Investigation of Self-compacting Mortars with Fly Ash and Crushed Brick

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Investigation of Self-compacting Mortars with Fly Ash and Crushed Brick

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Abstract

The use of industrial by-products and waste materials in cement composites production has been one of the most intriguing topics in construction materials science for several decades. This paper reports an investigation into effects of fly ash (FA) and crushed brick powder (CBP), on the properties of fresh and hardened self-compacting mortars (SCM). These waste materials partially replace limestone powder (LP) which was used as mineral filler. Also, special attention is paid to the combined effects of the mentioned mineral fillers and crushed brick (CB) and recycled concrete aggregate (RCA) on properties of SCM. These waste materials were used as a fine river aggregate replacement (0.09/0.25 mm). The composition of one reference and eight more different mixtures with the mentioned materials were adopted in such a manner to preserve the constant ratio between all the solid components. Following data were deduced: filling and passing ability (slump flow test, V-funnel test), bulk density of fresh and hardened mortar, compressive and flexural strength, ultrasonic pulse velocity, dynamic modulus of elasticity and adhesion (pull-off strength). These values were used for the global comparison of mortar properties and for the comparison of the effects that each of the recycled components produces. The results of the slump flow test ranged from 15 cm to 28 cm. Most of the mixtures after 28 days reached satisfactory compressive strengths (ranged from 26.5 to 48.4 MPa) and flexural strengths (ranged from 6.0 to 8.8 MPa). The results indicate higher final strengths in mixtures with FA used as a mineral filler replacement than in those with CBP. Also, although similar results were obtained in mixtures with CB and RCA used as aggregate replacement, mixtures with RCA showed higher values of the measured physical and mechanical properties. Based on the experimental results, a good correlation between compressive strength and dynamic modulus of elasticity, dependent upon material properties, was obtained.

Keywords: Crushed brick, Fly ash, Recycled aggregate, Self-compacting mortar.

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Introduction

Self-compacting mortar and concrete by definition need to be placed into formwork without vibrating or any additional actions. Due to this, both materials have to fulfill certain demands on behalf of their workability, fluidity and passing ability. Those properties are achieved by optimizing the mix’s proportions and incorporating mineral and chemical admixtures that, apart from influencing the fluidity and viscosity, act to avoid segregation and/or bleeding [1].

Self-compacting mortars (SCM) were investigated mostly as a step in self-compacting concrete mixtures design, since they are made only with a fine aggregate fraction (for example in method proposed by Nepomuceno [2]). More recently the developed application of self-compacting mortars is in the rehabilitation and repair of reinforced concrete structures. Apart from their good properties in a fresh state, necessary for adequate placement on the damaged concrete elements, self-compacting repair mortars have to achieve equal or improved mechanical properties compared to the concrete in question.

Since the composition of mortars could sometimes consist of more than one type of cement (i.e. special cement, like ultra-fine alumina cement) together with additions (i.e. silica fume, slag, brick powder or fly ash), aggregates (normal, lightweight and special types, fillers), admixtures such as super plasticizer (SP), air entrainers and accelerators, polymer additives and fine polymer fibres, it is important to investigate influence of each of these components on properties of fresh and hardened SCM.

Sahmaran at al. [3] and Da Silva and De Brito [1] both showed that combination of fly ash and limestone filler used as a filler component (particles of stone or rock smaller than 0.063 mm) in SCM improved workability of the mixtures. It was also recommended that crushed brick powder should not be used as the only mineral filler. The experiments showed that fineness, smooth surface and spherical shape of particles should all be considered as parameters when choosing the optimal filler content [3]. Ganaw and Ashour [4] confirmed that as the surface area of aggregate increases, more paste is needed to cover the surface and attain a certain rheology. This implies that type and mass of the aggregate, as well as its granulometry, would influence the amount of paste used for SCM.

