Improving the mechanical properties of lightweight Porcelanite aggregate concrete using different waste material

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Abstract

Improving the mechanical properties of lightweight concrete using waste material is the goal of this work to get both structural and environmental advantage besides cost saving. Porcelanite aggregate was used as lightweight aggregate. First plastic bottles were cut into slices and used as fibers with these percentages: 0.0%, 0.5%, 0.75%, 1.0%, 1.25% and 1.5% by volume. The results of tests under compression and tensile stress showed that mix 1% plastic fiber (PF) gave the best results when compared to reference mix without PF. Eggshell (rich with CaO) and glass wastes (rich of silica) were crashed and powdered to desired size and used as partial replacement of cement with these percentage: 0%, 5%, 10%, 15% and 20%. Compressive strength, flexural strength, density, absorption and modulus of elasticity were tested. Comparison was made with reference mix (without waste powder) to figure the efficiency of using these waste in lightweight Porcelanite concrete. The results of tests showed that mixes with 1% PF and 5% eggshell powder (ESP) gave results so close to reference mix. Using more than 5% ESP made no improvement in lightweight concrete, while the mix with 1% PF with any glass powder (GP) percentages used in this research gave good improvement in the tested properties especially at 20% GP.

Keywords: Porcelanite; Lightweight concrete; Eggshell powder; Glass powder; Plastic fiber

1. Introduction

The utilization of lightweight aggregate in concrete is mainly to reduce the self-weight of concrete, which leads to reduce the dimension of foundation and that results in cost saving. According to ACI committee 213 Structural Lightweight Concrete (SLWC) is defined as a concrete with an air-dried density at 28 days in the range of 1120 and 1920 kg/m³ and a compressive strength above 17.2 MPa. In 1986 investigations were undertaken by the State Company of Survey and Mining which led to discovery of Porcelanite rocks in Traifawi in the Iraqi Western Desert, near Rutba (Bassam et al., 1986). Many studies were made to discover its mineral and chemical properties, as well as estimating reserve of these rocks. Depending on these studies, the State Company of Survey and Mining recommended using Porcelanite as a lightweight coarse aggregate in concrete (Kdair and Aboud, 1993).

AL-Rawi investigated the properties of Porcelanite concrete with cement content between 272 and 687 kg/m³, water cement ratios from 0.65 to 1.6 and a strength ceiling above 17.2 MPa. In 1986 investigations were undertaken by the State Company of Survey and Mining which led to discovery of Porcelanite rocks in Traifawi in the Iraqi Western Desert, near Rutba (Bassam et al., 1986). Many studies were made to discover its mineral and chemical properties, as well as estimating reserve of these rocks. Depending on these studies, the State Company of Survey and Mining recommended using Porcelanite as a lightweight coarse aggregate in concrete (Kdair and Aboud, 1993).

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with density between 1400 and 1960 kg/m\(^3\) and 28 days compressive strength between 13.0 and 22.4 MPa (AL-Dhaher, 2001). Al-Duleimy studied the effect of addition of superplasticizer and SBR on some properties of Porcelainite lightweight aggregate concrete. A density and compressive strength ranging between 1965–1818 kg/m\(^3\) and 17.08–34.8 MPa at 28 days, respectively were observed using a cement content of 550 kg/m\(^3\) (Al-Duleimy, 2005).

Other researchers used metakaoline to produce high-strength lightweight Porcelainite concrete (Fawzi et al., 2013).

To deal with the brittle nature of light weight concrete, adding fibers to the concrete mix has been proposed by many researchers (Ritchie and Kayali, 1975; Perez-Pena and Mobasher, 1994; Chen and Liu, 2005; Libre et al., 2011). According to Balendran et al. (2002), steel fibers had improved flexural strength and tensile split strength of lightweight concrete clearly when compared with normal concrete without fibers. Also Hama used steel fiber to improve Porcelainite concrete tensile strength (Hama Sheelan, 2013).

