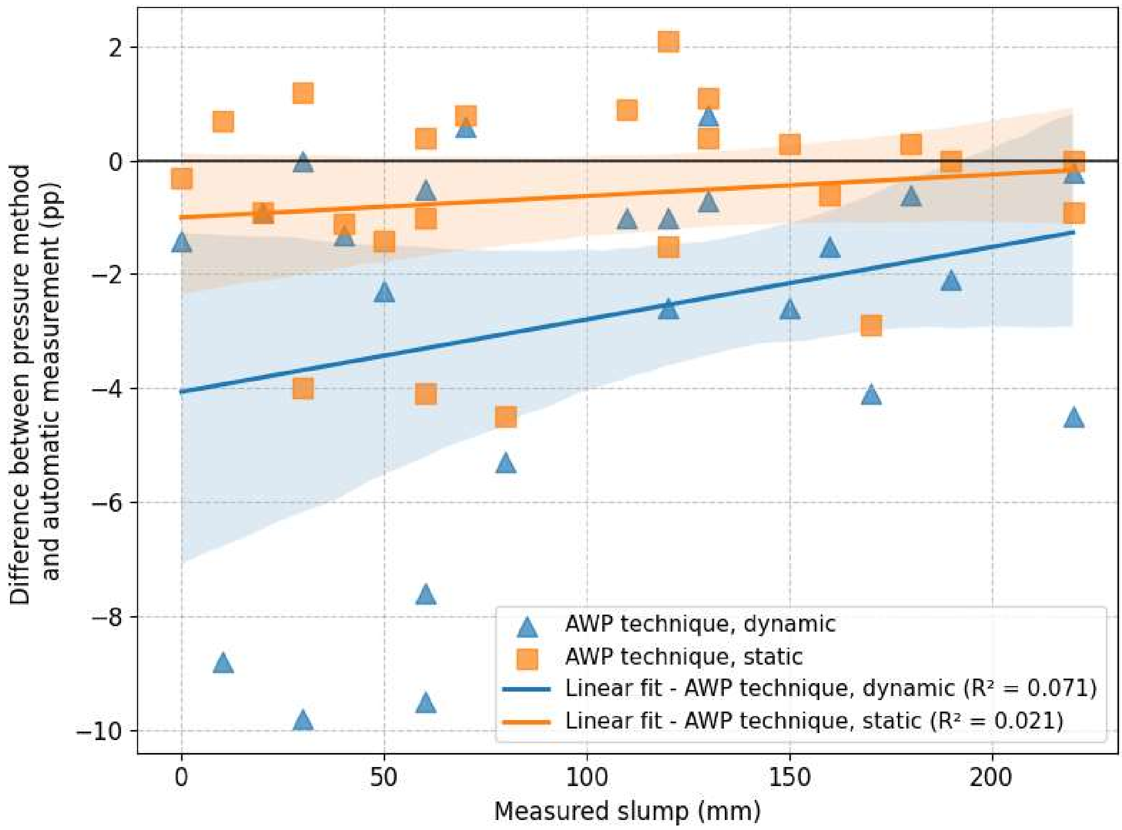

Figure 5 – Effect of the slump on the difference between air content and the AWP technique, indicating an arithmetic error in the volumetric air content. The AWP technique is divided into dynamic and static measurement types.

3.2 General discussion

The quality control of fresh concrete is based on laborious and user-dependent measurement methods that are rarely performed, leaving majority of the concrete untested. This creates a demand for automatic measurement methods that could be used to measure concrete continuously, detecting possible defects in real-time. Importantly, as the concrete industry moves towards more complex mix compositions with low-carbon concretes, developing robust automatic methods becomes crucial. These methods must accurately assess critical properties of fresh concrete, such as water content, air content, and workability, across a wide range of mix compositions. This challenge presents an opportunity for researchers to refine existing methods and potentially develop new technologies that can provide more precise and reliable data.

The sensors of the automatic measurement systems investigated in this paper are intended for concrete industry where the production volume is high and the downtime is expensive, causing serious delays in the supply chain. This means that in-contact sensors, such as in this study, must have a good resistance against abrasion and must be integrable with the existing production infrastructure. For instance, some mixer types are compatible with certain types of sensors that may require electrical connection. The cost of these automatic measurement systems and their upkeep must also be recognized. Depending on the demand and supply, the installation and maintenance costs can become comparable to the mixer itself. With more complex quality control systems, an expert is also needed to maintain the sensors and to guarantee the continuous monitoring without major interruptions. In addition, these measurement systems should be connected to each other without causing interference to maximise their potential. Additionally, some constituents of the concrete, such as metal fibres, may not function with electrical sensors as they cause sudden variation in the dielectric properties.

