INFLUENCE OF THE AIR VOIDS DISTRIBUTION IN CONCRETE ON THE RATE OF WATER ABSORPTION

Mariusz DĄBROWSKI*, Kinga DZIEDZIC, Aneta ANTOLIK, Michał A. GLINICKI
Institute of Fundamental Technological Research Polish Academy of Sciences
5B, Pawińskiego Str., 02-106 Warszawa, Poland, *e-mail: mdabrow@ippt.pan.pl

ABSTRACT

Prolonged durability of concrete structures is closely related to the minimization of the transport of liquids in cement matrix. Capillary suction is a dominant mechanism of liquid transport, especially in moderate climate, where cyclic wetting-drying and freeze-thawing cycles occur. Air-entraining of concrete is the efficient way to prevent deterioration impact from environment. However, the influence of air voids distribution on the capillary suction is not well known. The purpose of the research was to assess the water absorption properties of the air entrained concrete. The concrete mixes with the air content from 1% to 16% and similar proportion of micropores to large air voids (A300/A) were prepared. The water absorption tests were performed using ASTM C1585 procedure. The following parameters were determined: $S_i$ – initial rate of water absorption, $S_s$ – secondary rate of water absorption, $t_n$ – time of nick point, $I_{1n}$ – water absorption for $t_n$, $I_{60}$ – initial 60 seconds of water absorption. The results were compared with the air content in concrete. Additionally the compressive strength, porosity accessible to water and concrete resistivity were measured.

The linear relationships between initial and secondary rate of water absorption and the air content in concrete were found. A significant changes of rate of water absorption in concrete when the air content change more than 6% were observed.

Keywords
water absorption, air-entrained concrete, nick point, concrete resistivity, porosity accessible to water.

INTRODUCTION

The application of air-entraining admixtures is the most common method to ensure frost and scaling resistance of concrete. Deterioration of durability during freezing and thawing cycles takes place when the moisture from outside penetrates into microstructure of concrete and fills connected capillary pores and air voids. There are three major mechanisms of fluid transport in concrete such as permeation, capillary suction and diffusion. The capillary suction is the most important one in terms of frost resistance [1-4]]. Furthermore, the measurement of the rate of water absorption is one of the easiest and most efficient method of assessing transport properties in cement-based composites and gives reliable information about potential durability of concrete [6, 7]. The water absorption is related to microstructure and initial moisture content and is therefore influenced by mix composition, degree of hydration and exposure conditions of concrete [4, 8]. The pore network in a cement based matrix provides a path for the transport of fluid into concrete. For cement-based materials, the water absorption mainly occurs in the connected capillary pores between 10 nm and 10 µm. The larger the capillary pore diameter, the faster the water absorption rate increases [9]. Currently, there are
many varieties of the capillary suction procedure [10-15], but the most consistent and widespread method is presented in ASTM C1585. Using capillary suction measurements and still developing the water absorption models we could calculate many factors connected to liquid ingress into concrete, e.g. profile of liquid penetration [16]. Water absorption strongly depends on the initial water content of the sample [17]. The correct determination of the water absorption rate is possible when the initial moisture content distribution is uniform. Hence, according to ASTM C1585, specimens before water absorption measurement are subjected to gentle conditioning procedure, ensuring an uniform distribution of moisture in tested concrete without deterioration of cement matrix [18]. Despite the uniform conditioning procedure, the final moisture content of specimen depends on the porosity of concrete and is generally unknown. The initial rate of water absorption, determined up after 6 h of testing, strongly depends on moisture content on surface of the specimen [19]. Additionally, increase of the initial and secondary (24-168 h) rates of water absorption is observed while increasing the air voids content in concrete [2]. The presence of air voids in concrete modifies the mechanism of water uptake, after 24h of testing, from capillary suction to diffusion [20]. Increase of air void content in concrete results in the increase of the rate of water absorption [2], however the quantitative aspect of that process is unknown.

The aim of the research was to evaluate the water absorption properties of air entrained concrete mixtures with assumed target of air content within the limits 1-16%. Only single types of cement and of AEA were used to achieve the stable air voids system in concrete mixtures, ensuring similar proportion of micropores to air voids content in hardened concrete. Two variants of concrete mixtures with different proportions of cement paste and aggregates were investigated. Additionally, the effects of air content on resistivity (CR) and on volume fraction of porosity accessible to water (PAW) of concrete were analyzed.

