Experimental Investigation of Physical and Mechanical Characteristics of Structural Foamed Concrete Containing Waste Marble Dust

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Abstract

Utilizing waste material in concrete production is an effective way to eliminate waste and develop environmentally friendly building materials. An experimental investigation was carried out to examine the physical, mechanical and durability characteristics of Polypropylene (PP) fibers foamed concrete (FC) that contains waste marble powder (WMP) as a substitute for conventional cement. Seven different FC mixtures were made utilizing WMD as a cement substitution at the rates of 0, 5, 10, 15, 20, 25 and 30%. Fresh properties of mixtures were investigated by performing slump and fresh density tests. Several tests that evaluated the mechanical strengths were conducted at 7 and 28 days. Moreover, the durability of FC specimens at high temperatures was also examined. Results indicate that by including WMD into FC mixtures, the desired physical, mechanical, and durability characteristics could be obtained. The highest compressive, splitting tensile, and flexural strength were 27.4, 2.34, and 4.2 MPa, respectively, with significant improvements of 39.01, 14.7, and 25% at 28 days. Furthermore, all FC specimens containing WMD showed satisfactory performance at temperatures of 300°C and 600°C.

Keywords: Structural Foamed Concrete; Waste Marble Dust; Physical Characteristics; Mechanical Characteristics; High Temperatures.
1. Introduction

Foamed Concrete (FC) is a lightweight mixture that is produced from cement, water, and air pores uniformly distributed throughout the matrix of the concrete. Based on the characteristics and their constituent's proportion, FC has dry density varying from 400 to 1900 kg/m$^3$. It has a low overall weight, high flow, and superior thermal performance, as well as ease of production. In addition, FC with densities larger than 1,400 kg/m$^3$ can be utilized for structural purposes, with a strength greater than 17 MPa according to ACI 213R. [1]

The building and construction industry is the most significant contributor to the emission of greenhouse gases, accounting for nearly 38% of the overall emissions of CO$_2$. The primary source of carbon dioxide is the cement manufacturing process. In the manufacturing process alone, the production of cement is associated with approximately 8% of global CO$_2$ emissions. [2] In light of these concerns, reducing the use of cement in concrete production is crucial, and prioritizing the replacement of cement with eco-friendly materials is essential to address needs regarding the environmental protection. As a result, there has been a consistent emphasis placed on discovering alternative concrete materials in order to lower CO$_2$ emissions, whilst maintaining good concrete performance and improving economics. Research in recent years has investigated the viability of using recycled by-products or waste materials as building materials. The majority of these waste products, such as marble powder, [3, 4] slag cement, [5] micro silica, and fly ash, are utilized as partial substitutes of cement, [6-8] fine aggregates, [9] mortar, and asphalt mixes. [10] Cutting marble bricks or slabs into the proper form and size results in the formation of wasted marble products. In many different concrete mixtures, the utilisation of waste marble powder (WMP) as an alternative
construction material in place of fine aggregate or cement has resulted in considerable improvements in various concrete mixture characteristics. Also, another advantage of utilising WMP as a substitute of cement is the economic savings that may be realized through this mixture, due to its low cost and potential availability for free, as well as the reduction in CO₂ emissions. [11]

