Behavior of mortars produced with construction wastes exposed to different treatments

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Performance of cement mortars prepared by replacing 30% and 60% of crushed calcareous fine aggregate (CNA) with waste fine aggregates namely, crushed brick aggregate (CBA), crushed marble aggregate (CMA) and crushed ceramic aggregate (CCA) is investigated. For this purpose, absorption, unit weight, compressive strength, flexural strength, modulus of elasticity, capillarity, drying shrinkage, resistance to high temperature up to 400°C and resistance to freeze-thaw cycles are determined. In addition, X-ray fluorescence (XRF) and X-ray diffraction (XRD) are performed on cement and aggregates and scanning electron microscopy (SEM) analysis is conducted on mortars in order to examine their mineralogy and morphology. It is found from the experimental results that CBA mortars exhibited the lowest strength values and the worst durability properties. However, CBA and CCA mortars are more effective in relative strength gain at 56 days. Residual strength values of CCA and CMA mortars after freeze-thaw and high temperature resistance tests are higher than those of other mortars.

Keywords: Mortar, Capillarity, Drying shrinkage, Morphology

Aggregates, usually provided from natural resources, occupy up to 80% of concrete by volume. Consumption of natural resources and energy has increased proportionately to civilization development and world population growth, and this is one of the biggest environmental concerns today1. In addition to the increasing emission of greenhouse effect gases, unbalanced consumption of natural resources will eventually lead to their exhaustion. In other words, the available natural aggregate used in concrete and mortar production will soon remain insufficient to supply all the demands of the construction industry. More than 25 billion tons of concrete are produced each year all around the world. Therefore, construction industry is seeking for other alternatives such as the use of recycled aggregates in order to meet the needs in concrete manufacturing.

Using construction based waste materials in cementitious mixtures have been seen revived interest in recent years. Many researchers2-4 analyzed some properties mainly strength and durability of mortars containing different types of ground brick (calcined clays) subjected to various treatments. The freeze-thaw resistance of the mortar was improved by the brick replacement5. However, the use of crushed brick as aggregate appeared not to reduce potential alkali-silica reaction. Mortars and plasters composed of a mixture of brick powder and lime have been used since ancient times due to their hydraulic properties6. The mortars and plasters were hydraulic owing to the presence of crushed brick powders that have good pozzolanicity. The properties of mortars and/or concretes containing ceramic waste aggregates were examined in some investigations7-10. The compressive strength of mortar made of the ceramic waste aggregate increased and the resistance to chloride ion penetration was significantly higher in comparison with mortar made of the river sand11. Ceramic waste did not interfere in either the hydration process or in the morphology of the hydrated products12. The microstructure present in the interfacial transition zone (ITZ) of the recycled aggregate-paste was more compact and stable than that of the natural aggregate-paste. Mortars and concretes containing marble waste were also studied by evaluating their fresh and hardened state properties13-16. Mechanical properties of concrete specimens produced using the marble wastes were found to conform with the concrete production standards and the substitution of natural aggregates by waste marble aggregates up to 75% of any formulation is beneficial for the concrete resistance17.

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The replacement of wastes can enhance or deteriorate the performance of mortars and concrete both in fresh and hardened states, improving or damaging their mechanical properties and durability. A very limited number of studies have been conducted to make a comparison among common wastes namely brick, marble and ceramic aggregates. It is difficult to make comparison between the results collected from different investigations which were studied these wastes individually. In addition, since such wastes are not biodegradable, deposit in landfills do not provide an environment-friendly solution. The main aim of this work is to compare the cementitious materials manufactured with common construction wastes and evaluate the effects of wastes on performance of specimens. Knowing these effects will aid in assessing the physical-mechanical performance and the durability of cementitious materials and also their compatibility with other building materials.

Materials and Methodology

Materials

Cement used in the mixtures was CEM II/A-M (P-L) 42.5N complying with TS EN 197-1\textsuperscript{18} with a specific gravity of 3.05. Initial and final setting times of cement were 194 and 306 minutes, respectively. All wastes (brick, marble and ceramic) were collected from construction sites and ground until a similar grading as of natural crushed sand were obtained (Fig. 1). Natural crushed fine aggregate utilized in the study was calcareous sand provided from Dirmil, Burdur. Chemical admixture used for providing consistency of mortars constant was a modified lignin sulphonate based water reducing/plasticizer admixture consistent with TS EN 934-2\textsuperscript{19}.

