Comparison of the pore size distributions of concretes with different air-entraining admixture dosages using 2D and 3D imaging approaches

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ABSTRACT

This study aims to more accurately investigate the pore size distribution of air voids in cement-based materials. For this purpose, micro-computed tomography (micro-CT) images were used to describe the inner structure of target materials, without damaging them. Together with the data obtained and the imaging techniques used, the pore structures of the specimens were visualized in 3D, with the pore size distributions being investigated using a volume-based method. The chord-length distribution, another approach to describe heterogeneous pore characteristics, was computed from 3D micro-CT images and compared with the conventional method. A RapidAir 457, an automated air void analyzer, was also used as a reference, with the results obtained being quantitatively and qualitatively compared using several curve fitting algorithms. The correlation between the pore characteristics and the mechanical properties of the specimens was examined, with the results indicating that the pore size distribution described using chord-length distribution is more effective than the conventional volume-based method. The results obtained can be utilized to investigate and predict material properties.

1. Introduction

As concrete structures are exposed to various harmful environments, studies relating to the durability of cementitious composites have been receiving a great deal of attention. Concrete is susceptible to damage during freezing and thawing cycles and can therefore noticeably deteriorate during winter. The threat related to the deterioration of concrete through freeze-thaw cycles is of high importance in major applications such as pavements, dams, foundations or bridges [1]. The performance of concrete under freezing and thawing conditions is strictly related to its air-void system. In addition, the content, size, and distribution of air pores, are critical not only regarding durability but also in reference to the physical/mechanical properties of concrete structures [2].

The frost-resistance of cementitious composites can be greatly enhanced by the entrainment of small air bubbles in cement paste by the addition of air-entraining admixtures (AEA). Nevertheless, the critical defining parameter necessary for the protection of concrete from freezing and thawing actions is not total porosity itself, but a spacing factor L, which is defined as the average distance from any point in the paste to the edge of the nearest void [1, 3]. Concrete with an L value < 0.2 mm is regarded as likely to be freeze-thaw durable. This spacing factor is the most important parameter characterizing the resistance of cement-based materials to freeze-thaw cycles, although other parameters such as total air content, the specific surface of air voids (α) or the percentage of pores < 0.3 mm (A300) also characterize the air-entrained pore system, with their values needing to be maintained within certain limits [4]. In addition to frost-related properties, other important properties of cement-based composites such as permeability, compressive strength, or thermal conductivity are strongly affected by the pore structures of a material [5-9].

Accurate measurements of void parameters are therefore necessary for properly designing and evaluating the performance and durability of concrete in an outdoor environment. At the moment, the most widely used method for evaluating the air void system in concrete, is the microscale-based ASTM C 457-90 "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete" [10] and its corresponding European version EN 480-11 "Determination of air void characteristics in hardened concrete" [11]. The test is performed on a cross-sectional polished slab,
prepared from a concrete specimen, which is placed on a mechanical stage and illuminated with an oblique light source. However, this manually conducted measurement is tedious and time-consuming and various automated methods have therefore been explored to increase measurement speed [12]. One such approach involves the use of automated air void analyzers (e.g., the RapidAir 457), enabling the performance of tests automatically with no operator interference [13]. In addition, the use of automated devices eliminates the “human factor” which results in incorrect judgment during the pore analysis process. With the use of this method, various parameters such as the spacing factor, micro-air-void content (A300), total air content, specific surface of an air-void system, and the average pore diameter can be determined [2]. Nevertheless, a certain amount of time is still required to prepare samples for testing by cutting, surface polishing, surface contrasting and drying [14, 15]. The incorporation of 2D based image techniques using a linear traverse method may not be as representative as the predicted air-void system, since in this method, measurements are limited to one-dimension (1D), while air-voids are actually distributed in a three-dimensional (3D) space in hardened concrete.

To overcome the limitations mentioned above and to more effectively investigate target materials, a different nondestructive approach which can describe both 2D and 3D objects is needed. X-ray micro-computed tomography (micro-CT) can be used for further investigation of the pore structure of concrete without damaging the material [16-19]. Micro-CT provides a series of cross-sectional images of a target material, with it being possible to obtain a 3D volumetric image by stacking 2D images. With the micro-CT image obtained, the spatial distribution of components in concrete, such as pores and aggregates, can be described and examined in 3D. In particular, more complex investigations, such as those involving elemental size and shape distributions, can be investigated qualitatively and quantitatively using the data obtained. It is due to these advantages that micro-CT has been used to investigate the pore structures of cementitious materials [15, 20-22].