Firat et al. [12] utilised marble dust, waste sand, and fly ash to stabilise the road sub-base in different percentages by mass of the soil. The results showed that waste products including marble dust, waste sand, and fly ash can be effectively utilised for stabilising road sub-base in medium and low-plasticity soil. Gameiro [13] found that the durability and carbonation resistance of concrete improved when 20% of WMP was utilised as a substitution for sand, in addition to an increase in capillarity. Another investigation conducted by Vardhan et al. [14] reported that the utilization of WMD as a substitute for sand in concrete can result in a 20% improvement in concrete strength while simultaneously reducing shrinkage by 30%. According to the findings of the study obtained by Singh et al., [15] substituting 15% of the weight of cement by WMD would lead to a decrease in both the water permeability as well as the abrasion of the mixture. Tiwari et al. [16] stated that the optimal substitution rate of WMD for cement, as well as sand, is up to 15% to develop concrete mixtures with satisfying compressive strength, and increasing this substitution percentage has a negative influence on the compressive strength. Singh et al. [17] conducted a study to examine the impact of WMD substitution for cement on the mechanical properties of concrete. The findings revealed that the optimum replacement ratio of WMP was approximately 12%. At this ratio, the concrete exhibited a significant improvement in compressive strength and split tensile strength when compared to the control specimens. Talah et al. [18] indicated that WMD can be utilised as a
substitution for 15% of cement without causing a decline in the material's strength, also resulting in an improvement in the material's durability. In the same year, Rana et al. [19] used WMD as a substitute for cement at levels up to 25% and found that 10% was the optimal substitution level for cement in terms of improving the material's durability. In a similar study conducted by Memon et al. [20] it was confirmed that concrete made using 5% WMP replacement by weight of cement showed an increase in the mechanical properties of hardened concrete at 28 days. Zhang et al. [21] examined the long-term performance and mechanical characteristics of lightweight concrete which was made by replacing cement with micro silica and WMP. The results indicated that replacing cement with 5–20% micro silica and WMP improved both the long-term performance and mechanical characteristics.

WMD can be utilised to substitute some of the cement or cementitious materials in the mixture. When WMD is utilised in place of cement, the total quantity of cement would be decreased while simultaneously increasing the water/cement ratio. Thus, a high cement substitution rate would result in a significant reduction in the strength and durability, which would impose limitations on the cement substitution ratio. [19] This study develops structural FC mixtures that contain WMP as a cement substitution, as there is a lack of studies in the literature about the effects of WMD as a cement substitution on the physical-mechanical durability of structural FC mixtures. Furthermore, in order to generate eco-friendly structural lightweight concrete for future applications in the construction industry, this investigation explores the influence of the primary considerations that have an influence on the flowability, density, compressive and splitting tensile strength. The ratio of WMD added to the mixtures was: 0, 5, 10, 15, 20, 25, and 30%, relative to
the cement weight in order to find the optimal environmentally friendly FC mixture that meets the requirements for structural utilisation and has a density of less than 1900 kg/m³ to be identified as lightweight. [22]

Allouzi et al. [23] developed the optimal mix of FC appropriate for structural applications utilising site trials in which 75 kg/m³ foam contents were employed at 0.4 w/c and 1% Polypropylene (PP) fibers without WMD and that mixture was utilised in this investigation as a control mixture. This study aims to develop foamed mixtures utilising WMP as a cement replacement at the rates of 5, 10, 15, 20, 25, and 30%, respectively. A detailed description of material properties and their quantities were outlined. Then, the set-up of the experimental tests was explained. Slump and fresh density which were the fresh properties of the mixtures were examined. The compressive, flexural and splitting tensile strength of FC specimens were evaluated, as well as high-temperature examinations. The conclusion summarizes the observed facts and points out the positive and negative aspects of this new system in producing eco-friendly structural lightweight concrete.

2. Experimental program

2.1 Materials

2.1.1 Cementitious Material

Regarding the cementitious materials, the most common type of cement that is utilised in FC is Ordinary Cement. Many researchers have also used other types of cement, such as Pozzolana Portland Cement (PPC) and rapid hardening Portland cement (RHPC). PPC, which has a relative density of 3.15, was utilised in this investigation. The characteristics of the chemical and physical
cement utilised in this investigation are listed in Table 1.

2.1.2 Waste Marble Powder (WMP)

This investigation utilised waste marble powder (WMP), a by-product of marble, that is produced by the marble industries in Karak, Jordan, as a substitute for cement which has a specific weight of 2.68 g/cm³, as shown in Fig. 1. The chemical components of WMP are listed in Table 1. The X-ray powder diffraction (XRD) spectra of WMP are shown in Fig. 2(a), which demonstrates that the examined material consists of dolomite and calcite (CaCO₃) which are the two primary crystallized minerals. Quartz (SiO₂) makes up the remainder of the marble powder. It was observed that the concentration of dolomite in this sample is marginally higher than the concentration of calcite. As given in Fig. 2(b), the majority of the particle sizes of WMP can be seen to be under 75 µm. It was found that 90% of the particles had a diameter that was less than 150mm (d₉₀ = 150 µm).