This paper highlights that measuring compositional properties of concrete accurately is challenging and understanding mix composition and mixing process is essential for proper calibration. While the measurement errors are similar to the allowed variation, more accurate measurements are needed to especially optimise the manufacturing process. In addition to the more frequent calibration practices, the authors cannot see significant improvement possibilities to the TRD, MWA, and AWP techniques themselves if the measurements are performed inside the mixer. The most measurement techniques for *w/c* ratio can only estimate the water content by detecting the dielectric properties of the concrete mixture. Fortunately, the variation of *w/c* ratio mainly comes from the fluctuation of water content of the aggregates. In addition to the in-mixer sensors, the moisture content of aggregate can be measured in the silos or during the aggregate batching. If the real-time moisture information about the aggregates can be used during batching process, more precise *w/c* ratios can be produced. What comes to the transportation of concrete, the water content, and thus *w/c* ratio, should remain the same after the concrete leaves the ready-mix plant, assuming that no extra water is added accidentally or purposefully at the construction site.

The correct air content is one of the key factors in achieving frost-resistant concrete. When air-entraining is introduced to the concrete, multiple factors impact the quality of air-entrainment. In addition to the proper amount of air content, the air entrainment must be stable and contain appropriate distribution of protective air bubbles. The AWP system can be used to measure the volumetric air content but not directly the quality of the air-void system. However, by monitoring the development of air content during the mixing, a deeper understanding of the stability of the air-void system can be achieved. For instance, the concrete should be mixed so that the air content stabilises during the mixing, supporting the idea that mixture does not contain unreacted AEA. These procedures also minimise the risk of air content to change during the transportation and casting of concrete.

The rheological properties are heavily related to the water and air content of concrete mixture. As such, sudden changes in the critical properties could indicate problems with the quality of concrete. Therefore, changes in air content or *w/c* ratio could also be detected by continuous workability measurement. Machine learning (ML) based measurement methods offer possibilities to interpret the data in new ways, including those measuring air and moisture content. These ML based approaches, combined with digital methods and advanced modelling techniques, could lead to fully automated concrete production systems that continuously optimize mix designs based on real-time feedback and predictive analytics. Recently, computer vision (CV) and ML have been used to supplement the current measurement technologies to measure more complex phenomena such as workability [28–31]. Alternatively, many studies have utilised mix composition data to estimate the fresh and hardened concrete properties using various ML techniques [32]. Consequently, concrete production would consist of less variability, allowing better optimization of the mix designs, which could be seen in a reduction of emission-heavy constituents such as cement.

4. CONCLUSIONS

This paper investigated automatic measurement techniques to measure the *w/c* ratio and air content of the fresh concrete which are critical parameters for concrete quality. The automatic techniques were compared to the reference methods that were the theoretical calculation of *w/c* based on the weighed constituents and the pressure method to measure the air content of compacted concrete. The experimented MWA and TDR techniques can determine the dielectric constant of concrete that is converted to a corresponding water content or a ratio of the concrete mixture. Hence, the effective *w/c* ratio must be calculated afterwards based on the information of the mix composition. To estimate the air content, the AWP technique determines the speed of sound in the concrete mixture, which is used to estimate the volumetric air content. The sensors of the MWA and AWP techniques were installed into the concrete mixer and sensor of the TDR technique was used as a handheld probe, measured from a concrete-filled plastic bucket after the mixing. The experimented techniques achieved a good correlation to the reference methods, but careful calibration is required. To test the conformity of the concrete, these methods allow detection of defected concrete in real-time, which in turn would decrease the cost and emission of the concrete production. As the different sensors can operate as a system, transferring information to each other, more precisely and automatically the sensors can be adjusted for different mix compositions. The key findings of each experimented automatic technique can be summarised as below:

- The MWA technique showed a high correlation ($R^2 = 0.808$) to the reference method. However, using a single calibration for all the concretes revealed that the system had a high sensitivity for different concrete mixtures. It was observed that increasing air content decreased the measured *w/c* ratio. This effect was also confirmed by statistical analysis where the air content had a marginally significant (p-value = 0.0513) effect on the difference between the reference method and the MWA technique. Interestingly, even the concrete mixture that was used in the calibration had an error of 0.05 for the *w/c* ratio. As such, using the MWA technique to verify that requirements for *w/c* ratio can be challenging.
- The TDR technique demonstrated a slightly higher correlation to ($R^2 = 0.858$) reference method than the MWA technique. The TDR technique seemed to greatly over-estimate the *w/c* ratio in the most observation points even after the correction for the effective water content and density. The TDR technique was also affected by the air content of the mix composition with marginal significance (p-value = 0.0722), which can be expected as both the techniques measure the dielectric properties. In contrast to MWA technique, the TDR system expects that the density of the concrete is set in-device before the measurement. This calibration can be seen also in the measurements where concretes without very high air content are more accurately measured. By introducing a measurement bias for certain mix compositions, the measurement error could be minimised.
- The AWP technique was divided into dynamic and static measurement types. The correlation to the reference method was poor-to-moderate ($R^2 = 0.365$) using the dynamic measurements, but more promising ($R^2 = 0.654$) using the static measurements. However, the measurement accuracy was clearly affected by the slump of the concrete mixture where stiff concrete (slump < 100 mm) caused high variability in the measurements, especially with the dynamic measurements. With real production concrete, a higher correlation can be assumed as their consistency is typically higher. The challenge with the AWP technique was to ensure a good coverage of the sensor. The over-estimation happens when the blades momentarily swipe the concrete from the sensor or if the concrete has significant amount

of entrapped air. Thus, the batched concrete volume must be sufficiently large to minimise the error.

REFERENCES

1. Kovler K & Roussel N: "Properties of Fresh and Hardened Concrete". *Cement and Concrete Research,* 2011, Vol. 41, No. 7 pp. 775–792.
2. Popovics S, Asce F & Ujhelyi J: "Contribution to the Concrete Strength versus Water-Cement Ratio Relationship". *Journal of Materials in Civil Engineering*, 2008, Vol. 20, No. 7, pp. 459–463.
3. Finnish Standards: "SFS-EN 206:2014 + A2:2021:en. Concrete. Specification, performance, production and conformity", Helsinki, Finland, 2021, 92 pp.
4. Park S H, Ryu H S & Park W J: "Influence of Unit Water Content Control on Concrete Performance in the Ready-Mixed Concrete Production Process", *Materials*, 2024, Vol. 17, No. 4:834.
5. Aliabdo A A, Abd Elmoaty A E M & Salem H A: "Effect of Water Addition, Plasticizer and Alkaline Solution Constitution on Fly Ash Based Geopolymer Concrete Performance". *Construction and Building Materials*, 2016, Vol. 121, pp. 694–703.
6. Hover K C: "The Influence of Water on the Performance of Concrete". *Construction and Building Materials*. 2011, Vol. 25, No. 7, pp. 3003–3013.
7. Mardmomen S, Chen H L & Leon G: "Revised Method for Rapid Determination of On-Site Water–Cement Ratio Using Microwave Oven". *Transportation Research Record*, 2019, Vol. 2673, No. 8, pp. 1–10.
8. Yu X & Liu Y: "Highway IDEA Program Development of Time Domain Reflectometry Instrument for QA/QC of Fresh and Early Stage Concrete", Final Report for Highway IDEA, Project 126, Case Western Reserve University, Civil Engineering Department, Cleveland, Ohio, USA, 2010, 53 pp.
9. Hu J: "Using Moisture Sensor to Monitor Fresh Concrete Uniformity", Thesis. Institute for Transportation, Iowa State University, Ames, USA, 2003.
10. Dowell A & Cramer S: "Field Measurement of Water-Cement Ratio for Portland Cement Concrete-Phase II Field Evaluation and Development", Wisconsin Highway Research Program, Technical Report, Report No. WHRP 02-002, Department of Civil Engineering, University of Wisconsin, Madison, USA, 2002, 50 pp.
11. Chen W, Shen, P & Shui Z: "Determination of Water Content in Fresh Concrete Mix Based on Relative Dielectric Constant Measurement", *Construction and Building Materials*, 2012, Vol. 34, pp. 306–312.
12. Makul N, Rattanadecho P & Agrawal D K: "Applications of Microwave Energy in Cement and Concrete – A Review". *Renewable and Sustainable Energy Reviews*, 2014, Vol. 37, pp. 715–733.
13. Naik T R & Ramme B W: "Determination of the Water Content of Concrete by the Microwave Method", *Cement and Concrete Research*, 1987, Vol. 17, No. 6, pp. 927–938.
14. Nagi M & Whiting D: "Determination of Water Content of Fresh Concrete Using a Microwave Oven". *Cement, Concrete and Aggregates*, 1994, Vol. 16, pp. 125–131.
15. Wang K & Hu J: "Use of a Moisture Sensor for Monitoring the Effect of Mixing Procedure on Uniformity of Concrete Mixtures", *Journal of Advanced Concrete Technology*, 2005, Vol. 3, No. 3, pp. 371–383.
16. Mehta P K & Monteiro P J M: "Microstructure, Properties, and Materials", Fourth edition, McGraw-Hill Education, New York, 2013, 672 pp.