In the investigation of pore characteristics using micro-CT, particularly pore size distribution, most studies have used volume-based measurement; where the radius (or diameter) of pores is calculated from the particle volume and the formula for calculating sphere volume [23-26]. Volume-based measurements, such as the maximal ball algorithm [27], have been used to describe the pore size distribution of a target material. However, conventional volume-based measurements assume that pores are perfectly spherical and these methods thus have limitations in describing the anisotropy or heterogeneity of pore characteristics. A supplementary approach to characterize the pore structures in 3D is therefore needed.

Various characterization methods have been used to quantify the pore characteristics of cementitious materials. Chord length distribution is a method for describing the morphological information of heterogeneous materials and can be used to investigate the pore size distribution of materials [28, 29]. Chords are the lengths between the intersections of lines with the interface [30] and the radius of a target pore (or a particle) can be computed using chord information. Since this approach is based on the measured length, it enables more accurate description of pore and particle size characteristics. Even though it is advantageous for describing material characteristics, the pore structures of concrete have rarely been investigated using chord length distribution, because of its computational complexity as compared to conventional methods [28].

The main objective of this study is to investigate the pore size distributions of concrete specimens using a chord length based method. As such, a set of concrete specimens with different air-entraining dosages were prepared as target materials, and a standard, RapidAir (Concrete Experts International, Sweden) air void analyzer, satisfying EN 480-11, was used for providing pore size distributions in 2D. Micro-CT was adopted to obtain a series of cross-sectional images of the specimens without damaging them. With the micro-CT images, the pore size distributions of the specimens were computed using both the volume-based method and the chord-length distribution in 3D. The micro-CT results obtained were compared with the RapidAir data and an analytical fitting was also performed for quantitative comparison. A relationship between the pore characteristics obtained and the compressive strength of the specimens was demonstrated, to prove the effectiveness of the investigations used in this study.

2. Materials and measurement tools

2.1. Type of materials

Rapid hardening Portland cement (CEM I 52.5 R in accordance with EN 197-1), tap water, natural sand fine aggregate (0–2 mm), and grit coarse aggregate with a maximum aggregate size of 8 mm, were used in this study. The chemical composition of the cement used is given in Table 1, while the particle size distribution of the dry components is presented in Fig. 1. An air-entraining agent (AEA), produced by Sika (Germany), was incorporated in order to produce air bubbles in selected concrete mixtures. The w/c ratio in this study was kept at 0.42 for all the mixes. To reach a comparable workability across concrete mixtures, polycarboxylic ether-based (PCE) superplasticizer (SP) with a density of 1.04 g/cm³ was used.

2.2. Concrete preparation and testing methods

Five different concrete mixtures were prepared and tested in this study. Four of the mixes contained different dosages of air entraining agents, to produce different levels of plastic air content, while the fifth mix was prepared without AEA and used as a reference mix. The plastic air content of the reference mix was measured as 2.4 vol.%. For the

![Fig. 1. Particle size distributions of the materials used.](image-url)
other mixes, different dosages of AEA were added to produce total plastic air contents of 4, 6, 8, and 10 vol.%. Due to the influence of air content on concrete consistency and workability, the superplasticizer dosage was not constant across all the mixes; it was adjusted to achieve a comparable consistency in the F3 class, in accordance with EN 206-1 (slump flow of 420–480 mm), while maintaining the required air content level. Normal concrete (without AEA admixtures) was designated as N0, while aerated concretes with predicted plastic air content of 4, 6, 8, and 10 vol.% were designated as NA4, NA6, NA8, and NA10, respectively. Detailed mixture compositions are presented in Table 2. A standard Zyklos mixer (Pemat Mischtechnick GmbH, Germany) was used to mix the concrete constituents. The dry constituents were mixed first and then water, AEA and SP were added to the mixture. After mixing, concrete consistency was measured using a flow table test in accordance with EN 12350-5. In addition, an air content measurement was conducted in the fresh mix; the pressure gauge method in a 5-liter standardized cylinder was used in accordance with EN 12350-7. The fresh density of all the concrete mixes was measured using a 5-liter cylindrical bowl, in line with EN 12350-6. After measuring the properties of the fresh concretes and obtaining the desired plastic air content, 15 × 15 × 15 cm³ cubical molds were filled with concrete. The samples were demolded after 24 h and stored underwater for curing at a temperature of (20 ± 1 °C) till the testing day. At the age of 28 days, hardened concrete properties including dry state density (EN 12390-7), compressive strength (EN 12390-3), water porosity and water permeability (EN 12390-8), were determined. Three samples were tested from each mix with the mean values as well as the standard deviations being taken into consideration.