<table>
<thead>
<tr>
<th>Chemical Compositions (%), PPC, WMD</th>
<th>WMD</th>
<th>PPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>52.5</td>
<td>47.05</td>
</tr>
<tr>
<td>SiO₂</td>
<td>24</td>
<td>5.40</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>6.4</td>
<td>0.95</td>
</tr>
<tr>
<td>MgO</td>
<td>3.2</td>
<td>3.98</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.6</td>
<td>-</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.95</td>
<td>0.12</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.8</td>
<td>0.17</td>
</tr>
<tr>
<td>L.O.I</td>
<td>2.8</td>
<td>40.95</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.18</td>
<td>2.68</td>
</tr>
<tr>
<td>Specific Surface Area m²/g</td>
<td>0.4</td>
<td>0.68</td>
</tr>
</tbody>
</table>
Fig. 1 WMD Utilised in This Study.

Fig. 2 (a) X-ray diffractogram and (b) Particle Size Distribution of WMP.

2.1.3 Polypropylene (PP) Fiber

Fibrillar polypropylene (PP) fibers with 12 mm length were utilised in this investigation. Table 2 lists several PP characteristics. The PP fiber content of all mixtures was 1% by cement weight.
Table 2. Technical Characteristics of PP Fiber.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Fibrillated mini bundle</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.90</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>140Mpa</td>
</tr>
<tr>
<td>Youngs Modulus</td>
<td>4.8Cpa</td>
</tr>
<tr>
<td>Elongation</td>
<td>25-40</td>
</tr>
</tbody>
</table>

2.1.4 Foam

ISOCEM foam agent, which is an aromatic sulphonate agent and also contains a stabilising element, is utilised. Table 3 lists the physical characteristics of the ISOCEM foaming agent.

Table 3. Physical Characteristics of Foaming Agent.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Composition</td>
<td>Air-entrapping liquid</td>
</tr>
<tr>
<td>Physical condition</td>
<td>Liquid</td>
</tr>
<tr>
<td>Colour</td>
<td>Dark Brown</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.015 Kg/l</td>
</tr>
<tr>
<td>PH</td>
<td>7</td>
</tr>
</tbody>
</table>
2.1.5. Water-Reducing Superplasticiser (SP)

The addition of a superplasticiser improves the mixture's flowability. The incorporation of PP fibers into the mixtures lead to a decrease in workability, which necessitated the utilisation of a superplasticiser despite the fact that FC is a flowable material that does not require compaction. In this investigation, Flocrete SP33 is utilised, which is in accordance with ASTM C494. \(^{[24]}\)

2.1.6. Sand and Mixing water

The sand of medium grade that conforms to ASTM C 144 \(^{[25]}\) and has a specific gravity (g/cm\(^3\)) of 2.54 will be utilised throughout this study. The sand was left to air-dry until it reached a surface-dry condition, and then it was screened to remove any lumps and other particles that were larger than 2.36 mm. The water that is utilised to mix the concrete has a temperature of 21 ± 2°C on average and PH within ranges of 6.8 to 7.0, as specified by BS EN 1008:2002. \(^{[26]}\)