In this study SCM were designed using a limestone filler, fly ash and crushed brick powder as mineral fillers and a river aggregate, crushed brick and a recycled concrete aggregate. the mixtures were created in such a way to show the influence of each of replacing components on self-compacting mortar properties in fresh and hardened state.

Experimental Work

Nine series of SCM were designed incorporating by-products (fly ash) and recycled materials (crushed brick and recycled concrete aggregate). These materials were used in two different ways. One was a partial replacement of limestone filler with fly ash (FA) or crushed brick powder
(CBP), and the second one was a partial and complete replacement of river aggregate with crushed brick (CB) and recycled concrete aggregate (RCA).

**Materials**

Cement CEM II/A-M (S-L) 42.5R Lafarge Beočin was used. The true density of this cement amounted to 3040 kg/m³.

Limestone powder from “Granit Peščar” Ljig, with the average diameter of 250 µm and true density of 2720 kg/m³, was used as a mineral filler in all of the mixtures.

Fly ash used in this research originated from the power plant “Kostolac”, with a true density of 2210 kg/m³ and a bulk density in a loose state of 650 kg/m³. It was sieved through the sieve 0.063 mm, and used without any other treatment.

The Danube river aggregate was used, with a true density of 2640 kg/m³, a bulk density of 1667 kg/m³ and water absorption of 1%. The aggregate was divided into subfractions (A1, A2, B, C, D) as shown in Figure 1.

Crushed brick and crushed brick powder originated from bricks produced in southern Vojvodina, Serbia. After crushing and milling brick powder component was gained by sieving through the sieve 0.063 mm. Crushed brick aggregate, with grains between 0.09 mm and 2 mm, was then divided into subfractions as shown in Figure 1.

Recycled concrete aggregate originated from concrete produced on Faculty of Civil Engineering as a part of the other experiments. It was obtained by crushing and dividing into subfractions, as shown in Figure 1.

Superplasticizer “Adium 132” produced by “Isomat”, was used in all the mixtures in the amount of 1.5% of cement mass. Density of this polycarboxylate-based admixture was 1030 kg/m³.

The aggregate/cement (AG/CEM) ratios were kept constant (AG:CEM = 3.375:1). The powder composition of all SCMs was: 50% cement, 25% of limestone filler and 25% of another filler (FA or CBP) depending on the mixture. All aggregates used were divided into subfractions, determined by the standard cement mortar production rules according to SRPS B.C8.022 [5] – A (0.09/0.25 mm), B (0.25/0.5 mm), C (0.5/1 mm) and D (1/2 mm), while for CB and RC subfraction A was divided into two: A1 (0.09/0.125 mm) and A2 (0.125/0.25 mm), as shown in Figure 1. These subfractions were used in the following mass ratios (A1:A2:B:C:D=1:1:4:6:6) according to the same standard. Although, SRPS EN 196-1 [6] defines granulometry of the sand somewhat differently, the adopted mixture was mostly confined within the limits given by this standard.
Nine series of mortars were created using the same ratios between the solid components \( (m_c:m_f:m_a=1:1:3.375) \), where \( m_c \) represents the mass of cement, \( m_f \) – mass of mineral filler and \( m_a \) – mass of aggregate. Mass of water for the series varied, due to targeted similar properties of fresh concrete (200 – 300 mm slump flow diameter), while the amount of superplasticizer was the same for all of the mixtures (1.5% \( m_c \)). This mix design method was adopted in order to establish the possibility of making rational and applicable mixtures with given components. The referent mixture (series I) contained cement, limestone powder, water, river aggregate (0/2 mm) and a chemical admixture, in amounts given in Table 1.

In eight other mixtures, the filler was partially replaced (in amount of 50%) with FA or CBP. In the six mixtures river aggregate was partially or completely replaced with CB and RC, as shown in Table 1. These mixtures have been marked differently, as defined in the legend below the Table 1.