As fundamental physical material characteristics, water absorption, specific gravity, rodded and loose bulk density of crushed aggregates were determined by following the test procedures in the relevant standards (Table 1). Specific gravity and water absorption of fine aggregates were determined according to ASTM C 29\textsuperscript{21}. Aggregates were tested in oven-dry condition utilizing the shoveling and rodding procedure to determine the unit weight (loose and rodded) and void content according to ASTM C 29\textsuperscript{21}. Sieve analysis was carried out in order to determine the particle size distribution of aggregates (Fig. 2).

Chemical composition of cement and waste aggregates found by X-ray fluorescence (XRF) analysis and the intensity of crystal diffraction peaks of waste aggregates measured by X-ray diffraction (XRD) analysis are given in Table 2 and Figs 3-5.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Water absorption (%)</th>
<th>Specific gravity (Dry)</th>
<th>Rodded bulk density (Dry) (kg/m(^3))</th>
<th>Loose bulk density (Dry) (kg/m(^3))</th>
<th>Void content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>2.24</td>
<td>2.71</td>
<td>1741</td>
<td>1589</td>
<td>35.63</td>
</tr>
<tr>
<td>Brick</td>
<td>14.08</td>
<td>2.57</td>
<td>1210</td>
<td>1093</td>
<td>57.39</td>
</tr>
<tr>
<td>Marble</td>
<td>2.96</td>
<td>2.63</td>
<td>1571</td>
<td>1399</td>
<td>40.15</td>
</tr>
<tr>
<td>Ceramic</td>
<td>2.57</td>
<td>2.49</td>
<td>1305</td>
<td>1196</td>
<td>51.87</td>
</tr>
</tbody>
</table>

**Table 1 – Physical characteristics of waste materials**

<table>
<thead>
<tr>
<th>Materials</th>
<th>LOI(^a)</th>
<th>Na(_2)O</th>
<th>MgO</th>
<th>Al(_2)O(_3)</th>
<th>SiO(_2)</th>
<th>ZrO(_2)</th>
<th>SO(_3)</th>
<th>K(_2)O</th>
<th>CaO</th>
<th>TiO(_2)</th>
<th>Fe(_2)O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>5.81</td>
<td>1.25</td>
<td>2.33</td>
<td>6.38</td>
<td>21.77</td>
<td>-</td>
<td>1.32</td>
<td>1.06</td>
<td>56.66</td>
<td>0.31</td>
<td>2.68</td>
</tr>
<tr>
<td>Brick</td>
<td>3.57</td>
<td>2.00</td>
<td>6.51</td>
<td>14.92</td>
<td>54.24</td>
<td>-</td>
<td>0.63</td>
<td>2.27</td>
<td>8.79</td>
<td>0.74</td>
<td>5.82</td>
</tr>
<tr>
<td>Marble</td>
<td>42.73</td>
<td>0.58</td>
<td>1.10</td>
<td>0.35</td>
<td>1.62</td>
<td>-</td>
<td>0.12</td>
<td>0.06</td>
<td>52.94</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>Ceramic</td>
<td>3.09</td>
<td>2.73</td>
<td>5.07</td>
<td>15.14</td>
<td>63.99</td>
<td>0.30</td>
<td>0.08</td>
<td>1.68</td>
<td>4.88</td>
<td>0.57</td>
<td>2.33</td>
</tr>
</tbody>
</table>