2.2. Mixture Proportions, Mixing and Testing procedures

The production of FC is performed by the use of the pre-formed foam method, which involves the introduction of air voids into the cement paste. Before adding the water, the cement, WMP, sand, and PP fibers were blended together for one minute. After that, the water was added and continued mixing for a further two minutes, and a slurry paste was finally created. After mixing, the required quantity of foam was then added to the wet mixture and mixed for two minutes; consequently, the foam was thoroughly incorporated into the mixture and the plastic FC was obtained, Fig. 3.
FC was emptied into moulds of varying sizes to conduct the relevant tests and before that, the moulds were oiled to ease the de-moulding procedure. FC was placed in three layers with no vibration. After that, a rubber hammer was used to lightly tap the sides of the mould while the moulds were being filled in order to achieve a flat surface as per ASTM C 495. [27] The de-moulding was conducted after 24 hours. Then, the FC specimens were cured in 20° C water for 28 days, as shown in Fig.4. Table 4 lists the proportions of all FC mixtures that were produced in this investigation. In contrast to the other mixture parameters, the SP dosage was not set in advance. Rather, trial mixtures were performed, with the addition of SP to each mixture in small amounts, which increased gradually with the increase in the WMD content, until the desired level of
workability was attained. After that, the SP appropriate amounts that had been established by trial mixtures were utilised in the experiments. According to ASTM C1437-15, the slump test was carried out in order to evaluate the flowability of fresh FC mixtures. Testing for dry density, in accordance with ASTM C642, was performed on FC specimens after 7 and 28 days of standard cure. In accordance with BS EN 12390-3, the compressive strength test was conducted after 7 and 28 days of standard cure. 150 mm cubes were utilised as moulds for compressive strength investigation. The results of the experiment were defined by determining the mean of the results of each of the specimens. Splitting tensile strength evaluations were carried out utilising cylindrical moulds of 150 ×300 mm after 28 days of curing as per ASTM C496M. The flexural test was done according to ASTM C78, as shown in Fig. 5. Beams of 100 × 100 × 500 mm were utilised to perform the test in accordance with BS 1881: Part 118 : 1983. Finally, the FC specimens were subjected to 300°C and 600°C , with a temperature rise of 10°C/minute then left in in a furnace to slowly cool down, as illustrated in Fig. 6. After exposure to the high temperature, mass loss, compressive and flexural strength tests were conducted in order to identify any internal damage that may have occurred in FC specimens.

![Concrete Specimens in Curing Water Tank.](image_url)
Fig. 5 Third-Point Loading Flexural Test Setup for Beams.

Fig. 6 Arrangement of Specimens inside the Furnace.

Table 4. Mixture proportions for 1m³.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>W/C</th>
<th>W/S</th>
<th>PP (%)</th>
<th>Cement (kg)</th>
<th>WMP (kg)</th>
<th>Sand (kg)</th>
<th>Foam (ltr)</th>
<th>PP (kg)</th>
<th>Water (kg)</th>
<th>SP (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>666.67</td>
<td>0</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N05</td>
<td>633.33</td>
<td>33.33</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N10</td>
<td>600.00</td>
<td>66.67</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.55</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N15</td>
<td>566.66</td>
<td>100</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N20</td>
<td>533.33</td>
<td>133.33</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.65</td>
<td></td>
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<tr>
<td>N25</td>
<td>500</td>
<td>166.66</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N30</td>
<td>433.33</td>
<td>233.33</td>
<td>666.67</td>
<td>2.67</td>
<td>6.67</td>
<td>178</td>
<td>2.75</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Test Results and Discussion

3.1 Workability

Although FC is a high flowability and self-compacting material, the incorporation of WMD as cement substitution influenced the workability, since water requirement increased while the WMD content increased. Similar results have reported that the specimens containing WMD as a substitute for cement required more water compared to the specimens without WMD. As a result of this, a mixture that has a high percentage of WMD is considered to be drier in general during the mixing process. Consequently, it required more SP quantities in order to improve the workability, as shown in Table 4. According to the results obtained, the quantity of SP varied from 2.44 to 2.75 kg/m³ and increased as the WMD volume increased.

From these results, we observe that there is an increasing demand for water in all mixtures that contain WMD, which could be attributed to the fact that the marble dust has a greater surface area than PPC to be 0.68 m²/g compared to 0.4 m²/g for PPC as displayed in Table 1. Consequently, the surface area of the mixtures that contain WMD was greater than that of the control mixture, which led to an increase in the amount of required water. As illustrated in Fig. 7, the influence of various WMD ratios on the consistency of FC mixtures was investigated. The forms of the slumped concrete range from a shear slump (Fig. 8(a)) to a collapse slump (Fig. 8(b)).
3.2 Density

The evaluation of the plastic density, as well as the density after 7 days and after 28 days was given in Table 5 and Fig. 9. These results show that the addition of WMD affected both fresh and dry densities, as the density values of the mixtures containing WMD tended to decrease. The values of fresh density of all mixtures were lower than the values of dry densities of those mixtures. This
is due to the fact that some bubbles were squished out by the weight of the concrete before it hardened. Consequently, the dry density of hardened cement pastes increased. As shown in Fig. 9, dry density of all specimens with WMD content was lower than the control specimen. Since WMD has a lower specific gravity than cement, the inclusion of WMD resulted in a decrease in the density of mixtures. The density increment was found to be 12.15% for NO5 specimen compared to the control specimen. This mix had the highest density and the lowest workability. Actually, the amount of water in this mixture decreased significantly when WMD was added, although a dose of superplasticiser was added to the mix (as previously mentioned). When compared to the control specimen, the density decreased by 0.58, 5.79, 15.87, 14.70, and 25.54% after 28 days as a clear consequence of an increase in WMD from 10 to 30%, respectively.