Manufacturing and Testing

The mixing parameters mostly followed the procedure of standard cement mortar mixing (SRPS EN 196-1[7]). First water, cement and mineral filler were mixed for 30 s, followed by an addition of aggregate during the next 30 s. In the following step the superplasticizer was added, and mixing continued for another 210 s. Mixing was performed at the same speed during the whole process of the series production.

In order to evaluate and compare their performances, mortar mixtures were tested in three stages. In the first stage, bulk density \( (\gamma) \), slump flow diameter \( (D) \) with the flow time \( (t_f) \), V-funnel flow time \( (t_v) \) and
temperature (T) measurements were conducted on fresh mortars. In the second stage, compressive (f_c) and flexural (f_f) strength, as destructive methods [6], ultrasonic pulse velocity (v) (SRPS U.M1.042:1998 [7]) and dynamic modulus of elasticity (E_D) (SRPS U.M1.026:1993 [8]), as nondestructive methods, were determined on 4 x 4 x 16 mm prisms at the ages of 1, 3, 7, 28, 56 and 90 days, by testing two specimens per mixture.

Table 1. Series Mix Design

<table>
<thead>
<tr>
<th>*</th>
<th>CEM</th>
<th>Mineral filler</th>
<th>Sp</th>
<th>W</th>
<th>Aggregate A1 (0.09/0.125)</th>
<th>A2 (0.125/0.25)</th>
<th>B (0.25/0.50)</th>
<th>C (0.50/1.00)</th>
<th>D (1.00/2.00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>**</td>
<td>1</td>
<td>1</td>
<td>0.015</td>
<td>-</td>
<td>0.188</td>
<td>0.188</td>
<td>0.750</td>
<td>1.125</td>
<td>1.125</td>
</tr>
<tr>
<td>I</td>
<td>386</td>
<td>386</td>
<td>-</td>
<td>5.8</td>
<td>290</td>
<td>145</td>
<td>290</td>
<td>434</td>
<td>434</td>
</tr>
<tr>
<td>II</td>
<td>359</td>
<td>180</td>
<td>180</td>
<td>5.8</td>
<td>295</td>
<td>135</td>
<td>270</td>
<td>404</td>
<td>404</td>
</tr>
<tr>
<td>III</td>
<td>329</td>
<td>164</td>
<td>164</td>
<td>4.9</td>
<td>384</td>
<td>62</td>
<td>247</td>
<td>370</td>
<td>370</td>
</tr>
<tr>
<td>IV</td>
<td>345</td>
<td>172</td>
<td>172</td>
<td>5.1</td>
<td>353</td>
<td>65</td>
<td>259</td>
<td>388</td>
<td>388</td>
</tr>
<tr>
<td>V</td>
<td>391</td>
<td>195</td>
<td>-</td>
<td>5.8</td>
<td>292</td>
<td>146</td>
<td>293</td>
<td>439</td>
<td>439</td>
</tr>
<tr>
<td>VI</td>
<td>333</td>
<td>167</td>
<td>-</td>
<td>5.0</td>
<td>377</td>
<td>63</td>
<td>250</td>
<td>375</td>
<td>375</td>
</tr>
<tr>
<td>VII</td>
<td>345</td>
<td>172</td>
<td>-</td>
<td>5.1</td>
<td>336</td>
<td>65</td>
<td>259</td>
<td>388</td>
<td>388</td>
</tr>
<tr>
<td>VIII</td>
<td>260</td>
<td>130</td>
<td>-</td>
<td>3.9</td>
<td>478</td>
<td>49</td>
<td>195</td>
<td>292</td>
<td>292</td>
</tr>
<tr>
<td>IX</td>
<td>364</td>
<td>182</td>
<td>-</td>
<td>5.4</td>
<td>486</td>
<td>68</td>
<td>273</td>
<td>409</td>
<td>409</td>
</tr>
</tbody>
</table>

| crushed brick used as aggregate replacement | recycled aggregate used as aggregate replacement |

*Amounts of all of the component materials are given in kg/m³. Abbreviation CEM represents mass of cement, LF – limestone filler, FA – fly ash, CB – crushed brick powder. Superplasticizer is marked as Sp, water as W, while aggregate masses are given per fractions.