17. Al-Neshawy F, Ojala T & Punkki J: "Stability of Air Content in Fresh Concretes with PCE-Based Superplasticizers". *Nordic Concrete Research*, 2019, Vol. 60, pp. 145–158.
18. Wang X, Wang X, Sadati S, Wang K, Taylor P & Sirotiak T: "Increase in Concrete Air Content Due to Excessive Internal Vibration". *Journal of Materials in Civil Engineering* 2024, Vol. 36, No. 2:04023576.
19. Finnish Standards: "SFS-EN 12350-7:2019. Testing fresh concrete. Part 7: Air content. Pressure methods", Helsinki, Finland, 2019. 25 pp.
20. Finnish Standards: "SFS-EN 480-11:2006, Admixtures for concrete, mortar and grout. Test methods. Part 11: Determination of air void characteristics in hardened concrete", Helsinki, Finland, 2006, 21 pp.
21. Lazniewska-Piekarczyk B & Gołaszewski J: "Relationship Between Air-Content in Fresh Cement Paste, Mortar, Mix and Hardened Concrete Acc. to PN-EN 480-1 with Air-Entraining CEM II/B-V*", IOP Conference Series: Materials Science and Engineering*, 2019, Vol. 471. No 3:032044.
22. Tregger N, Loose D, Durning T, Jeknavorian A, Mansky E, Klaus S: "Introducing a new sensor for in-mixer air volume measurement", *Proceedings of 2013 PCI Convention*, 2013.
23. Finnish Standards, SFS-EN 12350-2:2019. Testing fresh concrete. Part 2: Slump test, 2019, 10 pp.
24. Yu X, Drnevich V P & Olek J: "Time Domain Reflectometry for Measuring Water/cement Ratio of Concrete", *In Proceedings of the International RILEM Symposium on Concrete Science and Engineering: A Tribute to Arnon Bentur*, RILEM Publications SARL, 2004.
25. Siddiqui S I, Drnevich, V P & Deschamps R J, "Time Domain Reflectometry Development for Use in Geotechnical Engineering". *Geotechnical Testing Journal*, 2000, Vol. 23, pp. 9–20.
26. Siddiqui S I & Drnevich V P: "A new method of Measuring Density and Moisture Content of Soil Using the Technique of Time Domain Reflectometry", Final Report, Report No. FHWA/IN/JHRP-95/9, Joint Highway Research Project, School of Civil Engineering, Indiana Department of Transportation, Indianapolis, Indiana, 1995, 282 pp.
27. Wood A B: "A Textbook of Sound: Being an Account of the Physics of Vibrations with Special Reference to Recent Theoretical and Technical Developments" First edition, The Macmillan Company, New York, 1930.
28. Yang L, An X & Du S: "Estimating Workability of Concrete with Different Strength Grades Based on Deep Learning", *Measurement*, 2021, Vol. 186:110073.
29. Coenen M, Vogel C, Schack T & Haist M: "Concrete Flow Transformer: Predicting Fresh Concrete Properties from Concrete Flow Using Vision Transformers", *2023 European Conference on Computing in Construction, 40th International CIB W78 Conference*, Crete, Greece, 2023.
30. Tuan N M, Hau Q V, Chin S & Park S: "In-Situ Concrete Slump Test Incorporating Deep Learning and Stereo Vision", *Automation in Construction*, 2021, Vol. 121:103432.
31. Ojala T & Punkki J: "Estimating the Workability of Concrete with a Stereovision Camera during Mixing", *Sensors*, 2024, Vol. 24, No. 14:4472.
32. Zhang X, Akber M Z & Zheng W: "Predicting the Slump of Industrially Produced Concrete Using Machine Learning: A Multiclass Classification Approach". *Journal of Building Engineering*, 2022, Vol. 58: 104997.

