



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 WMP 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 indicated that by including WMP 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 WMP showed satisfactory performance at temperatures of 300 and 600 °C.

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

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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/m³. 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/m³ can be utilized for structural purposes, with a tensile 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 CO₂. The primary source of CO₂ is the cement manufacturing process. In the manufacturing process alone, the production of

cement is associated with approximately 8% of global CO₂ 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 CO₂ 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 utilizing WMP as a substitute of cement is the economic savings that may be realized through

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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 stabilize 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 were 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 WMP 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 WMP 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 WMP for cement, as well as sand, was 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 WMP substitution for cement on the mechanical properties of concrete. The findings revealed that the optimum replacement rate of WMP was approximately 12%. At this rate, 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 WMP could be utilized as a substitution for 15% of cement without causing a decline in the material's tensile strength, also resulting in an improvement in the material's durability. In the same year, Rana *et al.*^[19] used WMP 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.

WMP can be utilized to substitute some of the cement or cementitious materials in the mixture. When WMP is utilized 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 tensile strength and durability, which would impose limitations on the cement substitution rate.^[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 WMP 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 rate of WMP 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 utilizing site trials in which 75 kg/m³ foam contents were employed at 0.4 w/c and 1% polypropylene (PP) fibers without WMP and that mixture was utilised in this investigation as a control mixture. This study aims to develop foamed mixtures utilizing 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 was marginally higher than the concentration of calcite. As given in Fig. 2(b), the majority of

the particle sizes of WMP could be seen to be under 75 μm . It was found that 90% of the particles had a diameter that was less than 150 μm ($d_{90} = 150 \mu\text{m}$).

Table 1. Chemical composition of PPC and WMP.

Chemical Compositions (%)	PPC	WMP
CaO	52.5	47.05
SiO ₂	24	5.40
Al ₂ O ₃	6.5	1.12
Fe ₂ O ₃	6.4	0.95
MgO	3.2	3.98
SO ₃	2.6	-
Na ₂ O	0.95	0.12
K ₂ O	0.8	0.17
L.O.I	2.8	40.95
Specific Gravity	3.18	2.68
Specific Surface Area m ² /g	0.4	0.68



Fig. 1 WMP utilised in this study.

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.

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 2. Technical characteristics of PP fiber.



Appearance	Fibrillated mini bundle
	
Specific Gravity	0.90
Tensile Strength	140 MPa
Youngs Modulus	4.8 GPa
Elongation	25-40%

Table 3. Physical characteristics of foaming agent.

Chemical Composition	Air-entrapping liquid
	
Physical condition	Liquid
Colour	Dark Brown
Specific Gravity	1.015 kg/L
pH	7

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 was a flowable material that did not require the compaction. In this investigation, Flocrete SP33 was utilised, which was in accordance with ASTM C494.^[24]

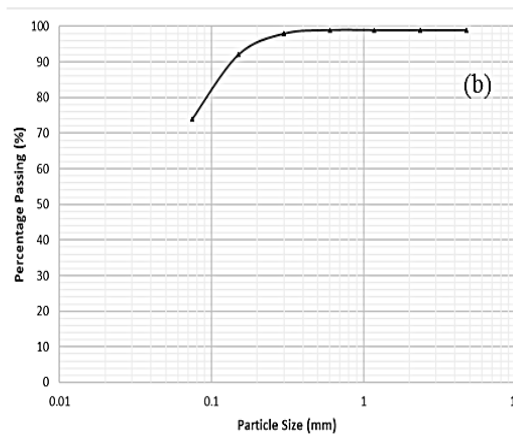
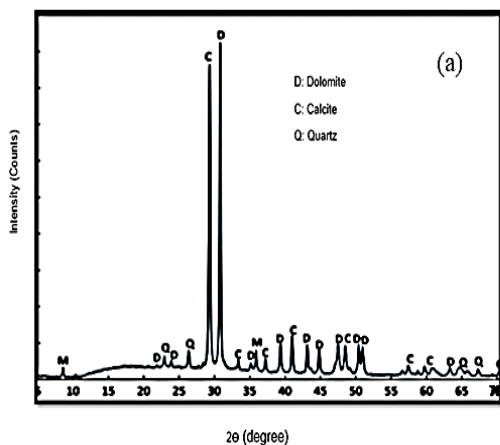


Fig. 2 (a) X-ray diffraction pattern and (b) Particle size distribution of WMP.