\(^a\) Loss on ignition
Preparation of Mortars for Tests

Seven different types of mortar mixes were prepared and their mix proportions and notations are given in Table 3. Natural crushed sand was replaced with waste aggregates in a ratio of 30% and 60%. All substitutions were made in volume. The flow diameter values of fresh mortar mixtures were remained constant as 210±14 mm by adjusting the percentage of plasticizer used in order to eliminate consistency difference. To achieve a constant slump value, the mortar mixes containing natural and marble aggregates required a lower superplasticizer content and the mortar mix, especially CBA60 mortar, containing slightly flaky and rough surface textured brick aggregates (Fig. 13) required much higher superplasticizer content. Moreover, these waste flaky aggregates are attributed to the fact that these aggregates had sharper and angular edges compared to natural aggregate. All sample preparations were processed in a similar manner, according to TS EN 196-1. The mortars were cast into 40×40×160 mm and 25×25×285 mm prismatic, 100 mm cubic and ø50×100 mm cylindrical moulds for 24 h. The hardened mortar specimens were then demoulded and maintained under lime-saturated water at 20 ± 2°C until the age of testing, except for 25×25×285 mm prismatic specimens. These specimens were kept in plastic bags for 7 days and then put in a controlled room (23°C and 60% RH) after initial length readings were taken for determination of drying shrinkage.

40×40×160 mm prismatic specimens were subjected to temperature of up to 400°C at an incremental rate of 10°C/min from room temperature, using an electrically-heated furnace and exposed to a treatment involving freeze in air and thaw in water treatment in a cabinet from -20°C to +20°C for 10 cycles completed in 2 days.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cement (g)</th>
<th>Natural sand (g)</th>
<th>Brick sand (g)</th>
<th>Ceramic sand (g)</th>
<th>Marble sand (g)</th>
<th>Water (g)</th>
<th>Chemical Admixture</th>
<th>Flow diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNA</td>
<td>450</td>
<td>1350</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>225</td>
<td>4.37</td>
<td>214</td>
</tr>
<tr>
<td>CBA30</td>
<td>450</td>
<td>945</td>
<td>384</td>
<td>-</td>
<td>-</td>
<td>225</td>
<td>6.32</td>
<td>214</td>
</tr>
<tr>
<td>CMA30</td>
<td>450</td>
<td>945</td>
<td>-</td>
<td>-</td>
<td>393</td>
<td>225</td>
<td>6.44</td>
<td>224</td>
</tr>
<tr>
<td>CCA30</td>
<td>450</td>
<td>945</td>
<td>-</td>
<td>372</td>
<td>-</td>
<td>225</td>
<td>5.17</td>
<td>213</td>
</tr>
<tr>
<td>CBA60</td>
<td>450</td>
<td>540</td>
<td>768</td>
<td>-</td>
<td>786</td>
<td>225</td>
<td>14.0</td>
<td>213</td>
</tr>
<tr>
<td>CMA60</td>
<td>450</td>
<td>540</td>
<td>-</td>
<td>-</td>
<td>786</td>
<td>225</td>
<td>6.00</td>
<td>217</td>
</tr>
<tr>
<td>CCA60</td>
<td>450</td>
<td>540</td>
<td>-</td>
<td>744</td>
<td>-</td>
<td>225</td>
<td>8.30</td>
<td>200</td>
</tr>
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</table>
Experimental procedures

The consistency test involves placing the mould in the center of the flow table and filling it in two layers each layer being tamped 20 times with the tamper according to ASTM C 270\textsuperscript{23}. The table was then jolted 25 times, and the diameter of the spread mortar was measured in two directions at right angles to each other using callipers.

The bulk density, water absorption and porosity values were obtained by testing 100 mm cube specimens according to ASTM C 642\textsuperscript{24} by using the following equations:

\[
A = \frac{W_1}{W_2-W_3} \quad \ldots (1)
\]

\[
B = \frac{W_2}{W_1-W_3} \quad \ldots (2)
\]

\[
C = \left(\frac{W_2-W_1}{W_2-W_3}\right) \times 100 \quad \ldots (3)
\]

\[
D = \left(\frac{W_2-W_1}{W_1}\right) \times 100 \quad \ldots (4)
\]

where \(A\) is the dry bulk density, \(B\) is the apparent bulk density, \(C\) is the apparent porosity (%); \(D\) is the water absorption by weight (%), \(W_1\) is the mass of oven-dried sample in air (g), \(W_2\) is the mass of surface-dry sample in air (g) and \(W_3\) is the mass of surface-dry sample in water (g).