**Table 5. Average Density of FC Mixtures.**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Plastic Density (kg/m³)</th>
<th>Dry Density (kg/m³) (7 days)</th>
<th>Dry Density (kg/m³) (28 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
<td>1595.87</td>
<td>1771.91</td>
<td>1784.54</td>
</tr>
<tr>
<td>N05</td>
<td>1613.03</td>
<td>1989.69</td>
<td>2001.47</td>
</tr>
<tr>
<td>N10</td>
<td>1510.23</td>
<td>1875.03</td>
<td>1774.05</td>
</tr>
<tr>
<td>N15</td>
<td>1506.26</td>
<td>1787.61</td>
<td>1681.15</td>
</tr>
<tr>
<td>N20</td>
<td>1389.15</td>
<td>1484.35</td>
<td>1501.23</td>
</tr>
<tr>
<td>N25</td>
<td>1428.69</td>
<td>1588.80</td>
<td>1522.15</td>
</tr>
<tr>
<td>N30</td>
<td>1261.71</td>
<td>1286.54</td>
<td>1328.65</td>
</tr>
</tbody>
</table>
3.3 Compressive Strength

The compressive strength test results of 7 and 28 days aged FC specimens are plotted in Fig. 10. It is apparent that as the WMD content increased up to 15%, there was a corresponding increase in compressive strength, which subsequently significantly decreased. At 20, 25, and 30% WMD addition, a decrease in compressive strength in comparison with the control specimen was observed. Aliabdo et al. [39] and Shirule et al. [40] reported that compressive strength increased with increasing rates of WMD as cement substitution up to 15%. According to Ashish, [36] an increase in the compressive strength of concrete cured at 7 and 28 days was 7.17 and 8.44%, respectively, when WMD was utilised to partially substitute cement in the amount of 10%. This is because the pore-filling influence of WMD increases the characteristics of the transition zone (TZ) that surrounds the aggregate. [39] As shown in Fig. 10, the compressive strength of all FC specimens improves with increasing curing ages. The compressive strength of 7 days aged FC specimens varied between 3.7 and 23.11 MPa. The compressive strength of the N30 specimen is the lowest,
whilst the compressive strength of the N05 specimen is the highest. The N05 specimen showed a considerable increase in compressive strength which was 86.5% higher than the compressive strength of the control specimen at 7 days. The compressive strength of 28 days aged FC specimens varied between 7.24 and 27.4 MPa for N30 and N05 specimens, respectively. It is seen that the compressive strengths of N05, N10, and N15 specimens are 39.01, 10.65, and 6.03% higher and N20, N25 and N30 specimens are 44.69, 42.56, and 63.26% lower than the control specimen at 28 days, respectively. Fig. 11 illustrates the relationship between the density and compressive strength of FC containing different rates of WMD. It is apparent that there is an increase in compressive strength associated with an increase in the density of FC specimens. This result agrees with the conclusion conducted by Jones et al. [41] and Nambiar et al. [42] that as density increases, the compressive strength of FC increases significantly.

![Graph](image)