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 was utilized 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 was utilized to mix the concrete had a temperature of $21 \pm 2^\circ\text{C}$ 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. 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 C495.^[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 WMP content, until the desired level of workability was attained. After that, the SP appropriate amounts that had been established by trial mixtures were utilized in the experiments. According to ASTM C1437-15,^[28] 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,^[29] was performed on FC specimens after 7 and 28 days of standard cure. In accordance with BS EN 12390-3,^[30] the compressive strength test was conducted after 7 and 28 days of standard cure. 150 mm cubes were utilized 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 utilizing cylindrical moulds of 150×300 mm after 28 days of curing as per ASTM C496M.^[31] The flexural test was done according to ASTM C78,^[32] as shown in Fig. 5. Beams of $100 \times 100 \times 500$ mm were utilized to perform the test in accordance with BS 1881:



Fig. 3 Production of FC.

Part 118: 1983.^[33] Finally, the FC specimens were subjected to 300 °C and 600 °C, with a temperature rise of 10 °C/minute then left 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.



Fig. 4 Concrete specimens in curing water tank.

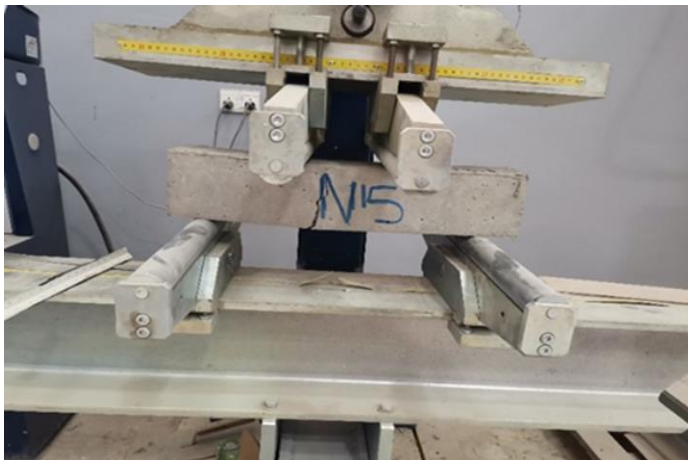


Fig. 5 Third-point loading flexural test setup for beams.



Fig. 6 Arrangement of specimens inside the furnace.

3. Test results and discussion

3.1 Workability

Although FC is a high flowability and self-compacting material, the incorporation of WMP as cement substitution influenced the workability, since water requirement is increased while the WMP content is increased. Similar results have reported that the specimens containing WMP as a substitute for cement are required more water compared to the specimens without WMP.^[34] As a result of this, a mixture that has a high percentage of WMP is considered to be drier in general during the mixing process. Consequently, it's required more SP quantities in order to improve the workability, as shown in Table 4. According to the results obtained, the quantity of SP is varied from 2.44 to 2.75 kg/m³ and increased as the WMP volume is increased.

From these results, we observe that there is an increasing demand for water in all mixtures that contain WMP, 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 WMP is greater than that of the control mixture, which lead to an increase in the amount of required water.^[35,36] As illustrated in Fig. 7, the influence of various WMP rates on the consistency of FC mixtures is investigated. The forms of the slumped concrete range from a shear slump (Fig. 8(a)) to a collapse slump (Fig. 8(b)).