**First row represents mass ratios between each component material and cement.

Figure 2. Measuring of First and Third Stage Properties: a) Slump-flow Test and b) Pull-off Test

The test specimens were stored in a water tank at a temperature of (20 ± 2) °C until the test age. Three plate samples, per mixture, with dimensions...
20 x 20 x 3 cm were used for the pull-off resistance test (SRPS EN 1542:2010 [9]) and for the frost–thaw resistance in the presence of defrosting salts (SRPS U.M1.055:1984 [10]), during the third stage of the experiment. First, the pull-off testing was conducted at the age of 28 days, and once again on chosen samples after the frost-thaw resistance testing was finished (Figure 2). These samples were stored in a water tank at a temperature of 20°C until the age of 7 days, and afterwards cured on air until the test age.

Results and Discussion

Properties of Fresh Mortars

The test results show that even with 1.5 % of the superplasticizer added, high values of water/cement (w/c) ratios were needed to achieve the targeted properties of fresh mortars in most of the designed mixtures. This applies mostly to the mixtures that contained CB as a partial or total aggregate replacement (series III - w/c=1.167, VI - w/c=1.132 and VIII - w/c=1.838), and where RC was used as a total aggregate replacement (IX - w/c =1.335). On the other hand, using CBP as a partial replacement of filler did not lead to such an effect (series V - w/c =0.747).

As shown in Table 2, the slump flow diameter ($\bar{D}$) for most of the mixtures ranged from 210 mm to 280 mm, with V-funnel time ($t_v$) varying from 2.8 s to 7.5 s. The exception occurred for the series VII, where the slump flow diameter was 150 mm, and the V-funnel time 10.8 s. It can be noticed that series containing variation in mineral filler achieved similar fresh state properties and w/c ratios as the referent mixture, which approves usage of CBP and FA as mineral filler in SCM mixtures. Mixtures III, IV, VI and VII, where subfractions A and B were replaced with CB or RCA, demanded higher but still reasonable w/c ratios, unlike mixtures VIII and IX, where this value was too high with visible bleeding. Interesting behavior was noticed with series VIII, where the slump-flow diameter ranged within the mentioned limits ($\bar{D}$=222 mm), reached in regular time ($t_f$=6.8 s). For this series V-funnel test failed, which shows that, although this mortar mixture possessed the targeted fluidity value, it did not show expected passing ability.

Mixtures containing the RCA as a partial aggregate replacement showed lack of stability in the fresh state. There were visible signs of slight segregation in samples of series IV, while series VII was rapidly losing its properties in the fresh state (flowing and filling ability), even during testing.

Figure 3 presents the slump-flow diameter plotted against water/powder (w/p) ratio. It can be noticed that the increase in the w/p ratio, leads to the increase in slump-flow diameter, although the increase rate depends on the type of aggregate used as well. For series VIII and IX average values of slump-flow diameters were recorded, in spite of the higher values of w/p ratios, which can be explained by a higher sorption rate of the aggregates used in these series, compared to the river aggregate.
Table 2. Fresh State Properties of the Self-compacting Mortar Mixtures