**Fig. 10** Measured Compressive Strength of FC Mixtures at 7 and 28 Days.
3.4 Splitting Tensile Strength

The Splitting Tensile strength test results of 28 days aged FC specimens with varying rates of WMD are plotted in Fig. 12. The results showed that when WMD was utilised as a substitution of cement at rates up to 15%, the splitting tensile strength increased. The FC specimens exhibited splitting strengths of 2.34, 2.09, and 2.16 MPa at WMD rates of 5, 10, and 15%, respectively, with significant improvements of 14.70, 2.45, and 6.37% relative to the control specimen. In fact, the improved results in compressive strength were the reason of this improvement in tensile strength - as the components that improve compressive strength would also improve tensile splitting strength. Similar results were observed by Ashish, [36] finding that the splitting tensile strength increases when WMD is utilised as a cement substitution up to 15% in comparison to the control specimen. Splitting tensile strength was shown to decrease by 14.06, 16.51, and 52.45 % when utilising WMP as a cement replacement at 20, 25, and 30%, respectively, in comparison with the
control specimen. Based on this, we can conclude that the utilisation of WMD results in an improvement of the compressive and splitting tensile strength of FC mixtures when cement is replaced with WMD up to 15% in comparison with the control specimen. According to ACI 318-14, the tensile splitting strength of lightweight concrete can be estimated as:

\[ f_t = \lambda \times 0.56 \times \sqrt{f_c} \text{ in MPa} \quad (1) \]

For lightweight concrete, \( \lambda = 0.75 \). Fig. 13\(^3\) illustrates the relationship between the results of splitting tensile strength and the compressive strength of all FC specimens. The suggested empirical equation for splitting the tensile strength of FC is:

\[ f_t = \lambda \times 0.5106 \times f_c^{0.5646} \text{ in MPa} \quad (2) \]

Fig. 13 also illustrates the results that were obtained by equation 2, which showed a good agreement with the measured results.

![Fig.12 Measured Splitting Tensile Strength of FC Mixtures at 28 Days.](image)

\(^3\) The error bar for all values was equal to 10%. 
Fig. 13 Measured and Calculated Splitting Tensile Strength Relative to the Corresponding Compressive Strength of FC Mixtures.

3.5 Flexural Strength

Fig. 14 illustrates the results of a flexural strength test of 7 and 28 days aged FC specimens. The effect of substituting WMP for cement on the flexural strength of FC specimens was significantly clear relative to the control specimen. At the curing ages of 7 and 28 days, the impact of WMD on flexural strength was clearly increased by 31.80 and 26.88%, respectively. As shown in Fig. 14, it was noted that the flexural strength noticeably increased with an increase in the WMD content up to 10%, but subsequently somewhat decreased with an increase of WMD to 15% compared to the control specimen. At 20, 25, and 30% WMD addition, the flexural strength of the specimen was measured to have significantly decreased in comparison to the control specimen. The flexural strength of 28 days aged FC specimens ranged from 1.63 to 4.2 MPa. As compared with all of the specimens, the flexural strength of the N30 specimen is the lowest, while the flexural strength of the N05 specimen is the highest. The flexural strengths of N05 and N10 are 25 and
18.75% higher than the control specimen, while the strengths of N15, N20, N25 and N30 mixtures are 3.57, 40.47, 22.02, and 41.48% lower than the control specimen, respectively. The ACI 318-14 code equation to calculate the flexural strength of lightweight concrete is:

\[
fr = \lambda 0.62 \sqrt{fc} \quad \text{in MPa} \quad (3)
\]

An equation to predict the flexural strength of FC is also proposed as part of this study as follows:

\[
fr = \lambda 0.54 fc^{0.7121} \quad \text{in MPa} \quad (4)
\]

The results obtained from equation 4 made an acceptable relationship between measured and calculated flexural strengths. The results of the flexural strength relative to the compressive strength for all of the specimens investigated in this study are illustrated in Fig. 15. It can be concluded therefore, that there is an effective positive association between the flexural strength and the compressive strength of the material. This indicates that the increase or decrease in flexural strength values, which is associated with the WMD rates, could be explained in the same way as was previously addressed with splitting tensile strength results.

![Fig. 14 Measured Flexural Strength of FC Mixtures at 7 and 28 Days.](image-url)
3.6 High Temperature Durability

The specimens were subjected to high temperatures at 300°C and 600°C for 3 hours, at a rate of 10°C /min. After that, the specimens were kept in the furnace to cool down.

3.6.1 Mass loss

FC consists of free water and chemically bond water. Evaporation of free water and some of the chemically bound water leads to dehydration of the FC, and as a result, it will have an impact on the hydration of the cement particles, as well as C-S-H and Ca (OH) \(_2\). Evaporation of the chemically bonded water and the gel water of C-S-H starts when the temperature reaches 300°C. At about 530°C, Ca (OH)\(_2\) can be converted into the anhydrous form of lime (CaO). These changes can result in concrete shrinkage up to 33%, an increase in micro cracks, and a reduction in the modulus of elasticity. \(^{[43]}\) Dehydration is also associated with a decrease in the mass of the FC.