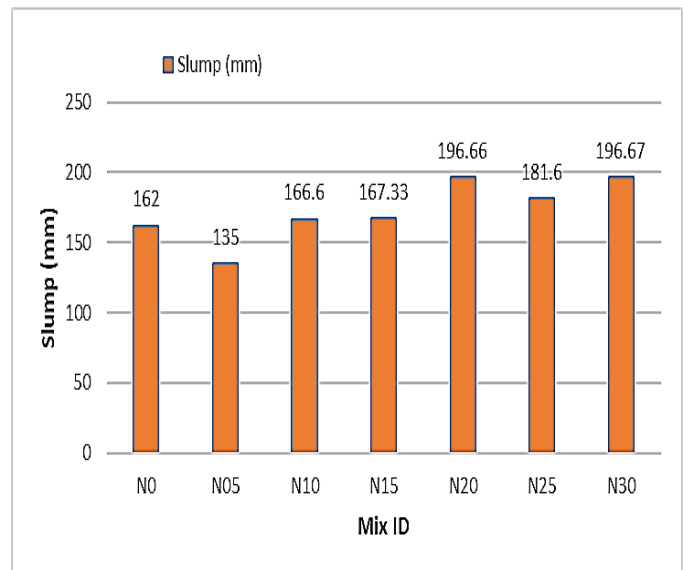


Fig. 7 Slump values of FC mixtures.

3.2 Density

The evaluation of the plastic density, as well as the density after 7 days and after 28 days are given in Table 5 and Fig. 9. These results show that the addition of WMP affected both fresh and dry densities, as the density values of the mixtures containing WMP are tended to decrease. The values of fresh density of all mixtures are lower than the values of dry densities of those mixtures. This is due to the fact that some bubbles are squished out by the weight of the concrete before it's hardened. Consequently, the dry density of hardened



Fig. 8 Slump test types; (a) Shear slump, and (b) Collapse slump.

Table 4. Mixture proportions for 1 m³.

Mix ID	W/C	W/S	PP (%)	Cement (kg)	WMP (kg)	Sand (kg)	Foam (L)	PP (kg)	Water (kg)	SP (kg/m ³)
N0				666.67	0	666.67	2.67	6.67	178	2.44
N05				633.33	33.33	666.67	2.67	6.67	178	2.50
N10				600.00	66.67	666.67	2.67	6.67	178	2.55
N15	0.4	1:1	1%	566.66	100	666.67	2.67	6.67	178	2.60
N20				533.33	133.33	666.67	2.67	6.67	178	2.65
N25				500	166.66	666.67	2.67	6.67	178	2.70
N30				433.33	233.33	666.67	2.67	6.67	178	2.75

cement pastes is increased. As shown in Fig. 9, dry density of all specimens with WMP content is lower than the control specimen. Since WMP has a lower specific gravity than cement, the inclusion of WMP results in a decrease in the density of mixtures.^[37] The density increment is found to be 12.15% for N05 specimen compared to the control specimen. This mix has the highest density and the lowest workability. Actually, the amount of water in this mixture is decreased significantly when WMP is added, although a dose of superplasticizer is added to the mix (as previously mentioned). When compared to the control specimen, the density is decreased by 0.58, 5.79, 15.87, 14.70, and 25.54% after 28 days as a clear consequence of an increase in WMP from 10 to 30%, respectively.

Table 5. Average density of FC mixtures.

Mix ID	Plastic Density (kg/m ³)	Dry Density (kg/m ³) (7 days)	Dry Density (kg/m ³) (28 days)
N0	1595.87	1771.91	1784.54
N05	1613.03	1989.69	2001.47
N10	1510.23	1875.03	1774.05
N15	1506.26	1787.61	1681.15
N20	1389.15	1484.35	1501.23
N25	1428.69	1588.80	1522.15
N30	1261.71	1286.54	1328.65