The flexural and compressive strength of hardened mortar specimens were determined in accordance with TS EN 1015-11\textsuperscript{25}. The flexural strength of a hardened mortar was evaluated by three point loading of a 40×40×160 mm prism specimen, subsequent to the failure and breakage of this specimen the compressive strength was determined on each half of the prism specimen. Also, \(\phi\)50×100 mm cylindrical specimens were tested to obtain compressive strength and modulus of elasticity.

Capillary water absorption test was carried out with the 100 mm cube specimens by measuring water contents absorbed at 1, 4, 9, 16, 25, 36, 49, 64 and 1440 min. The capillary absorption coefficient was obtained using the following equation:

\[
K = \frac{Q}{(A^*t^{1/2})} \quad \ldots (5)
\]

where \(K\) is the coefficient of capillarity (cm/s\textsuperscript{1/2}), \(Q\) is the amount of water absorbed (cm\textsuperscript{3}), \(A\) is the area of the surface exposed to the water (cm\textsuperscript{2}) and \(t\) is the time (s).

\(25\times25\times285\) mm prismatic specimens were used for determining the drying shrinkage values for 90 days. Compressometer with a 0.001 mm sensitivity was used in order to take the length change readings. Three specimens of each formulation were prepared for each test.

SEM analysis was performed on representative specimens to examine the paste matrix, aggregates and interfacial transition zone.

Results and Discussion

The bulk density, water absorption and porosity test results of mortars are shown in Table 4. In contrast to CNA mortars, CBA mortars had the highest porosity and thus water absorption. However, the lowest apparent bulk density and dry bulk density were obtained by CCA and CBA mortars, respectively. In parallel with these results, bulk void content of CBA was the highest value (57.39%) among the other aggregates as shown in Table 1. This bulk void content required a more cement paste amount. However, the cement paste amount was constant for each mortar mix. Therefore, CBA mortars had the highest apparent porosity.

<table>
<thead>
<tr>
<th>Age</th>
<th>Specimen</th>
<th>Dry bulk density (kg/dm\textsuperscript{3})</th>
<th>Water absorp. (% wt)</th>
<th>Apparent bulk density (kg/dm\textsuperscript{3})</th>
<th>Apparent porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 Days</td>
<td>CNA</td>
<td>2.09</td>
<td>5.72</td>
<td>2.37</td>
<td>11.93</td>
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<tr>
<td></td>
<td>CBA30</td>
<td>1.96</td>
<td>7.98</td>
<td>2.32</td>
<td>15.61</td>
</tr>
<tr>
<td></td>
<td>CMA30</td>
<td>2.03</td>
<td>6.28</td>
<td>2.32</td>
<td>12.73</td>
</tr>
<tr>
<td></td>
<td>CCA30</td>
<td>2.02</td>
<td>5.96</td>
<td>2.30</td>
<td>12.07</td>
</tr>
<tr>
<td></td>
<td>CBA60</td>
<td>1.88</td>
<td>10.50</td>
<td>2.34</td>
<td>19.76</td>
</tr>
<tr>
<td></td>
<td>CMA60</td>
<td>2.05</td>
<td>6.08</td>
<td>2.34</td>
<td>12.47</td>
</tr>
<tr>
<td></td>
<td>CCA60</td>
<td>2.01</td>
<td>5.26</td>
<td>2.24</td>
<td>10.56</td>
</tr>
<tr>
<td>56 Days</td>
<td>CNA</td>
<td>2.08</td>
<td>5.48</td>
<td>2.35</td>
<td>11.42</td>
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<tr>
<td></td>
<td>CBA30</td>
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<td>7.96</td>
<td>2.29</td>
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</tr>
<tr>
<td></td>
<td>CMA30</td>
<td>2.10</td>
<td>6.04</td>
<td>2.40</td>
<td>12.66</td>
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<tr>
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<td>5.61</td>
<td>2.30</td>
<td>11.42</td>
</tr>
<tr>
<td></td>
<td>CBA60</td>
<td>1.94</td>
<td>8.78</td>
<td>2.34</td>
<td>17.03</td>
</tr>
<tr>
<td></td>
<td>CMA60</td>
<td>2.07</td>
<td>5.71</td>
<td>2.34</td>
<td>11.79</td>
</tr>
<tr>
<td></td>
<td>CCA60</td>
<td>2.01</td>
<td>4.09</td>
<td>2.19</td>
<td>8.24</td>
</tr>
</tbody>
</table>
values, 15.71% and 19.76% for 28-day CBA30 and CBA60 and 15.41% and 17.03% of 56-day CBA30 and CBA60, respectively. Besides, the particle densities of the wastes were lower than that of natural aggregate, so justifying the same trend for mortar’s density. The different shape and superficial texture of the aggregates (waste and sand) determine different arrangements of the particles and influence the rheological characteristics, implying a change on the mixing water needed for adequate workability as shown in Table 3. The use of recycled brick aggregates gave consistently lower workability than the corresponding mix with natural aggregates. This result was attributed to the rough surface of the recycled aggregates. Both different arrangements and different water contents have as a consequence, variations in porosity and pores size, especially those formed in the interface aggregate-matrix. This was reflected in the hardened mortar, since dry bulk density also decreased as the waste incorporation increased. The air entrapped during mixing of mortars with waste crushed aggregate also contributed to the decrease of the bulk density. These results showed similarity with the aggregate property test results given in Table 1. The corresponding values dropped while the replacement ratios increased due to the high porosity of brick and ceramic aggregates shown in Table 1.