Fig. 16 shows the values of mass loss of 28 days-aged FC specimens that have been
subjected to high temperatures. As shown in Fig. 16, the increasing temperature caused an increase in mass loss. The mass of all mixtures dropped as the temperature increased. The control specimen showed the highest mass loss of 11.64 and 19.17% at 300°C and 600°C, respectively. Mass loss decreases proportionally with increasing WMD. The mass loss of specimen of 5% WMD is 10.29 and 14.88% at 300°C and 600°C, respectively, which continuously declines as the amount of WMD increases. The lowest mass loss of 7.71 and 12.97% was seen in specimen N30 at 300°C and 600°C, respectively.

![Mass Loss Results of FC Mixtures at High Temperature.](image)

**Fig. 16** Mass Loss Results of FC Mixtures at High Temperature.

### 3.6.2 Compressive Strength

Fig. 17 illustrates the influence of high temperatures on the compressive strength of specimens of 28 days-aged FC. The decreases in compressive strength of FC at temperatures of 300°C and 600°C are depicted in Fig. 18. As seen in Fig. 17 and Fig. 18, the compressive strength of all FC specimens decreased as the temperature increased relative to the compressive strength at
20°C. The control specimen showed the lowest high temperature resistance, with the highest reduction in compressive strength of 22.21 and 55.92% at 300°C and 600°C, respectively. All specimens with WMD as a partial cement substitute demonstrated a higher high temperature resistance than the control specimen at both 300°C and 600°C. The specimens with 5 and 10% WMD content demonstrated the greatest performances when subjected to high temperatures with a reduction in compressive strengths of 9.78 and 9.90% at 300°C, and 17.66 and 16.58% at 600°C, respectively. According to Mydin et al., [44] when FC is subjected to high temperatures, it will lose the absorbed free water in addition to some of the water that is chemically bonded to the FC. Cracks would appear as a result of the loss of water in the specimens. The compressive strength of the FC specimens experienced a significant reduction as a result of these cracks, which corresponds to a reduction in the cohesion of Van der Waals forces (interatomic or intermolecular interaction that is reliant on distance) between the layers of C, S, and H. This leads to the formation of silanol bands, which have a lower bonding strength. [44,45] There was a correlation between the mass loss values of all FC specimens and their compressive strength, as the more the mass loss, the lower the compressive strength. Fig. 19 illustrates the relationship between compressive strength and mass loss at 300°C and 600°C of all FC specimens. As shown, there are relatively higher relationships between the compressive strength and mass loss at 300°C than at 600°C. It is worth mentioning that the error bar was equal to 10% and all points approximately touched the lines except for one specimen.
**Fig. 17** Measured Compressive Strength of FC Mixtures at High Temperature.

**Fig. 18** Compressive Strength Change of FC Mixtures at High Temperature.
3.6.3 Flexural Strength

The results of the flexural strength of 28 days-aged FC specimens are shown in Fig. 20. Fig. 21 indicates reductions of flexural strength of the FC specimens at the temperature of 300°C and 600°C. It is evident from Fig. 20 and Fig. 21 that the flexural strength of all FC specimens generally decreases at a temperature increase, compared to the flexural strength of FC at 20°C. The control specimen showed the best performance against the high temperature with a maximum reduction of 16.62 and 29.19%, at 300°C and 600°C respectively. It can be seen that the FC specimens as a whole are losing strength as the WMD content is increasing. For the mixture with 5% WMD, the strength reduction slightly increased to 21.68 and 33.33% at 300°C and 600°C respectively. All specimens containing different percentages of WMD showed almost similar decreases in flexural strength at both temperatures. The specimen with 30% WMD demonstrated the largest flexural strength decreases of 45.40 and 70.55% at 300°C and 600°C, respectively. As stated in related
literature, $[44, 45]$ this decline in strength is due to the loss of free water as well as some of the water that is chemically bonded as a result of the exposure to high temperatures. As a consequence of this, the compressive strength would decrease, and its flexural strength would also decline significantly.