<table>
<thead>
<tr>
<th>Testing method Series</th>
<th>W/C ratio</th>
<th>Bulk density $\gamma$ (kg/m$^3$)</th>
<th>$t_v$ (s)</th>
<th>$D_{sr}$ (mm)</th>
<th>$t_f$ (s)</th>
<th>Temperature $T$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.751</td>
<td>2297</td>
<td>4.3</td>
<td>215</td>
<td>6.3</td>
<td>23.1</td>
</tr>
<tr>
<td>II</td>
<td>0.822</td>
<td>2219</td>
<td>4.8</td>
<td>280</td>
<td>12.3</td>
<td>21.9</td>
</tr>
<tr>
<td>III</td>
<td>1.167</td>
<td>2089</td>
<td>5.2</td>
<td>270</td>
<td>12.3</td>
<td>20.8</td>
</tr>
<tr>
<td>IV</td>
<td>1.023</td>
<td>2081</td>
<td>4.4</td>
<td>240</td>
<td>11.7</td>
<td>25.7</td>
</tr>
<tr>
<td>V</td>
<td>0.747</td>
<td>2232</td>
<td>7.5</td>
<td>210</td>
<td>8.3</td>
<td>24.5</td>
</tr>
<tr>
<td>VI</td>
<td>1.132</td>
<td>1940</td>
<td>2.8</td>
<td>270</td>
<td>12.9</td>
<td>24.5</td>
</tr>
<tr>
<td>VII</td>
<td>0.974</td>
<td>2140</td>
<td>10.8</td>
<td>150</td>
<td>4.7</td>
<td>25.1</td>
</tr>
<tr>
<td>VIII</td>
<td>1.838</td>
<td>1848</td>
<td>-</td>
<td>222</td>
<td>6.8</td>
<td>24.2</td>
</tr>
<tr>
<td>IX</td>
<td>1.335</td>
<td>1970</td>
<td>3.8</td>
<td>240</td>
<td>6.0</td>
<td>24.8</td>
</tr>
</tbody>
</table>

Figure 3. Results of the Slump-flow Testing Compared with the Water/Powder Ratio of Each Series

Properties of Hardened Mortars

The test results concerning the dynamic modulus of elasticity, flexural and compressive strength are presented in Table 3, while bulk density and ultrasonic pulse velocity results are presented in Table 4. Each number represents the mean value of 4 results in the case of compressive strength ($f_c$), 2 results for flexural strength ($f_f$) and 2 results for dynamic modulus of elasticity ($E_D$), bulk density ($\gamma$) and ultrasonic pulse velocity ($v$). After three days, flexural strengths ranged from 1.3 MPa (series VIII) to 5.6 MPa (series I), while compressive strengths ranged from 4.1 MPa (series VIII) to 26.1 MPa (series I). After the final measurements, 90 days after mixing, flexural strengths ranged between 5.1 MPa (series VIII) and 9.4 MPa (series
II), and compressive strengths ranged between 18.3 MPa (series VIII) and 60.3 MPa (series II). The final values of dynamic modulus of elasticity, at the age of 90 days, ranged between 15.4 GPa (series VIII) and 36.1 GPa (series I).

Bulk density ranged between 1913 kg/m$^3$ (series VIII) and 2274 kg/m$^3$ (series I) at the age of 28 days. At the same age, ultrasonic pulse velocity ranged between 3098 m/s (series VIII) and 4694 m/s (series I).

Table 3. Hardened State Properties of the Self-compacting Mortar Mixtures (Flexural Strength $f_f$, Compressive Strength $f_c$, Dynamic Modulus $E_D$)

<table>
<thead>
<tr>
<th>Series</th>
<th>$f_f$ (MPa)</th>
<th>$f_c$ (MPa)</th>
<th>$E_D$ (GPa)</th>
</tr>
</thead>
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<tr>
<td>I</td>
<td>5.6</td>
<td>8.1</td>
<td>9.0</td>
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<tr>
<td>II</td>
<td>4.6</td>
<td>8.8</td>
<td>9.4</td>
</tr>
<tr>
<td>III</td>
<td>3.4</td>
<td>7.9</td>
<td>8.5</td>
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<tr>
<td>IV</td>
<td>3.6</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>V</td>
<td>5.3</td>
<td>7.6</td>
<td>8.6</td>
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<tr>
<td>VI</td>
<td>2.9</td>
<td>6.0</td>
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<td>6.8</td>
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<tr>
<td>VIII</td>
<td>1.3</td>
<td>4.3</td>
<td>5.1</td>
</tr>
<tr>
<td>IX</td>
<td>1.4</td>
<td>5.4</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The best results were achieved for the series I, II and V, that is, a referent mixture and mixtures where only mineral filler was partially replaced with FA (series II) and CBP (series V). These results can be compared with the ones obtained by Sahmaran et al. [3] on mixtures containing FA and LF and CBP and LF, as filler components. First mixture corresponding to the series II of their research reached compressive strength of 40.4 MPa, ultrasonic velocity pulse of 4565 m/s with bulk density of