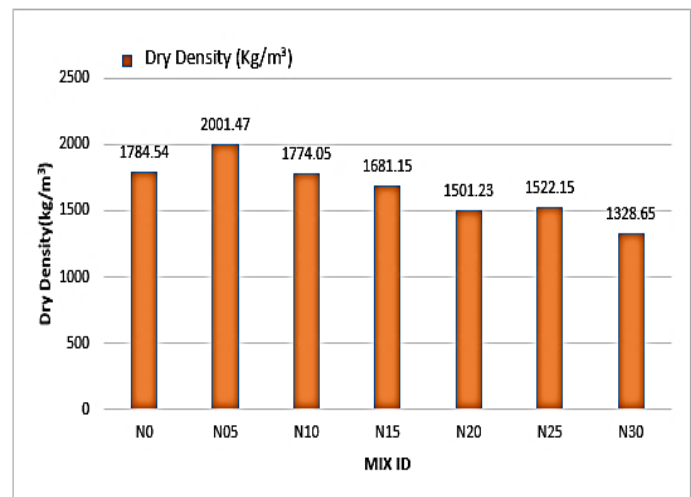


Fig. 9 Measured density of foamed mixtures at 28 days.

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 WMP content is increased up to 15%, there was a corresponding increase in compressive strength, which is significantly decreased. At 20, 25, and 30% of WMP addition, a decrease in compressive strength in comparison with the control specimen is observed. Aliabdo *et al.*^[39] and Shirule *et al.*^[40] reported that the compressive strength was increased with increasing rates of WMP as cement substitution up to 15%. According to Ashish,^[36] an increase in the compressive

strength of concrete cured at 7 and 28 days is 7.17 and 8.44%, respectively, when WMP was utilized to partially substitute cement in the amount of 10%. This is because the pore-filling influence of WMP 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 is 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 shows a considerable increase in compressive strength which is 86.5% higher than that of the control specimen at 7 days. The compressive strength of 28 days aged FC specimens is 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 WMP. 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.

3.4 Splitting tensile strength

The splitting tensile strength test results of 28 days aged FC specimens with varying rates of WMP are plotted in Fig. 12. The results show that when WMP is utilized as a substitution of cement at rates up to 15%, the splitting tensile strength is increased. The FC specimens exhibit splitting strengths of 2.34, 2.09, and 2.16 MPa at WMP 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 are the reason of this improvement in tensile strength-as the components that improved compressive strength would also improve tensile splitting strength. Similar results have been observed by Ashish,^[36] finding that the splitting tensile strength was increased when WMP was utilized as a cement substitution up to 15% in comparison to the control specimen. Splitting tensile strength is shown to decrease by 14.06, 16.51, and 52.45% when utilizing 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 utilization of WMP results in an improvement of the compressive and splitting tensile strength of FC mixtures when cement is replaced with WMP 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 Eq. (1).

$$f_t = \lambda 0.56 \sqrt{f_c} \text{ in MPa} \tag{1}$$

For lightweight concrete, $\lambda = 0.75$. Fig. 13 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 Eq. (2).

$$f_t = \lambda 0.5106 f_c^{0.5646} \text{ in MPa} \tag{2}$$

Fig. 13 also illustrates that the results obtained by Eq. 2 shows a good agreement with the measured results.

3.5 Flexural Strength

Figure 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 is significantly clear relative to the control specimen. At the