3. Measurement tools

3.1. RapidAir

A standardized 2D image based technique was incorporated in this study to analyze the solid and porous concrete structures. An automatic characterization of the air-void structure of hardened concrete, using a linear traverse method, was performed with the use of a RapidAir 457 Automated-Air-Void-Analyzer (Concrete Experts International, Sweden), as presented in Fig. 2 (a). The determination of the air void characteristics in hardened concrete was performed in accordance with EN 480-11:2005-admixtures for concrete, mortar and grout-Test characteristics in hardened concrete was performed in accordance with Sweden), as presented in Fig. 2 (a). The determination of the air void characteristics in hardened concrete was performed in accordance with Sweden), as presented in Fig. 2 (a). The determination of the air void characteristics in hardened concrete was performed in accordance with Sweden), as presented in Fig. 2 (a). The determination of the air void characteristics in hardened concrete was performed in accordance with Sweden), as presented in Fig. 2 (a). The determination of the air void characteristics in hardened concrete was performed in accordance with Sweden), as presented in Fig. 2 (a).

To investigate the pore structure, micro-CT, non-invasive and non-destructive examinations, was used. Micro-CT is a radiographic imaging method which can describe the inner structure of a target object without damaging the material at hand [17-19]. With this method, a set of cross-sectional images of the target object can be obtained using X-rays. The 1st image in Fig. 3 is an example of micro-CT imagery. In general, a micro-CT image is composed of a pixel, being the unit of a digital image, with the images being expressed in 8-bit or 16-bit grayscale. 8-bit images expressed with 256 values, from 0 (black) to 255 (white), were used in this study. The image resolution was 800×800 pixels, with a 29.7 μm pixel size. To classify a specific phase from the original images, image segmentation processing, which generates binary images, can be conducted. The 2nd image in Fig. 3 is a binary image generated from the original micro-CT image. In this image, the black region represents the pore phase, which is the target component of this study. A modified Otsu method [18, 31] was adopted for the image segmentation. The initial binary image contains clustered pores which should be separated in real samples. A modified watershed algorithm [32] was used for a clearer description of these pores. In the 3rd image in Fig. 3, different colors denote every single pore. A 3D segmented image was subsequently obtained by stacking the processed cross-sectional images (the 4th image in Fig. 3), with it being possible to conduct a volumetric investigation of the pore characteristics using this 3D microstructural data. The entire imaging procedure was performed using the MATLAB imaging toolbox [33].

3.3. Pore characterization methods using micro-CT images

Pore characteristics of concrete specimens are one of the most dominant factors in determining the mechanical properties of concrete. In particular, pore size distribution is an important parameter for describing the pore characteristics of materials [5, 21]. Since pore size is not precisely defined, various approaches have been proposed to measure it in different materials. In reference to micro-CT images, several researchers have used ‘volume-based’ measurement to investigate the pore size distribution of cement-based materials [15, 22, 24, 25, 32, 34]. In this method, the pore size is computed using the volume of each pore particle, and with the particle volume being measured by counting the number of voxels. The radius (or diameter) of the pore can be calculated using the formula for the sphere volume. Because of its simplicity, this approach has been used widely to examine material's pore size distribution. However, as the formula shows, volume-based calculation has limitations, because all pores are

| Concrete designation | N0   | NA4  | NA6  | NA8  | NA10 |
|----------------------|------|------|------|------|------|
| CEM I 52. R          | 400  | 400  | 400  | 400  | 400  |
| Water                | 168  | 168  | 168  | 168  | 168  |
| Natural sand (0–2 mm)| 689  | 689  | 689  | 689  | 689  |
| Grit (2–8 mm)        | 1123 | 1123 | 1123 | 1123 | 1123 |
| Air-entraining admixture (AEA) | –   | 0.2 (0.05%) | 0.4 (0.1%) | 1.2 (0.3%) | 2.0 (0.5%) |
| Superplasticizer (SP) | 2 (0.50%) | 1.6 (0.4%) | 1.3 (0.33%) | 1.1 (0.28%) | 0.9 (0.23%) |
| Plastic air content [vol. %] | 2.4 | 4.2 | 6.1 | 7.9 | 10.2 |
| Fresh density [t/m³]  | 2.33 | 2.29 | 2.23 | 2.07 | 1.93 |

*(' in AEA and SP denote wt. %.