MATERIALS AND METHODS

Materials
The effect of air voids characteristic on sorptivity of concrete with different air content with two cement paste to aggregate proportions was investigated. The Portland Cement CEM I 42.5 R (according with PN-EN 197-1 [21]) was used. The chemical composition of cement is given in Table 1. The specific surfaces of cement determined by Blain method was 4300 cm²/kg, density of cement measured by the pycnometer method was 3.10 kg/m³.

Table 1. Chemical composition of cement
(XRF analysis; LOI – up to 1000°C; SO₃ – elemental analysis method)

<table>
<thead>
<tr>
<th>Component</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>63.64</td>
</tr>
<tr>
<td>SiO₂</td>
<td>19.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.84</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.22</td>
</tr>
<tr>
<td>MgO</td>
<td>1.15</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.97</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.53</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.21</td>
</tr>
<tr>
<td>LOI</td>
<td>3.34</td>
</tr>
</tbody>
</table>

The mix proportions of the concrete mixtures are given in Table 2. The natural quartz sand as fine aggregate, gravel and amphibolite as coarse aggregate were used for concrete mix design. The content of sand is given as oven-dry mass and extra water was added to compensate for the absorption of sand (0.8% by mass). The gravel grains had a natural oval shape and smooth texture and the amphibolite was crushed before use. The first set of concrete mixes (series G) was characterized by the same volume of cement paste in cubic meter of concrete. Increased amount of air voids was compensated by reduction of aggregate volume, ensuring the same
proportion of fine and coarse aggregate. Series A of concrete mixes was characterized by the same cement paste to aggregate volume ratio. The air content was intentionally modified by an adequate dose of AEA. The densities of dry ingredients were: quartz sand and gravel 2.65 kg/dm³, crushed amphibolite aggregate 2.90 kg/dm³.

Table 2. Concrete mix design – the series with variable air content
(AEA – air entrainment agent, WR – water reducer)

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Cement [kg/m³]</th>
<th>Water [kg/m³]</th>
<th>Sand [kg/m³]</th>
<th>Gravel [kg/m³]</th>
<th>Amphibolite [kg/m³]</th>
<th>Admixture [% cement mass]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1%</td>
<td>330</td>
<td>155</td>
<td>668</td>
<td>946</td>
<td>303</td>
<td>3.2</td>
</tr>
<tr>
<td>G-8%</td>
<td>330</td>
<td>155</td>
<td>604</td>
<td>854</td>
<td>273</td>
<td>3.2</td>
</tr>
<tr>
<td>G-16%</td>
<td>330</td>
<td>155</td>
<td>530</td>
<td>750</td>
<td>239</td>
<td>3.2</td>
</tr>
<tr>
<td>A-2%</td>
<td>448</td>
<td>179</td>
<td>522</td>
<td>-</td>
<td>-</td>
<td>1332</td>
</tr>
<tr>
<td>A-4%</td>
<td>438</td>
<td>175</td>
<td>510</td>
<td>-</td>
<td>-</td>
<td>1302</td>
</tr>
<tr>
<td>A-6%</td>
<td>434</td>
<td>173</td>
<td>504</td>
<td>-</td>
<td>-</td>
<td>1288</td>
</tr>
<tr>
<td>A-8%</td>
<td>425</td>
<td>170</td>
<td>495</td>
<td>-</td>
<td>-</td>
<td>1263</td>
</tr>
<tr>
<td>A-10%</td>
<td>420</td>
<td>168</td>
<td>489</td>
<td>-</td>
<td>-</td>
<td>1249</td>
</tr>
<tr>
<td>A-12%</td>
<td>411</td>
<td>164</td>
<td>478</td>
<td>-</td>
<td>-</td>
<td>1221</td>
</tr>
</tbody>
</table>

The selection of proper dosage of admixtures was an important part of the technological process. At first the water reducer agent (WR) was added to achieve slump 100-200 mm. The next step was addition of air-entrained agent (AEA) to achieve the target air entrainment in fresh mix verified by gravimetric measurement. The fresh mix properties are given in Table 3. These include air content measured by pressure method, density by the gravimetric method, and consistency by slump.