### 2. Research significance

According to European Environment Agency (2014) the waste material can be defined as an unwanted or undesired material that remained from a manufacturing process such as industrial, commercial, mining or agricultural operations or from household activities. There is no sufficient literature available on the effect of waste material on lightweight Porcelainite aggregate concrete. This work tries to fill the gap in existing literatures. An attempt has been made to improve the mechanical properties of lightweight Porcelainite concrete using different waste materials like glass waste, egg shell and plastic bottle waste. Both eggshell and glass wastes were crushed to powder and used as partial replacement of cement while plastic bottles were cut into slices and used as fibers.
3. Experimental program

The experimental program of this work consists of the following types of mixtures:

1. Lightweight Porcelainite aggregate concrete (LWPC) as reference mix.

2. Lightweight Porcelainite aggregate concrete reinforced mixes with plastic fibers at these mixture proportions by volume of the concrete; 0.50%, 0.75%, 1.00%, 1.25% and 1.50%, to find the optimum percentage that gave the best results.

3. Fixed the fiber content with one that gave the best results.

4. Lightweight Porcelainite aggregate concrete reinforced mixes with optimum plastic fiber percentage and glass powder (as partial replacement of cement) at these mixture proportions; 0%, 5%, 10%, 15%, and 20% by weight of cement.

5. Lightweight Porcelainite aggregate concrete reinforced mixes with optimum plastic fibers percentage and egg shell powder (as partial replacement of cement) at these mixture proportions; 0%, 5%, 10%, 15%, and 20% by weight of cement.

4. Materials

- Cement; Ordinary Portland cement (OPC-type I) from Al-Mass Company was used. Chemical analysis and physical properties indicated that the adopted cement satisfying the requirements of Iraqi specification as recorded in Tables 1 and 2.
Aggregate; In this work local sand is used, sieve analysis and physical properties, which are listed in Tables 3 and 4, are satisfying the requirements of Iraqi specification No.45/1984. Crushed Porcelanite was used as coarse aggregate (see Fig. 1) with maximum size 9.5 mm. Porcelanite aggregate properties are satisfying ASTM C330-05 requirements, as shown in Tables 5, 6 and 7, respectively.

Superplasticizer (SP); high range water – reducing agent Sikament – 163 was used as superplasticizer in this work (see Fig. 2); which complies with ASTM C494-05, type F. The technical description of its properties is given in Table 8.

Plastic fiber; Waste plastic fibers with rectangular shape and dimension (30 x 3 mm²), thickness of (0.3) mm and specific gravity of 1.13 were utilized in this work. Shredder machine (see Fig. 3) was used to cut the plastic beverage bottles to uniform shapes and dimensions.

Glass powder; Wastes of broken glass, which are available locally, were collected then crushed to powdered and passed through 100 µm sieve (<100 µm). (see Fig. 4) Chemical analysis of glass powder is presented in Table 9. The utilized glass powder has strength activity index 87.6%, which is conformed to the strength activity index requirements of ASTM C311-05 and ASTM C1240-05 for Portland cement, and a specific gravity of 2.31.

Egg shell powder; Broken egg shells were collected from the local sources. The shells were washed and air dried for several days. After drying the shells were crushed and ground to a powder then passed through 100 µm sieve. (see Fig. 5). Chemical analysis of ESP is presented in Table 9. The specific gravity of using ESP was 2.07.

<table>
<thead>
<tr>
<th>Chemical analysis</th>
<th>Tests results of glass powder (% by weight)</th>
<th>Tests results of egg shell powder (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>10.99</td>
<td>50.09</td>
</tr>
<tr>
<td>SiO₂</td>
<td>72.13</td>
<td>0.13</td>
</tr>
<tr>
<td>MgO</td>
<td>2.60</td>
<td>0.02</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.03</td>
<td>0.61</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.52</td>
<td>0.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.69</td>
<td>0.03</td>
</tr>
<tr>
<td>Na₂O</td>
<td>13.60</td>
<td>0.16</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.16</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 3. Plastic fiber.