Table 2

Compositions of concrete [kg/m³].
considered to be perfect spheres, and because it is difficult to describe pore shape and anisotropy. In addition, because the volume of pores is computed on the basis of voxel numbers, the degree of precision of the measurement is highly dependent on image resolution.

An alternative approach is that of chord-length distribution. Chord-length is a geometrical parameter that describes the length between the intersections of lines with the interface [28, 30], as shown in Fig. 4(a). In this figure, \(l_1\) and \(l_2\) are the chord-length of the specimen. The chord itself presents morphological information and can be used to determine pore size in both 2D and 3D [28, 29]. In Fig. 4(b), \(l\) is the chord-length. Once the chord-length and the center of a pore are measured, the radius of the pore in a specific direction can be calculated. The radius obtained from the chord-length distribution does not need to be spherical and the directional characteristics of pores can be examined with this method; the chord-length-based approach can measure pore sizes more accurately than conventional volume-based methods. In general, the chord-length function can be used in 2D for describing the characteristics of random heterogeneous materials [28]. However, the use of only 2D images has limitations in describing the overall characteristics of a target material [35, 36], particularly for materials with specific components such as anisotropic pores. Therefore, the use of 3D images is needed for more detail and accurate characterization of a target material. In this study, both the volume-based method and the chord-length distribution were utilized to investigate the pore size distributions of the air-entrained concrete specimens incorporating 3D micro-CT images. The pore size distributions obtained in 3D were then compared with the 2D standard method (RapidAir) and correlated with the mechanical properties of the specimens.

4. Results and discussions

4.1. Material properties

In this investigation, five concrete mixes were prepared and tested in order to study the porosity and microstructure of concrete using different measurement techniques. The properties of fresh concrete which were measured included consistency, fresh density, and air content. The experimental results of concrete consistency in the fresh state were measured using the flow table test, showing that it was in the target range of 440–480 mm (F3). It was noticed that as the AEA content increased, the required dosage of superplasticizer for achieving the same consistency class decreased; from 2 kg/m³ at 0% AEA to 0.90 kg/m³ when 0.5 wt.% of AEA was added, as can be seen in Table 2. In addition, as expected, the density of fresh concrete was found to be negatively correlated to the AEA content. As the air entraining agent content increased, fresh density decreased. The reference mix (without AEA) had a fresh density of 2.33 t/m³, which decreased gradually with an increase in the AEA dosage 1.93 t/m³ when 0.5 wt.% AEA was added to the mixture. Similarly and also as expected, more air bubbles were generated in plastic concrete with the addition of AEA. Theoretically, it was planned to have concrete mixes with air contents of 4, 6, 8, and 10 vol.% using AEA. The obtained values of actual air content in fresh concrete were 4.1, 6.1, 7.5, and 10.5 vol.%, through the incorporation of AEA at 0.05, 0.1, 0.3, and 0.5 wt.%, respectively. The measured values were in good agreement with the planned values.

Table 3 shows the experimental results of the hardened concrete properties including dry density, open porosity (water porosity), water penetration depth, as well as 28 days compressive strength. The trend of dry density was the same as that of fresh density. The dry density of concrete decreased by about 3, 5, 11, and 17% with an increase in the air content from 2 to 4, 6, 8, and 10 vol.% respectively. A high air content in concrete has a negative effect on its transport properties, which is clear from the results of water porosity and permeability. The water penetration depth increased from 17 mm (reference mix) to 120 mm for mix NA10 with 10 vol.% air content. The water porosity was measured on the basis of differences between the saturated surface dry samples and oven-dried samples; details of this method can be found in [13]. In the case of water porosity, no significant differences

**Fig. 2.** RapidAir measurements: (a) RapidAir 457 device, (b) sample surface for evaluation of pore characteristics.

**Fig. 3.** Micro-CT image processing of concrete microstructures. (Note: in the 2nd and 4th images, the white regions represent solid (matrix) while the black region represents pores. In the 3rd image, the colored regions are pores.)
between specimens were observed; this is due to the fact that air bubbles introduced have the characteristics of closed pores, and thus they do not participate in the capillary transfer of liquid water under normal conditions. Compressive strength tests were carried out to evaluate the effects of increasing air content on the mechanical properties of concrete. The results indicate that strength decreased dramatically as the air content increased. In good agreement with [37], where it was argued that compressive strength decreases by 5.5% with every 1 vol.% increase in air content. In our investigation, compressive strength decreased to about half (mix NA10) with a 5 vol.% increase in air content, while decreasing to 25 MPa after an increase in air content by about 8 vol.%. Pore structure, including both porosity and pore size distribution, can significantly affect compressive strength; accordingly, a more detailed investigation of pore characteristics is presented in the following section.