Table 3. Basic fresh and hardened concrete properties

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Slump [mm]</th>
<th>Apparent density [kg/m³]</th>
<th>Air content [%]</th>
<th>Cube compressive strength after 28 days of hardening [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1%</td>
<td>190</td>
<td>2340</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>G-8%</td>
<td>190</td>
<td>2240</td>
<td>8.5</td>
<td>-</td>
</tr>
<tr>
<td>G-16%</td>
<td>160</td>
<td>2030</td>
<td>16.4</td>
<td>-</td>
</tr>
<tr>
<td>A-2%</td>
<td>110</td>
<td>2480</td>
<td>1.9</td>
<td>56.3</td>
</tr>
<tr>
<td>A-4%</td>
<td>80</td>
<td>2420</td>
<td>4.1</td>
<td>54.1</td>
</tr>
<tr>
<td>A-6%</td>
<td>100</td>
<td>2390</td>
<td>5.2</td>
<td>53.2</td>
</tr>
<tr>
<td>A-8%</td>
<td>110</td>
<td>2340</td>
<td>7.1</td>
<td>51.1</td>
</tr>
<tr>
<td>A-10%</td>
<td>120</td>
<td>2320</td>
<td>8.3</td>
<td>48.6</td>
</tr>
<tr>
<td>A-12%</td>
<td>100</td>
<td>2260</td>
<td>10.6</td>
<td>42.8</td>
</tr>
</tbody>
</table>
Concrete mixes were produced in the laboratory mixer of 50 litre capacity. Standard specimens were manufactured for determination of:

- compressive strength according to PN-EN 12390-3 [22] – 100 mm cubes,
- air void characteristics – 150 mm cubes,
- water absorption, CR and PAW – cylinders Ø=100 mm, h=200 mm.

Specimens were maintained for 28 days in saturated curing conditions before testing or conditioning.

**METHODOLOGY AND TESTS PERFORMED**

**Water absorption test** was carried out in accordance with ASTM C 1585. Three concrete discs (thickness 50 mm and diameter 100 mm) were cut out from cylinder specimens of each concrete mixture and then placed in an environmental chamber at temperature of 50°C and RH of 80% for 3 days. After that, each specimen was stored in an individually sealed container for 15 days to achieve equilibration of internal humidity. The specimens were then covered with plastic water-proof sheets, completely sealed on their sides and bottom, leaving only the top surface exposed. The exposed surface of the specimen was placed face down on the support device (plastic rods) inside the container filled with water up to 3 ± 1 mm above the top of the device. The mass of the specimens were measured at regular intervals – more frequently for the first 6 h and less frequently afterwards – for 8 days. The initial sorptivity ($S_i$) was calculated based on mass intake during the first 6 h, and secondary sorptivity ($S_s$) based on the mass intake in the 24 h to 8 day exposure period. Both $S_i$ and $S_s$ were obtained for all concrete mixtures that were initially cured for 28 days in saturated curing conditions. The point of intersection of linear functions of initial and secondary sorptivity (the nick point) was recorded. Time of nick point ($t_n$) and water absorption value for $t_n$ ($I_n$) was indicated. Additionally, the first measurement of water absorption after 60 seconds of capillary suction ($I_{60}$) was indicated. Average values of sorptivities for two specimens of each mixture are reported.

**The air void characteristic** in hardened concrete was determined using a computer-driven system of automatic image analysis. Tests were performed using polished surface of concrete specimens 100x100x25 mm cut out from cube specimens (150 mm). The automatic measurement procedure was designed to comply with the requirements imposed by PN-EN 480-11:2008 [23]. Results of measurements were available as a set of parameters for air void microstructure characterization: spacing factor – $L$ [mm]; specific surface – $\alpha$ [1/mm]; air content in hardened concrete – $A$ [%]; content of air voids with diameter less than 0.3 mm – $A_{300}$ [%].

**Concrete resistivity (CR)** measurements, for specimens cured in water, were carried out using the Giatec RCON2 device. A cylindrical specimen of hardened concrete was placed between two parallel plates of the device (electrodes) connected to an alternate current source. The device calculates the bulk electrical resistivity of concrete based on the measured potential drop between the electrodes and predefined dimensions of the specimen. According to [24], resistivity is well correlated with porosity of cement matrix and water absorption rate. Average values of resistivities for the three specimens of each mixture are reported.

**Porosity accessible to water (PAW)** was measured according to French standard NF P18-459 [25]. Three cylindrical specimens (Ø=100 mm, h=50 mm) cut out from cast cylinder (Ø=100 mm, h=200 mm) have been vacuum saturated with water. Specimens were weighted in three states: full saturated on the hydrostatic weight, full saturated and dried to constant mass on laboratory weight. Based on the measurements (average of three specimens) the volume fraction of PAW was calculated.
RESULTS AND DISCUSSIONS

The air void characteristics of hardened concrete series A are given in Table 4. The loss of air voids content in hardened concrete compared to measurement of air content in fresh concrete was up to 20% for all concrete mixtures except A-2%. For concrete mixture A-2% loss of air voids reached 40%.