In ceramic industry, tiles sintered at high temperatures exhibited lower water absorption and discontinuous pore structure. Therefore, less amount of water absorption and apparent porosity of CCA mortars can be attributed to the higher exposure temperatures in manufacturing process compared to brick and thus more closed pore ratio. Also, Senthamarai and Manoharan reported that ceramic waste had lower water absorption than natural aggregates. Furthermore, they obtained lower bulk density for recycled ceramic aggregates (2.5 kg/dm³) than for natural aggregates (2.7 kg/dm³).

Figures 6 and 7 give the mechanical properties of 28 and 56-day mortars. Specimens without treatment showed similar flexural strength varying from 6.8 to 8.6 MPa whereas the differences in compressive strength results were large varying from 37.4 to 43.8 MPa for 28 days. A decrease in flexural strength of 10.5%, 5.8%, 1.2%, 20.9%, 9.3% and 8.1% for 28-day CBA30, CMA30, CCA30, CBA60, CMA60 and CCA60 mixes, respectively, was observed. The reduction in 28-day compressive strength of mortar mixes prepared by replacing 30% and 60% of natural sand by brick, marble and ceramic waste aggregates were respectively 11.0%, 3.9%, 1.8%, 14.6%, 8.2% and 2.3% with respect to the control mix. The strength loss ratios due to the various treatments were higher for flexural
strength than those for compressive strength. In case of freeze-thaw exposure, flexural strength varied from 5.06 to 14.7 MPa and compressive strength varied from 2.6 to 12.3 MPa while in case of high temperature exposure 28-days flexural strength varied from 16.2 to 32.6 MPa and compressive strength varied from 9.1 to 18.8 MPa. There was a relatively less reduction in strength loss for 56-day specimens. For all situations, CBA mortars exhibited the lowest mechanical and elastic properties and these properties worsened with the substitution level owing to the high water absorption and open porosity percentages of brick aggregates. Zong et al.\textsuperscript{31} also found that both the compressive strength and flexural strength of brick aggregate were lower than those of natural aggregate concrete and a greater loss in strength was observed when more brick aggregate was incorporated. Although other mortars prepared with CNA, CCA and CMA showed close values, the best performance was observed by CCA mortars when considering reduction in strength values at overall situations. The resistance to high temperature was high for the CCA and CBA mortars when considering the relative residual compressive strength values. Besides, analyzing the relatively residual flexural strength values presented the superiority of CBA mortars. This fact can be attributed to the higher temperatures experienced by the bricks and ceramics previously in the manufacturing process, therefore, these materials could maintain their stability when subjected to temperature below manufacturing temperature. In addition, generally one face of ceramic aggregates was glazed, thus in the case of high temperature, the proper adherence could not be achieved due to the disruption of glaze with the melting effect of temperature resulting in lower flexural strength compared to CBA mortars. Exposing the freeze-thaw cycles to mortars weakened CBA mortars mostly rather than the other mortars. Despite similar behavior could be expected for CCA mortars, CCA mortars deteriorated less than CBA mortars. The reason of this result could be the structure of voids in the aggregates. Alves et al.\textsuperscript{1} stated that brick aggregates presents significantly higher water absorption than natural aggregates and recycled ceramic aggregates. The last two types of aggregates have small and similar values of water absorption. Furthermore, in contrast to CCA, CBA had mostly open and water accessible porosity seen also in SEM images. Water expands approximately 9% by volume when it freezes. This expansion damages the specimen in saturated state.
The strength gain was more pronounced in the case of CBA and CCA mortars as relevant to the pozzolanic behavior of these mentioned aggregates containing amorphous silica and alumina phases. Additionally, the temperature used in brick production was relatively below crystallization temperature compared to ceramic production. Therefore, strength gain increase was more remarkable in CBA mortars. As shown in Table 3, the content of brick aggregate in the CBA30 and CBA60 mixes are 384 and 768 g, respectively. 7% of brick aggregate particles were under 0.075 mm (Fig. 2). Therefore, particle fractions under 0.075 mm were 26.9 and 57.6 g. These amounts are adequate for pozzolanic reaction when considering the cement amount as 450 g for each mix. XRD contributed to identification of crystalline mineral components in the aggregates in Figs 3-5. Ceramic and brick aggregates presented a crystalline formation and amorphous phase. While quartz, albite and heulandite were detected as the main crystalline phases in the XRD of ceramic aggregates, brick aggregates presented peaks of quartz, anorthoclase and sodiumalum. However, in the case of marble aggregates, calcite magnesium was predominant mineral present as usual in dolomitic marbles followed by calcite. Dolomite occurs in widely extended rock masses as dolomitic limestone. It is often intimately mix with calcite. It is formed from ordinary limestone by the replacement of calcium by magnesium. The most remarkable broad hump was observed due to the glass content in diffractogram of brick aggregates.