Fig. 4. Glass powder.
5. Mixing, compaction, curing and testing of concrete

Mechanical mixer of (0.1) m³ capacity was using for mixing procedure. Table 10 illustrates the mix proportion. Initially, about half of the quantity of Porcelanite was placed in the mixer with half of the quantity of the sand. Then, the full quantity of cementious materials was poured over them. The remaining portion of Porcelanite and the sand was added in sequence, and premixed for about 1 min as dry mix. The SP was added to the mixing water at the beginning. The solution (water + SP) was thoroughly stirred before using. The required quantity of the solution was added. Then whole contents were mixed for another 3 min and left for a 2 min rest. Finally, the concrete was mixed for additional 2 min to complete the production. Then the specimens were casted and wrapped with a plastic sheet to avoid water evaporated and left in the laboratory for 24 h at 20 ± 2 °C temperature. The specimens were demolded next day and tested after 28-days of water curing period.

The following tests were made:

- Compressive Strength; this test was made according to BS 1881-116. An average of three (100 × 100 × 100) mm cubes, for each mix, were tested at 28 days of age.
- Flexural strength; flexural strength is determined according to the ASTM C78-03.
- Static Modulus of Elasticity; this test was made according to ASTM C469-02. The modulus of elasticity was determined from stress–strain relationships at 40% of ultimate load at 28-day age.
- Density: This test was carried out on (100 × 100 × 100) mm cubes according to ASTM C642-97 at 28-day age.
- Absorption: The test was determined according to ASTM C642-06 on (100 × 100 × 100) mm cubes.

6. Results and discussions

6.1. Lightweight concrete with plastic fibers

Six percentages of plastic fibers (0.00%, 0.50%, 0.75%, 1.00%, 1.25%, and 1.5%) were added to the lightweight concrete. Then compressive strength and flexural tensile strength were investigated. Figs. 6 and 7 show the experimental results. Fig. 8 shows compressive strength test. The percentage difference in compressive strength in comparison to reference mix without fibers was: 6.9%, 11.3%, 7.8%, −8.1%, and −15.3% for 0.50%, 0.75%, 1.00%.

Table 10
Mix Proportions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Cement (kg/m³)</th>
<th>Fine aggregate (kg/m³)</th>
<th>Course aggregate (kg/m³)</th>
<th>Super plasticizer (%) of cement content</th>
<th>Plastic Fibers (%) of mixture volume</th>
<th>Glass powder (%) of cement content</th>
<th>Egg shell powder (%) of cement content</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPC</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>0.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF0.50</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>0.50</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF0.75</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>0.75</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF1</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF1.25</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.25</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF1.50</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.50</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF1G5</td>
<td>427.5</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCF1G10</td>
<td>405</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
<td>3.5</td>
<td>1.00</td>
</tr>
<tr>
<td>10.0</td>
<td>0.0</td>
<td>PCF1G15</td>
<td>382.5</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
</tr>
<tr>
<td>15.0</td>
<td>0.0</td>
<td>PCF1G20</td>
<td>360</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
</tr>
<tr>
<td>20.0</td>
<td>0.0</td>
<td>PCF1E5</td>
<td>427.5</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
</tr>
<tr>
<td>PCF1E10</td>
<td>405</td>
<td>500</td>
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<td>3.5</td>
<td>1.00</td>
<td>0.0</td>
<td>10.0</td>
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<tr>
<td>PCF1E15</td>
<td>382.5</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
<td>0.0</td>
<td>15.0</td>
</tr>
<tr>
<td>PCF1E20</td>
<td>360</td>
<td>500</td>
<td>550</td>
<td>3.5</td>
<td>1.00</td>
<td>0.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

1.25%, and 1.5% plastic fibers respectively, while the percentage difference in flexural strength in comparison to reference mix without fibers was; 22.9%, 64.0%, 82.2%, 84.7% and 89.4% for 0.50%, 0.75%, 1.00%, 1.25%, and 1.5% plastic fibers respectively. The increasing in the flexural strength due to fiber might be because of bridging of the cracks as shown in Fig. 9. From these results one can see that 0.75% plastic fiber gave the highest compressive strength, while 1.5% plastic fiber gave the highest flexural strength, but it caused reduction in compressive strength. The percentage 1.0% plastic fiber was fixed and chosen because it improved both compressive and flexural strength.

The density of all mixes was decreasing as percentage of plastic fibers increasing as shown in Fig. 10. This was because of the low density of the plastic fibers.