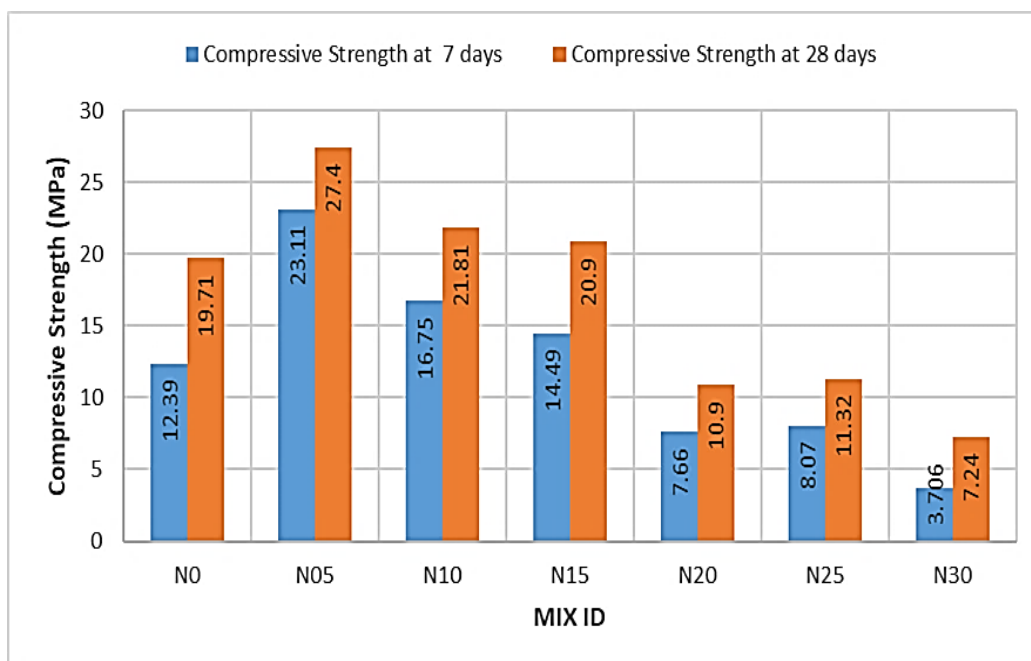


Fig. 10 Measured compressive strength of FC mixtures at 7 and 28 days.

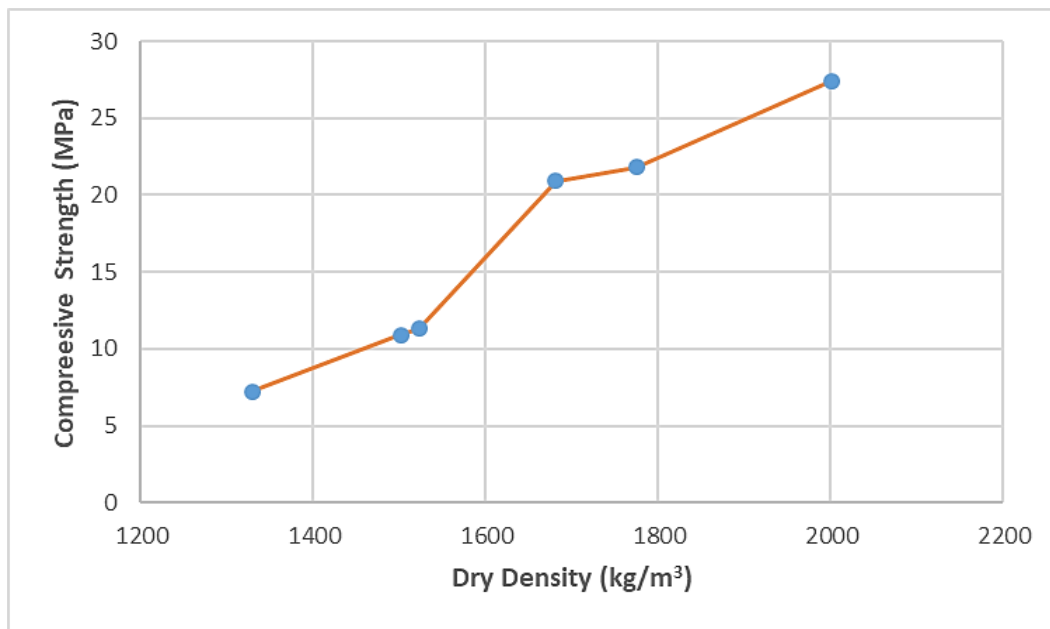


Fig. 11 Variation of compressive strength with dry density at 28 days.