Table 4. Quantitative characteristics of air voids in hardened concrete

<table>
<thead>
<tr>
<th></th>
<th>( L ) [mm⁻¹]</th>
<th>( L ) [mm]</th>
<th>( A_{300} ) [%]</th>
<th>( A_{300}/A ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-2%</td>
<td>1.19</td>
<td>0.42</td>
<td>0.58</td>
<td>49</td>
</tr>
<tr>
<td>A-4%</td>
<td>3.21</td>
<td>0.19</td>
<td>1.78</td>
<td>55</td>
</tr>
<tr>
<td>A-6%</td>
<td>4.61</td>
<td>0.16</td>
<td>2.16</td>
<td>47</td>
</tr>
<tr>
<td>A-8%</td>
<td>6.22</td>
<td>0.15</td>
<td>3.26</td>
<td>52</td>
</tr>
<tr>
<td>A-10%</td>
<td>7.16</td>
<td>0.13</td>
<td>3.55</td>
<td>50</td>
</tr>
<tr>
<td>A-12%</td>
<td>9.52</td>
<td>0.14</td>
<td>3.29</td>
<td>35</td>
</tr>
</tbody>
</table>

Similar proportion of micropores to air voids content in hardened concrete \( (A_{300}/A) \) was provided. The \( A_{300}/A \) ratio was around 50%, except mixture A-12%. In that case a lot of micropores accumulated creating the large pores, hence the proportion \( A_{300}/A \) decreased compared with other concrete mixtures (Fig. 1). Assuming similar air void distribution for all tested concrete mixtures the rate of capillary suction can be attributed to the air voids content in the cement matrix.

Fig. 1. Picture of air voids distribution in concrete (a) A-6% and (b) A-12% – the same scale

The summary of water absorption kinetics results of concrete mixtures with different air content is shown in Figure 2. For both series of concrete mixture the tendency was similar to Liu [2] investigation, however comparison of results of water absorption is difficult because many factors have impact on rate of sorptivity. The rate of water absorption can be considered only for the same w/c, because tendency is not linear for conditioning presented in ASTM C1585 [7]. The function of water absorption to square root of time (initial rate of water absorption) is close to linear relationship. S-shaped curves [8] and decrease of water absorption rate over time (at the end of first 6 h) [25] are not observed. Influence of air content on initial rate of water \((S_i)\) absorption is statistically significant for mixes with more than 6% of entrained air. The secondary rate of water absorption slightly decreases between 24 h to 72 h and remains constant after 72 h. Phenomenon is typical for high quality concrete.
conditioned according to ASTM C1585 [7]. Statistically significant differences of secondary rate of water absorption (Ss) between concrete mixes were observed after 72-96 h of water absorption measurement.

Fig. 2. Comparison of water absorption kinetics of concrete with different air content
(a) series G, (b) series A

The indication procedure of the parameters describing capillary suction of concrete is shown in Figure 3. Initial rate of water absorption (Si) and secondary rate of water absorption (Ss) were calculated using the least squares method. The coordinates of nick points: time (tn) and absorption for tn (In) were also determined. Those parameters are widely known and used to
assess the fluid transport properties of concrete [4]. In addition, the water absorption after 60 seconds of measurement ($I_{60}$) was indicated.

Calculation results of capillary suction measurement were collected in Table 5. Results of $S_i$ ranged from $28.9 \cdot 10^{-4}$ mm/s$^{1/2}$ to $44.0 \cdot 10^{-4}$ mm/s$^{1/2}$ and from $36.1 \cdot 10^{-4}$ mm/s$^{1/2}$ to $48.0 \cdot 10^{-4}$ mm/s$^{1/2}$ for concrete series G and A, respectively. The $S_s$ results do not exceed $19.1 \cdot 10^{-4}$ mm/s$^{1/2}$ and $15.9 \cdot 10^{-4}$ mm/s$^{1/2}$ for concrete series G and A, respectively. Indicated time of nick point $t_n$ ranged from 9 h to 28 h. No significant relation between nick point and the air content of concrete was found. Observation is contradictory to Liu [2] conclusion, that increase of air content in concrete extends time of appearance of nick point of water absorption.