Table 4. Bulk Density $\gamma$ and Ultrasonic Pulse Velocity $v$ of the Self-compacting Mortar Mixtures

<table>
<thead>
<tr>
<th>Series</th>
<th>$\gamma$ (kg/m$^3$)</th>
<th>$v$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 days</td>
<td>28 days</td>
</tr>
<tr>
<td>I</td>
<td>2267</td>
<td>2274</td>
</tr>
<tr>
<td>II</td>
<td>2209</td>
<td>2223</td>
</tr>
<tr>
<td>III</td>
<td>2142</td>
<td>2085</td>
</tr>
<tr>
<td>IV</td>
<td>2086</td>
<td>2101</td>
</tr>
<tr>
<td>V</td>
<td>2236</td>
<td>2246</td>
</tr>
<tr>
<td>VI</td>
<td>2004</td>
<td>2015</td>
</tr>
<tr>
<td>VII</td>
<td>2144</td>
<td>2148</td>
</tr>
<tr>
<td>VIII</td>
<td>1904</td>
<td>1913</td>
</tr>
<tr>
<td>IX</td>
<td>2025</td>
<td>2028</td>
</tr>
</tbody>
</table>
2193 kg/m$^3$. Second mixture corresponding to the series V of this research showed compressive strength of 43.8 MPa, ultrasonic velocity pulse of 4576 m/s with bulk density reaching 2242 kg/m$^3$ at the same age. It can be concluded that with similar fresh mortar properties, similar values of compressive strengths after 28 days were obtained with a smaller amount of cement and larger amount of filler used. Although bulk densities had very similar values, series II and V reached lower ultrasonic pulse velocity values than the corresponding series in the mentioned paper [3].

**Figure 4.** Change of the Compressive Strength through Time for Series I, II and V (Series made with River Sand as Aggregate)

**Figure 5.** Change of the Compressive Strength through Time for Series III, IV, VI, VII, VIII and IX (Series made with CB or RCA as Partial or Total River Aggregate Replacement)

The results obtained on series III and IV (FA used as a partial replacement of mineral filler, while river aggregate was partially replaced with CB and RCA, respectively) were followed with the series VI and VII
(CBP used as a partial replacement of mineral filler, while river aggregate was partially replaced with CB and RCA, respectively). As was expected, the lowest values were measured for the series VIII and IX, which were designed with CBP as a partial replacement of mineral filler and CB (VIII) or RCA (IX).

Figures 4 and 5 present the change of compressive strength through time, where the previously mentioned grouping of the results is visible. Pozzolanic nature of FA [11] is confirmed by the slower development of the compressive strength, but high values at the later ages noted for the series II, III and IV. Results for all of the series followed the logarithmic function of type: 

\[ f_c = a \ln x + b \]

with good accuracy.

Excluding the series II and V, all the series had lower values of flexural and compressive strength, compared to the referent mixture. The highest differences are measured in the early stages (at the age of 3 days). After 90 days, drop of values was in reasonable limits of 30% for all of the series, except for the series VIII and IX.