### 4.2. Pore size distribution investigation

The pore size distributions of the specimens were investigated using 2D (RapidAir) and 3D (micro-CT) approaches. In particular, the pore size distributions in 3D were measured from the volume-based and chord-length-based methods incorporating micro-CT images. The 3D images of the pore structures for each specimen are presented in Fig. 5. In this image, the gray colored particles represent the pores within the specimens, with the pore structure analysis having been performed on the basis of this data. The porosity values of the specimens measured from the RapidAir and micro-CT images are presented in Table 4, with the results being in good agreement. For both porosity and pore size distribution, only pores larger than the image resolution used (29.7 μm) were considered. The investigative methods referring to the pore size distribution were introduced in Section 3, and the obtained results are compared below.

Fig. 6 shows comparison of the pore size distributions of the specimens, where the pore size distributions obtained from different approaches are overlaid. The y-axis shows the frequency of the pore size for describing relative occurrence depending on the AEA dosages in the specimens. The RapidAir data was treated as a reference measurement, since the device satisfies the relevant standards [26]. The pore size distributions in Fig. 6 show that the general trends were similar in all cases. For all measurement approaches, the areas of the graphs tended

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**Table 3**

Fundamental properties of concrete specimens.

| Specimens | N0  | NA4 | NA6 | NA8 | NA10 |
|-----------|-----|-----|-----|-----|------|
| Dry state density [kg/m³]  | 2265 | 2211 | 2161 | 2022 | 1887 |
| Water porosity [vol.%]     | 10.8 ± 0.2 | 10.8 ± 0.1 | 10.7 ± 0.2 | 10.8 ± 0.2 | 10.9 ± 0.1 |
| Water penetration depth [mm]| 17 ± 2.8   | 23 ± 3.4   | 23 ± 3.5   | 50 ± 2.8   | 120 ± 4.3  |
| Compressive strength at 28 days [MPa]| 79 ± 2.4 | 69 ± 2.8 | 64 ± 2.1 | 41 ± 1.7 | 25 ± 1.1 |

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**Table 4**

The measured calculated porosity from RapidAir and micro-CT images.

| Specimens | N0  | NA4 | NA6 | NA8 | NA10 |
|-----------|-----|-----|-----|-----|------|
| RapidAir [vol.%]      | 4.43 | 6.55 | 8.13 | 12.93 | 14.38 |
| Micro-CT [vol.%]      | 4.28 | 5.05 | 7.69 | 13.17 | 15.46 |

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![Fig. 4. Description of chord-length distribution: (a) schematic of the chord-length, (b) illustration of chord-length in a spherical sample.](image-url)
to increase with an increase in the AEA content of the specimen. However, differences were also present across measurement approaches, with the RapidAir results showing dual-modal distribution with peaks, especially in specimens with large amounts of AEA. The size distribution of the small pores showed a similar pattern in all cases. In contrast, in all measurements, the portion of pores > 0.2 mm tended to increase as the amount of AEA dosage increased, indicating that AEA tends to produce relatively large pores.

Based on the RapidAir results, the similarity of each method using the micro-CT can be compared. In the case of the volumetric measurement, the dual-modal distributions described by the RapidAir were not clearly observed. The proportion of small pores (< 0.15 mm) was more pronounced, with the large pores being less clearly visible than in the RapidAir and micro-CT chord-length measurement. Since volume-based measurement considers all pores to be spheres, in practice the sizes of anisotropic or heterogeneous pores can appear smaller than they really are for a specific direction. However, the chord-length-based data from micro-CT showed a trend similar to that of the RapidAir

Fig. 6. Comparison of pore size distributions measured with different approaches: (a) N0, (b) NA4, (c) NA6, (d) NA8, (e) NA10.
result. In the chord-length results, the relatively large pores (> 0.3 mm) were effectively described, indicating that the large pores produced by AEA can be effectively measured using the chord-length-based method incorporating micro-CT. In particular, the chord-length-based method incorporating 3D micro-CT provides more information as compared to the 2D method (RapidAir), indicating that it can lead to a better understanding of material characteristics.