Table 5. Calculation of water absorption parameters
($S_i$ – initial rate of water absorption, $S_s$ – secondary rate of water absorption, $t_n$ – time of nick point, $I_n$ - water absorption for $t_n$, $I_{60}$ – initial 60 second of water absorption)

<table>
<thead>
<tr>
<th></th>
<th>$S_i$ [·$10^{-4}$ mm/s$^{1/2}$]</th>
<th>$S_s$ [·$10^{-4}$ mm/s$^{1/2}$]</th>
<th>$t_n$ [h]</th>
<th>$I_n$ [mm]</th>
<th>$I_{60}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-1%</td>
<td>44.0</td>
<td>8.3</td>
<td>10.3</td>
<td>0.85</td>
<td>0.048</td>
</tr>
<tr>
<td>G-8%</td>
<td>38.8</td>
<td>12.5</td>
<td>20.3</td>
<td>1.06</td>
<td>0.062</td>
</tr>
<tr>
<td>G-16%</td>
<td>28.9</td>
<td>19.0</td>
<td>28.1</td>
<td>0.94</td>
<td>0.096</td>
</tr>
<tr>
<td>A-2%</td>
<td>48.3</td>
<td>7.0</td>
<td>10.8</td>
<td>0.96</td>
<td>0.028</td>
</tr>
<tr>
<td>A-4%</td>
<td>45.0</td>
<td>5.6</td>
<td>19.0</td>
<td>1.18</td>
<td>0.046</td>
</tr>
<tr>
<td>A-6%</td>
<td>45.9</td>
<td>10.2</td>
<td>13.8</td>
<td>1.01</td>
<td>0.041</td>
</tr>
<tr>
<td>A-8%</td>
<td>37.6</td>
<td>14.6</td>
<td>12.3</td>
<td>0.83</td>
<td>0.058</td>
</tr>
<tr>
<td>A-10%</td>
<td>36.6</td>
<td>15.9</td>
<td>14.7</td>
<td>0.87</td>
<td>0.059</td>
</tr>
<tr>
<td>A-12%</td>
<td>36.1</td>
<td>17.9</td>
<td>9.1</td>
<td>0.68</td>
<td>0.071</td>
</tr>
</tbody>
</table>

Fig. 3. Example of calculation of water absorption parameters - concrete mixture A-4%

$y = 0.0045x + 0.0052$

$R^2 = 0.9995$

$y = (0.0004x + 1) \div 81$

$R^2 = 0.9064$

Not included in calculation
($R^2 < 0.99$)
A linear correlation between the rate of water absorption and the content of air was found for both series of concrete specimens (Fig. 4). The $S_i$ decrease with the increase of air content in cement matrix, for $S_i$ the linear relationship is opposite. Results confirm observation presented by authors of papers [2;4].

![Diagram](image)

**Fig. 4.** Effect of air content on water absorption in concrete (a) series G, (b) series A

Water absorption for first 60 seconds of measurement capillary suction ($I_{60}$) increases linearly with the air content in tested specimens of concrete (Fig. 5). Phenomenon is related to the air content in concrete - the increase of air voids in cement matrix increases a specific surface area of concrete specimen. At the beginning of capillary suction measurement the partially dried surface contacts with water causing water uptake of concrete surface. Appearance of small holes on the surface of air entraining concrete increases the surface area available to
wetting. Linear correlations between $I_{60}$ and air content are presented in Figure 5. The results for both concrete series were similar, regardless the concrete composition. Therefore $I_{60}$ value is strictly related to specific surface area and does not represent the capillary suction of cement matrix.

![Figure 5](image1)

**Fig. 5.** Effect of air content on the initial 60 seconds of capillary suction in concrete

Increase of the air content in concrete does not influence the porosity accessible to water (PAW) and resistivity (CR) of concrete (Fig. 6). The variation of air content in concrete caused negligible statistically changes of PAW and CR. The PAW results were 13.5%, 13.5% and 14.3% for the air content 1%, 8%, 16%, respectively. The similar small differences were observed for the CR results: 27.5 kΩcm, 27.2 kΩcm and 30.9 kΩcm, respectively.

![Figure 6](image2)

**Fig. 6.** Effect of air content on porosity accessible to water and resistivity of concrete
Many authors [4;19;7] presented an influence of the capillary porosity on the rate of water absorption in cement matrix. According to Wong et al. [27] the air voids in cement matrix have no impact on transport of a liquid. Only capillary pores are associated with capillary suction. The same cement paste content for series G of concrete ensured the repeatable capillary pores distribution and consequently the same volume of open porosity. The PAW measurement confirmed repeatable capillary porosity distribution.