Comparing the results of destructive and nondestructive testing methods, good correlation was found between the compressive strength and the dynamic modulus of elasticity. Conclusion was driven that this connection strongly depends on the mortar composition. Exponential function in the form:

\[ f_c = A_1 \times e^{A_2 \times E_d} \]

was adopted as a correlation function between these two parameters for all of the series. Through the analysis of these correlations it was found that \( A_1 \) depends on w/c ratio and on the type of mineral filler, while \( A_2 \) depends on the type of the aggregate and also on the properties of the mineral filler used, as shown in Figures 6 and 7.

Group 1 in figure 6 represents paired values of w/c ratio and coefficient \( A_1 \) for the series V, VI, VII, VIII and IX in which CBP was used as a partial mineral filler replacement. Group 2 represent values for the series II, III and IV, where FA was used as partial mineral filler replacement. Logarithmic functions were adopted as the best fitting function for both of the groups.

True density presented in Figure 7, describing the joint effect of aggregate and the mineral filler used, was calculated as the average true density (taking into account mass and the type of aggregate, and filler used in the mixtures, for the known true densities):

\[ \gamma = \frac{m_{f1} \times \gamma_{s,f1} + m_{f2} \times \gamma_{s,f2} + m_{a1} \times \gamma_{s,a1} + m_{a2} \times \gamma_{s,a2}}{m_{f1} + m_{f2} + m_{a1} + m_{a2}} \]

The values \( m_{f1} \) and \( m_{f2} \) represent the mass of the filler components, and \( m_{a1} \) and \( m_{a2} \), mass of the aggregate components in the series mix design; \( \gamma_{s,f1} \) and \( \gamma_{s,f2} \) represent the true densities of mineral fillers used, while \( \gamma_{s,a1} \) and \( \gamma_{s,a2} \) represent the true densities of the used aggregate.

These conclusions lead to the following functions that could be used in the future mix design of similar mortars:

\[ f = (-0.804 \times \ln(\frac{W}{c}) + 1.0906) \times e^{(-0.4635x+1.317)\times E_d} \]

when FA is used as a partial replacement of mineral filler, and
\[ f = (-1.022 \times \ln\left(\frac{w}{c}\right) + 1.6072) \times e^{(-0.4635x+1.317)\times E_b}, \]
when CBP is used as a partial replacement of mineral filler.

**Figure 6. Dependency of the Coefficient A_1 on the Water to Cement Ratio and Type of Mineral Filler**

![Graph showing dependency of A1 on water to cement ratio](image)

**Figure 7. Dependency of the Coefficient A_2 on the Combined True Density of the Aggregate and Mineral Filler Used**

![Graph showing dependency of A2 on density](image)

*Pull-off Strength and Durability Testing*

Pull-off strength testing results are presented in Table 5 as mean values gathered on 3 samples, for each of the series. Results from Table 5 showed the similar behavior already noticed during flexural and compressive testing. Highest value (3.23 MPa) was reached for the referent mixture (series I), while the lowest value (1.18 MPa) was reached for the series VIII.
Nevertheless, all the results satisfy a standard non-traffic condition, where the pull-off strength should be higher than 1 MPa, according to SRPS EN 1504 [12], while most of the series (except series VIII and IX) had pull-off strength higher than required 2.1 MPa from the same standard.

Table 5. Pull-off Strength Testing Results

<table>
<thead>
<tr>
<th>Series</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull-off strength (MPa) after 28 days</td>
<td>3.23</td>
<td>2.90</td>
<td>2.25</td>
<td>2.44</td>
<td>2.38</td>
<td>2.26</td>
<td>2.78</td>
<td>1.18</td>
<td>2.00</td>
</tr>
<tr>
<td>Pull-off strength (MPa) after freeze-thaw cycles</td>
<td>&lt;0.1</td>
<td>0.99</td>
<td>&lt;0.1</td>
<td>0.40</td>
<td>0.49</td>
<td>2.05</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

The other side of the plates for the pull-off test was tested for durability through freeze-thaw cycles in the presence of the defrosting salts. After the first 5 cycles only 10 out of 27 samples had lower scaling of the material from the surface than recognized by the standard - 1 mg/mm². Average results on three samples for each of the series are presented in Figure 8.