curing ages of 7 and 28 days, the impact of WMP on flexural strength is clearly increased by 31.80 and 26.88%, respectively. As shown in Fig. 14, it is noted that the flexural strength noticeably is increased with an increase in the WMP content up to 10%, but subsequently somewhat decreased with an increase of WMP to 15% compared with the control specimen. At 20, 25, and 30% WMP addition, the flexural strength of the specimen is measured to have significantly decreased in comparison to the control specimen. The flexural strength of 28 days aged FC specimens is 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 that of 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 that of the control specimen, respectively. The ACI 318-14 code equation to calculate the flexural strength of lightweight concrete is as Eq. (3).

$$f_r = \lambda 0.62 \sqrt{f'_c} \text{ in MPa} \tag{3}$$

An equation to predict the flexural strength of FC is also proposed as part of this study as following Eq. (4).

$$f_r = \lambda 0.54 f'_c{}^{0.7121} \text{ in MPa} \tag{4}$$

The results obtained from Eq. 4 make 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

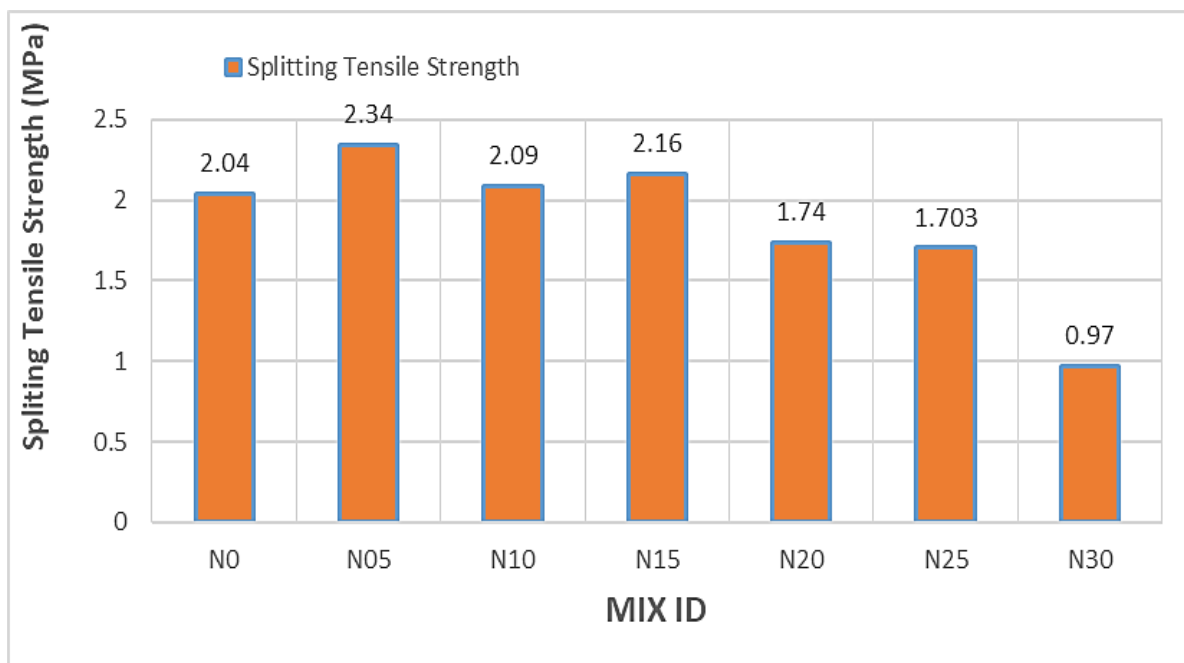


Fig. 12 Measured splitting tensile strength of FC mixtures at 28 days.