As compared to test results of specimens subjected to high temperature, the strength loss ratios of specimens exposed to freeze-thaw cycles were lower. The reason of this result could be the less number of cycles applied on specimens. Strength loss ratios in the case of exposure to both high temperature and freeze-thaw cycles were higher in flexure than in compression. While defects such as cracks and voids in the specimens closed under compression, the resistance to high temperature and freeze-thaw cycles were reduced under bending due to the extreme deterioration of interfacial transition zone.

While modulus of elasticity values of mortars varied from 23890 to 28450 MPa and 29360 MPa in 28 days and 56 days, respectively, as shown in Fig. 8, the lowest values was obtained by CBA mortars and the highest values belonged to CCA and CNA mortars. The elastic properties of concrete are known to be influenced by elastic properties of the constituent materials and nature of the interfacial zone between aggregates and paste. Not only aggregate stiffness, but also aggregate type, affects the elastic modulus. An increase in compressive strength was matched by an increase in the modulus of elasticity. Similar findings were also obtained by some other researchers.

Fig. 9 – Coefficient of capilarity of mortars in 28 and 56 days

When considering the 28 and 56-day capillary water absorption coefficient values, CMA30 mortars had the least capillary permeability while CBA60 mortars exhibited the highest capillary water absorption (Fig. 9). In terms of water absorption by capillary action, results from the studies consulted reveal greater water absorption and porosity, which are both typical of recycled aggregates. Increased water penetration was observed when a higher replacement rate of recycled brick aggregate was used. This is attributed to the more porous characteristic of recycled aggregates made from clay brick waste. Open and connected void structure of brick aggregates behaved as the shortest and the most convenient way to transmit the water rather than as a barrier. Other aggregates exhibited a blocking effect by preventing the water passage forcing water to follow a path around aggregate. This enforcement caused more time need for the penetration of the same amount of water. On the other hand, Bogas et al. reported that contrary to compressive strength, capillary absorption was affected far more by the volume of paste than by the aggregate’s properties. In this study, bulk void contents of aggregates namely, natural sand, brick, marble and ceramic were 35.63%, 57.39%, 40.15% and 51.87%, respectively. Higher bulk void content means more cement paste amount. However, the cement paste amount was constant for each mortar mix. Thus, one of the main parameters affecting the capillarity was the porosity of mortars beside aggregate type and paste volume.