**Fig. 20** Measured Flexural Strength of FC Mixtures at High Temperature.

**Fig. 21** Flexural Strength Change of FC Mixtures at High Temperature.
3. Conclusions

In this investigation, a series of FC mixtures, with varying waste marble dust (WMD) content, were examined in order to test their workability, wet and dry density, compressive strength, splitting tensile strength, and flexural strength – in order to investigate the influences of WMD utilised as a partial substitute of cement on the physical and mechanical properties of structural FC. The durability of FC specimens at high temperatures was also investigated. The following conclusions may be derived from the experimental results:

1. The addition of WMD as cement substitution affects the workability of the FC mixture, as water requirement increases while the WMD content increases. The lowest workability was 16.67% lower than the control specimen while the highest workability was 21.4% higher than the control specimen.

2. The addition of WMD as cement substitution decreases the density of all FC specimens. WMD has a lower specific gravity than cement, so adding WMD to the mixture reduces the density of specimens relative to the control specimen without WMD. The lowest density was gained for the specimen with 30% WMD which was 25.54% lower than the control specimen at 28 days.

3. The addition of WMD as cement substitution improves the compressive strength of FC up to 15%. The highest compressive strength of 23.11 and 27.4 MPa was gained for the specimen with 5% WMD content at 7 days and 28 days respectively, which were 86.5 and 39.01% higher than the control specimen. The reason for this is that the pore-filling influence of WMD increases the characteristics of the transition zone (TZ) that
surrounds the aggregate.

4. The addition of WMD as cement substitution up to 15% would increase the splitting tensile strength of FC specimens. At 28 days, the specimen with 5% WMD content had the largest splitting tensile strength of 2.34 MPa. This value was 14.70% larger than the value of the control specimen. Enhanced tensile strength may be the result of a relevant increase in compressive strength. This signifies that the influence of WMD on compressive strength is similar to the trend observed in the tensile strength of WMD-containing mixtures.

5. The addition of WMD as cement substitution up to 10% will lead to the improvement in the flexural strength of FC specimens. The flexural strengths of 28 days-aged FC specimens were 4.2 and 3.99 MPa for specimens with 5 and 10% WMD content, which were 25 and 18.75% higher than the control specimen, respectively.

6. Exposure to 300°C and 600°C decreases the mass of all FC specimens. The control specimen showed the highest mass loss of 11.64 and 19.17% at 300°C and 600°C, respectively. The lowest mass loss of 7.71 and 12.97% was seen in the specimen with 30% WMD content at 300°C and 600°C, respectively. Accordingly, it could be concluded that mass loss reduces as WMD content increases.

7. Exposure to 300°C and 600°C decreases the compressive strength of all FC specimens in comparison to concrete specimens at 20°C. All specimens containing WMD as partial cement substitution revealed a less compressive reduction than the control specimen. The specimen that contained 5% WMD demonstrated the greatest high temperature
performance, with a compressive strength decrease of 9.78 and 9.90%, while the control specimen demonstrated the worst high temperature performance, with the highest reduction in compressive strength of 22.21 and 55.92% at 300°C and 600°C, respectively.

8. Exposure to 300°C and 600°C decreases the flexural strength of all FC specimens compared to concrete specimens at 20°C. The control specimen showed the best performance against the high temperature, with a maximum reduction of 16.62 and 29.19%. The specimen with 30% WMD content showed the worst performance against the high temperature of 45.40 and 70.55% at 300°C and 600°C, respectively.

9. In general, it is possible to obtain the desired physical, mechanical, and durability properties by utilisation of the WMD content as a cement substitution of up to 10% with reference to low density, compressive strength, splitting tensile strength, and flexural strength. Also, all specimens containing WMD show satisfactory performance at temperatures of 300°C and 600°C. Furthermore, utilising WMD as a cement substitute reduces the cement content. Cement is an expensive component, and utilising WMD as a substitute leads to the generation of environmentally friendly and cost-effective concrete. Moreover, this effective practice will eliminate the cost of overheads, which solves the environmental problems that are related to the disposal of this waste.

**Supporting information**

Not applicable.
Conflict of interest

The authors declare no conflict of interest.

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