The CR measurement results were unexpected. Full saturated concrete with increased content of air should provide a decrease of concrete resistivity. Air voids of specimens cured in water probably were only partially saturated with water and the CR measurements did not account for presence of air entrained porosity without water.

The research showed opposite conclusion to Wong et al. [27]. Occurrence of more than 6% of air voids significantly affected the initial and secondary rate of water absorption. Such large differences of air content in common used concrete do not occur at building sites and can only be considered theoretically. Probable dominant mechanism is a result of intersection of capillary pores in cement matrix by air voids and decrease of capillary suction force at the beginning of water absorption. This is manifested by decrease of initial rate of water absorption and increase of secondary rate of water absorption and is consistent with the observations of other authors, e.g. [2;28].

CONCLUSIONS

The study focused on investigation of the influence of air voids content on the rate of water absorption. Concrete mixtures were designed to obtain the similar distribution of air voids in cement matrix, which was proved by image analysis of polished sections. On the basis of results obtained in this investigation the following concluding remarks are derived:

- Linear correlation of the initial and secondary water absorption and the air content in concrete was found. Increase of the air content in concrete decreases the initial rate of water absorption and increases the secondary rate of water absorption.
- The increase in air content by less than 6% has no significant influence on the rate of concrete water absorption.
- Correlation between of the air content and the coordinates of nick point is not observed.
- The water absorption after 60 seconds of measurements is linearly correlated with the air content of concrete.
- The change of air content up to 16% has no significant impact on porosity accessible to water and on the resistivity of concrete.

ACKNOWLEDGEMENTS

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BRITTLE MATRIX COMPOSITES

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Edited by

Michał A. GLINICKI
Institute of Fundamental Technological Research
Polish Academy of Sciences Warsaw, Poland

Daria JÓŹWIAK-NIEDŹWIEDZKA
Institute of Fundamental Technological Research
Polish Academy of Sciences, Warsaw, Poland

Christopher K.Y. LEUNG
Hong Kong University of Science and Technology, Hong Kong, China

Jan OLEK
Purdue University, West Lafayette, USA

Institute of Fundamental Technological Research
Warsaw 2019
PREFACE

The 12th International Symposium on Brittle Matrix Composites (BMC-12) took place from September 23-24, 2019 on the campus of the Institute of Fundamental Technological Research (IFTR) of the Polish Academy of Sciences in Warsaw, Poland. This conference built on the legacy of the eleven previous meetings, starting with the 1st symposium in 1985 and continuing on the three-year cycle until 2015, the date of the 11th symposium (BMC-11). With the exceptions of the BMC-1, which was held in Jablonna, and the BMC-2 held in Cedzyna near Kielce, Poland, all subsequent symposia were held in Warsaw. In each case, the IFTR served as the host and the main organizer of the meeting.

The conference focused on key subjects in contemporary brittle (or quasi-brittle) materials that are of relevance to both academic and practitioners communities. As was the case with the previous eleven volumes in this series, the 25 papers included in the current proceedings cover a wide range of topics that reflect latest developments in the areas related to science and technology of cement, concrete and composite materials. The main topics represented in this volume include:

- characterization techniques and test methods
- durability
- use of recycled materials
- modeling and prediction of properties
- mechanical behavior of fiber composites
- geopolymers and other composite materials

The BMC-12 brought together leading experts in the field of brittle composite materials from 18 different countries and offered the opportunity to discuss recent progress, share insights on research priorities, identify and discuss the approaches toward further developments and facilitate exchange of information across disciplines and institutions.

The organizing committee would like to thank all authors who provided their original papers and shared their expertise during the presentations and discussions.

A very special thanks is extended to Prof. Andrzej M. Brandt who has led the BMC organizing committee for all these years. His extensive knowledge of the topic, and his numerous contacts within the international community, were essential to organization of the first Symposium in 1985 and contributed greatly to successful continuation of this series over the last 34 years. His attention to details while editing the papers was indeed legendary, and the Symposium itself is inseparable from the name A.M. Brandt. As he shifts his focus toward retirement, it is our hope that he will continue to serve as a "spiritual guardian" of this Symposium for a long time.

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D. Jóźwiak-Niedźwiedzka
C.K.Y. Leung
J. Olek

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http://www.zturek.pl, zturek@zturek.pl
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