6.2. Comparison between efficiency of using glass powder and eggshell powder as partial replacement of cement

In this stage the lightweight concrete mix with 1% plastic fiber without cement replacement was used as reference mix to figure the efficiency of using different percentage of GP and ESP each alone as partial replacement of cement through investigated their effect on some properties of lightweight concrete as follow:

6.2.1. Compressive strength

According to tests results the compressive strength of the mixes with GP was increasing with increasing of GP content (see Fig. 11). The percentage increasing in compressive strength in comparison to reference mix without GP was; 5.9%, 14.1%, 25.3% and 37.2% for 5%, 10%, 15% and 20% GP respectively, while the percentage decreasing in compressive strength in comparison to reference mix without ESP were; 1.1%, 4.5%, 7.4% and 11.5% for 5%, 10%, 15% and 20% ESP respectively. The mixes with ESP were showing different results. The 5% ESP gave...
a close compressive strength to that for reference mix, but with increasing of %ESP more than 5% the compressive strength is decreasing (see Fig. 12). These results show that GP was more effective than ESP. That may be due to rich silica content of GP.

6.2.2. Flexural strength

According to tests results the flexural strength of the mixes with GP was increasing with increasing of GP content (see Fig. 13). The percentage increasing in flexural strength in comparison to reference mix without GP was 3.5%, 8.8%, 15.3% and 18.4%, for 5%, 10%, 15% and 20% GP respectively. The GP was more effective in improving compressive strength than flexural strength.

While the percentage decreasing in flexural strength in comparison to reference mix without ESP was; 0.5%, 3.7%, 7.4% and 11.6% for 5%, 10%, 15% and 20% ESP respectively. The 5% gave a similar flexural strength as reference mix, but the other percentages of ESP reduced the flexural strength (see Fig. 14).
6.2.3. Modulus of elasticity

According to the test results, the modulus of elasticity of the mixes with GP was increasing with increasing GP content (see Fig. 15). The percentage increasing in modulus of elasticity in comparison to the reference mix without GP was; 3.8%, 9.0%, 13.7%, and 18.8% for 5%, 10%, 15%, and 20% GP respectively.

The percentage decreasing in modulus of elasticity for ESP mixes in comparison to the reference mix ESP was; 3.33%, 5.8%, 10.4%, 13.3% and for 5%, 10%, 15% and 20% ESP respectively. The ESP was affected in the same manner as on compressive strength (see Fig. 16).

6.2.4. Density

According to the test results, the mixes with glass powder were being more dense with increasing glass powder content. The increasing of glass powder improved hydration processes which led to more dense structure (see Fig. 17).

But the increasing of %ESP led to decreasing in density because of low specific gravity of eggshell powder (see Fig. 18).
6.2.5. Absorption

According to tests results the absorption of the specimens with GP was decreasing with increasing of glass powder content (see Fig. 19). The percentage decreasing in absorption percent was 6.7%, 19.9%, 27.2% and 33.8% for 5%, 10%, 15% and 20% GP respectively, while the percentage increasing in absorption due to ESP replacement was; 0.5%, 3.2%, 11.5% and 18.7% for 5%, 10%, 15% and 20% ESP respectively. The absorption of 5% GP was close to that for reference mix without ESP, but with increasing of %ESP more than 5% the absorption increasing (see Fig. 20). Due to rich silica content of glass powder the structure of lightweight concrete will be more dense with increasing of GP content which results in less void content and that leads to reduce absorption ability of concrete.

7. Conclusions

The following conclusions were made based on experimental results of this work:

1. The utilization of PF clearly improved the flexural strength of lightweight Porcelanite concrete, but it was not so effective in improving compressive strength. 1% PF gave the best results for both compressive and flexural strengths. Besides the increasing in PF content there was a decrease in the density of concrete.

2. The use of different percentage of GP as partial replacement of cement with 1% PE improved the lightweight concrete properties especially the compressive strength, and the improvement in properties was clearer with increasing the percentage of GP to 20%.

3. The use of ESP as partial replacement of cement is not effective as GP. Mix with 5% ESP and 1% PE gave results so close to reference mix. More than 5% ESP was not effective.

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