Figure 8. The Average Loss of Mass (in mg/mm²) after 5 Freeze-thaw Cycles in the Presence of the Defrosting Salts for All of the Series

<table>
<thead>
<tr>
<th>Series</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
</tr>
</thead>
<tbody>
<tr>
<td>STDEV</td>
<td>0.0</td>
<td>1.1</td>
<td>0.1</td>
<td>1.7</td>
<td>0.1</td>
<td>0.3</td>
<td>1.2</td>
<td>0.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>
The samples that showed acceptable freeze-thaw resistance after 5
cycles were then tested through another 20 cycles, while the loss of mass
was measured after each 5 cycles. Measured values after 25 cycles are
presented in Figure 9.

All of the tested samples encountered severe scaling after 25 cycles, and
have dropped out of the standardized classification. Nevertheless, series II,
IV, V and VI showed greater resistance than the referent mixture. The level
of degradation of the chosen samples is presented in Figure 10.

Finally, these samples were exposed to pull-off test again, after the
cyclic treatment. The measured values were much lower than those
previously obtained on the intact samples, as shown in Table 5.

**Figure 9.** Loss of Mass (in mg/mm$^2$) after 25 Freeze-thaw Cycles in the
Presence of the Defrosting Salts on the Chosen Samples

![Figure 9](image)

**Figure 10.** Samples of Series I (up) and V (down) Before and After the
Exposure to Freeze-thaw Cycles

![Figure 10](image)
Conclusions

The focus of the work presented in this paper was on possibilities of the application of FA and CBP as a partial mineral filler replacement, as well as CB and RCA as a partial or complete aggregate replacement in self-compacting mortars.

Nine series of SCM were made and tested in three stages, with the measurement of the properties of fresh mortars, mechanical properties of hardened mortars, and finally pull-off strength and frost-thaw resistance in the presence of defrosting salts (durability assessment).

The measured properties in fresh state show that it is possible to design SCM using mentioned component materials. It is also evident that, if the amount of the superplasticizer is kept within the normal boundaries, very high water to cement ratios will be reached. Special attention must be paid to the possible signs of the segregation.

The mechanical strengths (both flexural and compressive) of the series made with natural aggregate (I, II and V) were the highest, and were very similar, apart from high 90 days strengths of series II that contained FA. They completely approve the use of FA and CBP as partial mineral filler replacements. Although a drop in measured values was noticed for the series III, IV, VI, VII compared to the referent mixture, it was kept within the reasonable boundaries of 20 and 30%. The mechanical properties of the series VIII and IX showed 30%-50% drop of values in the case of the flexural strength and 50%-70% in the case of the compressive strength measurements, compared to the referent mixture. Mixtures containing FA (II, III and IV) gave almost 25% higher 90 days strengths then the corresponding mixtures with CBP used as mineral fillers. These results confirm pozzolanic nature of FA.

After the analysis of the connection between the compressive strength and dynamic modulus of elasticity, the conclusion has been drawn that this correlation depends on the components and the ratios between the components used in the mortar design. These observations were used to calculate approximate dependencies between the compressive strengths of the series and w/c ratio, true bulk density of the aggregate and filler, type of the mineral filler used and the measured dynamic modulus of elasticity. These functions could be used in future series design, as a helpful tool in deciding the optimal content of the chosen components in the mortar design.

The pull-off strength of the most of the series (except for the series VIII and IX) satisfied the condition for the repair concrete materials, which is important for the application of these mortars. Although, due to the high w/c ratios, all of the mixtures showed the low frost-thaw resistance, it is interesting that series II, VI and V showed less scaling than the referent mixture (when the relative change of the properties after the treatment is observed).

Further investigation should be directed to the optimization of the content of these components, and possibilities of their application in self-compacting concrete.
References