4.3. Quantitative pore characteristics and their correlation with compressive strength

Qualitative and quantitative analysis was conducted for a more detailed investigation of the pore size distribution obtained with different approaches. Different curve-fitting approaches were adopted for the purpose of comparison. The Weibull [38, 39] and lognormal [15, 40] fittings, which have widely been used for describing pore size distribution, were utilized. In Fig. 6, the pore size distributions of the specimens with AEA have additional peak in the relatively large pore (> 0.2 mm) region, and the use of additional fitting is needed to describe this aspect. For the purpose, a multimodal (bimodal) normal distribution fitting was also performed in consideration of the shape of the pore size distribution, which had two peaks. The curve fitting was performed using the ‘cftool’ and ‘fiddit’ functions in the MATLAB toolbox [32].

Fig. 7 shows the pore size distributions of the NA4, NA8, and NA10 specimens obtained using different measurement approaches, as well as their fitted curves from different algorithms. As shown in Fig. 6, the volume-based and chord-length-based measurements were slightly different, with the latter being more similar to the reference (RapidAir) measurement. Though both lognormal and Weibull distributions described well the pore size distributions in general, it can be seen that the relatively large pores away from the peak are not fully taken into

| Specimen | Measurement | Weibull | Lognormal | Bimodal distribution |
|----------|-------------|---------|-----------|----------------------|
| NA4      | RapidAir    | 0.7636  | 1.3475    | 0.3149               |
|          | CT-volumetric | 1.1564  | 0.8373    | 1.0503               |
|          | CT-chord length | 0.6750  | 0.7732    | 0.3039               |
| NA8      | RapidAir    | 0.8544  | 1.5880    | 0.2020               |
|          | CT-volumetric | 2.7594  | 2.6617    | 0.3744               |
|          | CT-chord length | 0.6804  | 0.6536    | 0.3344               |
| NA10     | RapidAir    | 0.7636  | 1.3475    | 0.3149               |
|          | CT-volumetric | 1.1564  | 0.8373    | 0.3554               |
|          | CT-chord length | 0.6750  | 0.7732    | 0.3039               |

Note: in each specimen, the 1st figure is the curve fitting for the RapidAir data, the 2nd figure is of micro-CT volumetric, and the 3rd figure is of micro-CT incorporating the chord-length distribution.
consideration by the fitting curves. To overcome this limitation, the bimodal normal distribution was used. In the figures, the bimodal fitting curves are better matched with the pore size distributions than the other curves, especially for the large pore region. The least square error between the pore size distribution and the fitting curves was computed for quantitative analysis and is presented in Table 5. It can be seen that the bimodal fitting curve shows the minimum error in all cases, thus confirming that the use of a bimodal (or multimodal) distribution can be effectively used for describing pore size distribution in a wide range. The other specimens (N0 and NA6) showed almost the same trend as shown in Fig. 7 and Table 5, though they are not presented in this paper.

To investigate the correlation between the pore size distribution and the mechanical behavior of concrete, selected parameters for the Weibull and bimodal distributions were determined, with the parameters and the compressive strengths of the materials being compared. Fig. 8 presents a linear relationship between the parameters and the compressive strength of all the cases examined here. The least square error between the pore size distribution and the fitting curves was computed for quantitative analysis and is presented in Table 5. It can be seen that the bimodal fitting curve shows the minimum error in all cases, thus confirming that the use of a bimodal (or multimodal) distribution can be effectively used for describing pore size distribution in a wide range. The other specimens (N0 and NA6) showed almost the same trend as shown in Fig. 7 and Table 5, though they are not presented in this paper.

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5. Conclusions

This study has investigated the pore size distributions of air-entraining concrete using different approaches. Micro-CT was used to visualize specimens' microstructures, with the images obtained being utilized for further pore structure investigations. To characterize the pore size distribution of the specimens under examination, the conventional volume-based method and the chord-length-based method were adopted and compared. Analysational fitting with different algorithms, such as the Weibull, lognormal, and bimodal normal distribution, was conducted for the purpose of comparison. The relationship between the pore characteristics obtained and the compressive strength of the specimens was demonstrated to prove the effectiveness of the investigation. The selected parameters of each fitting method were also computed and correlated with the compressive strength of the materials. The conclusions of this study can be summarized as follows:

- The use of an air-entraining agent (AEA) contributes to an increase in the relatively large pores in concrete. The portion of pores > 0.3 mm increases with the AEA dosage.
- Chord-length distribution can be effectively used to describe pore
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