Analyzing the drying shrinkage behavior of mortars, at the end of 180 days, mortars with brick aggregates presented the highest shrinkage strains and CNA, CCA30 and CCA60 mortars exhibited the lowest values (Fig. 10). CMA30 and CMA60 mortars had relatively low shrinkage values. Especially drying shrinkage strain values of CCA60 mortars considerably reduced after 90 days. Considering the mortars and concrete in the building system, they may crack due to the restrained shrinkage stresses resulting from reinforcement in the column-beam areas where the values of these stresses exceed the value of tensile strength. Therefore, drying shrinkage is the volumetric strain which needs to be in negligible level. All mortars except CBA mortars experienced drying shrinkage below 1000 microstrain. Even after 90 days, they were quite close to each other. High volumetric contraction values in CBA mortars due to the desertion of high amount of water in the body. Drying shrinkage could be controlled by appropriate aggregate characteristics and reducing the total amount of water content.

As seen in SEM images illustrated in Figs 11-14, discontinuous spherical pore structure was seen especially in ceramic aggregates. Also, it is realized
Fig. 10 – Drying shrinkage of mortars

Fig. 11 – SEM images of mortars with marble aggregate

Fig. 12 – SEM images of mortars with calcareous aggregate
that interfacial properties in other words adherences between cement pastes and aggregates were in good condition for all types of mortars. The specimen with limestone aggregate showed the smallest shrinkage strain among all specimens due to its relatively great static modulus of elasticity. Enhancing the bonding stress of the interface zone between aggregate and the paste system results in increasing the modulus of elasticity and thus decreasing the shrinkage in turn. Mechanical bonding was also responsible for high performance of CNA mortars due to the rough texture of aggregates as shown in Fig. 12. As shown in Fig. 13, similar bonding mechanism could also be pronounced for the CBA mortar. However, the surface textures of marble and ceramic aggregates were relatively smooth.

Conclusions

Following conclusions can be drawn from the experimental results:

The lowest apparent bulk density and dry bulk density were obtained by mortars with CCA and CBA, respectively. Less amount of water absorption and apparent porosity of CCA mortars can be attributed to the higher exposure temperatures in manufacturing process compared to brick and thus more closed pore ratio.

Although the replacement of natural sand by waste aggregates reduced the flexural and compressive strength, mortar specimens prepared by replacing certain proportions of crushed calcareous fine aggregate with marble and ceramic aggregates with adjusted gradations exhibited similar behavior as those prepared by only crushed calcareous fine aggregate. However, contrast to
these deterioration of common properties, the strength gain values of mortars with crushed brick and ceramic aggregates was higher than those of mortars with marble and normal natural aggregates. Also, residual strength values after freeze-thaw and high temperature resistance tests of ceramic aggregate mortars were higher than those of other mortars.

Strength loss ratios after high temperature exposure tests of CCA and CBA mortars were lower than those of CMA and CNA mortars. However, particularly CBA had highest strength loss in the case of freeze-thaw cycle exposure due to the open void structure allowing high penetrability of water. Strength development was higher for CCA and CBA mortars at later age probably owing to the pozzolanic reactions resulting from high glassy phase content produced by sintering during manufacturing process.

CMA30 mortars had the least capillary permeability while CBA60 mortars exhibited the highest capillary water absorption. The replacement of 30% and 60% brick aggregate significantly increased the drying shrinkage of mortar: up to 1.5 times more than the shrinkage exhibited by the natural sand used as control. Especially drying shrinkage strain values of CCA60 mortar considerably reduced after 90 days.

Construction industry wastes can be successfully used as aggregates. Their introduction in mortar production provides to conserve natural and non-renewable resources, and contributes to the reduction of the potential environmental impacts caused by landfill deposit.

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References
18 TS EN 197-1, Cement - Part 1: Composition, specifications and conformity criteria for common cements, Turkish Standard Institute, Ankara, Turkey, 2000.
22 TS EN 196-1, Methods of testing cement. Determination of strength, Turkish Standard Institute, Ankara, Turkey, 2009.