APPENDIX A

Table A.1 – Combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixtures with w/c ratio of 0.40 for water/cement ratio laboratory investigation

Aggregate type	Fraction (Diameter in mm)	Weight Proportion (%)	Sieve size (mm)									
			0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0
Filler	< 0.1	7	29	66	88	94	97	99	100	100	100	100
Fine Aggregates (FA)	0.1 – 0.6	9	9	31	70	100	100	100	100	100	100	100
	0.5 – 1.2	12	1	2	4	73	100	100	100	100	100	100
	1.0 – 2.0	14	2	6	11	15	81	100	100	100	100	100
	2.0 – 5.0	16	0	0	0	0	1	56	100	100	100	100
Coarse Aggregates (CA)	5.0 – 10.0	20	0	0	0	0	0	3	78	99	100	100
	8.0 – 16.0	22	0	0	0	0	0	0	1	97	100	100
Combined Aggregates (%)			3	8	14	26	39	52	74	99	100	100

Table A.2 – Combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixtures with w/c ratio of 0.50 for water/cement ratio laboratory investigation

Aggregate type	Fraction (Diameter in mm)	Weight Proportion (%)	Sieve size (mm)									
			0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0
Filler	< 0.1	6	29	66	88	94	97	99	100	100	100	100
Fine Aggregates (FA)	0.1 – 0.6	9	9	31	70	100	100	100	100	100	100	100
	0.5 – 1.2	11	1	2	4	73	100	100	100	100	100	100
	1.0 – 2.0	14	2	6	11	15	81	100	100	100	100	100
	2.0 – 5.0	17	0	0	0	0	1	56	100	100	100	100
Coarse Aggregates (CA)	5.0 – 10.0	20	0	0	0	0	0	3	78	99	100	100
	8.0 – 16.0	23	0	0	0	0	0	0	1	97	100	100
Combined Aggregates (%)			3	8	14	25	37	50	73	99	100	100

Table A.3 – Combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixtures with w/c ratio of 0.60 for water/cement ratio laboratory investigation

Aggregate type	Fraction (Diameter in mm)	Weight Proportion (%)	Sieve size (mm)									
			0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0
Filler	< 0.1	8	29	66	88	94	97	99	100	100	100	100
Fine Aggregates (FA)	0.1 – 0.6	14	9	31	70	100	100	100	100	100	100	100
	0.5 – 1.2	14	1	2	4	73	100	100	100	100	100	100
	1.0 – 2.0	15	2	6	11	15	81	100	100	100	100	100
	2.0 – 5.0	16	0	0	0	0	1	56	100	100	100	100
Coarse Aggregates (CA)	5.0 – 10.0	16	0	0	0	0	0	3	78	99	100	100
	8.0 – 16.0	17	0	0	0	0	0	0	1	97	100	100
Combined Aggregates (%)			4	11	19	34	48	60	80	99	100	100

Table A.4 – Combined aggregates sizes and their weight proportions of the total aggregates for the concrete mixture for air content laboratory investigation

Aggregate type	Fraction (Diameter in mm)	Weight Proportion (%)	Sieve size (mm)									
			0.125	0.25	0.5	1.0	2.0	4.0	8.0	16.0	32.0	64.0
Filler	< 0.1	8	42	81	93	97	98	100	100	100	100	100
Fine Aggregates (FA)	0.1 – 0.6	9	3	21	76	100	100	100	100	100	100	100
	0.5 – 1.2	9	0	2	6	70	100	100	100	100	100	100
	1.0 – 2.0	15	0	1	2	7	79	100	100	100	100	100
	2.0 – 5.0	15	0	0	1	1	1	47	100	100	100	100
Coarse Aggregates (CA)	5.0 – 10.0	12	0	0	0	0	0	3	82	100	100	100
	8.0 – 16.0	32	0	0	0	0	0	0	5	99	100	100
Combined Aggregates (%)			4	9	15	24	38	48	67	100	100	100