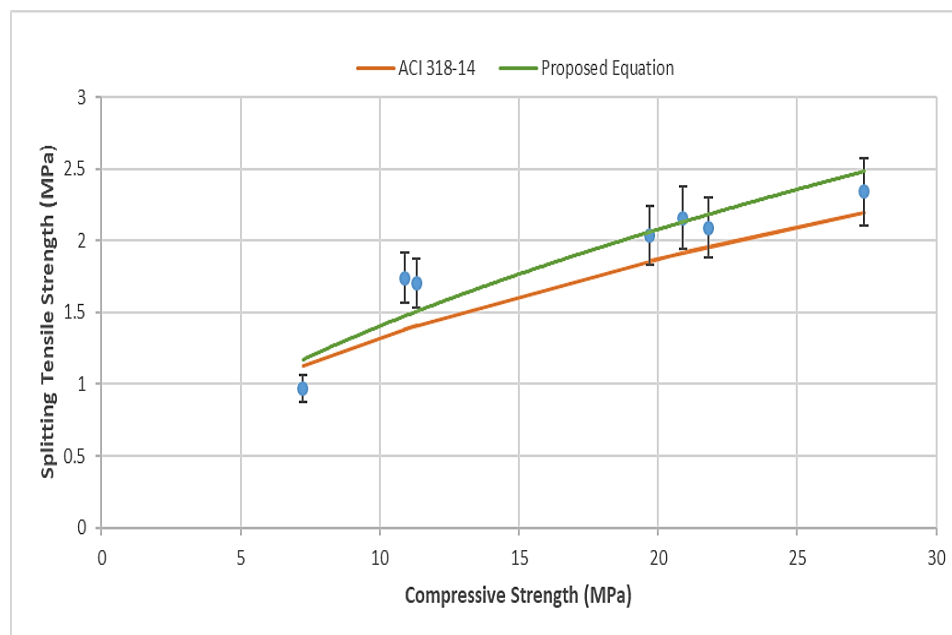


Fig. 13 Measured and calculated splitting tensile strength relative to the corresponding compressive strength of FC mixtures. (The error bar for all values is equal to 10%.)

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 WMP rates, could be explained in the same way as is previously addressed with splitting tensile strength results.

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 bonded water. Evaporation of free water and some of the chemically bound

water leads to dehydration of the FC, and as a result, it may 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.

Figure 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 is dropped as the temperature is increased. The control specimen shows the highest mass loss of 11.64 and 19.17% at 300 °C and 600 °C,

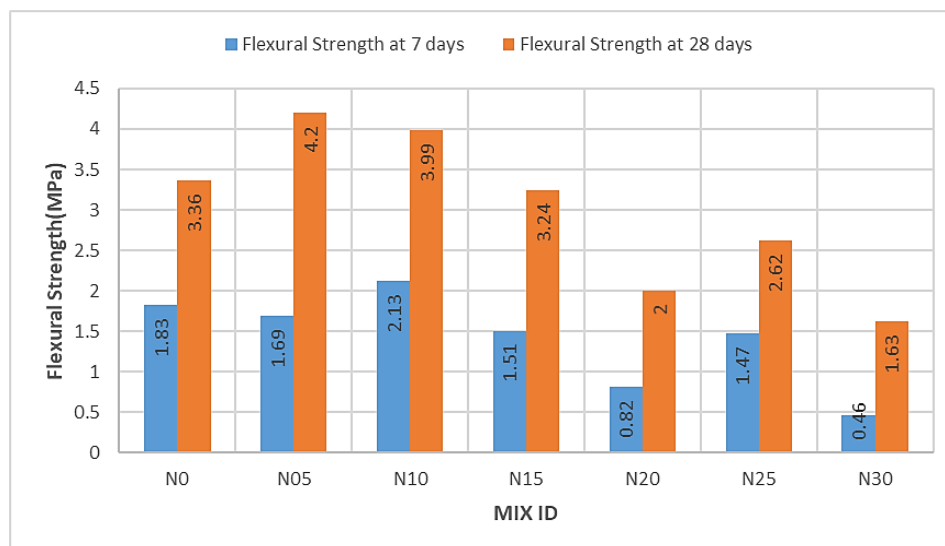


Fig. 14 Measured flexural strength of FC mixtures at 7 and 28 days.

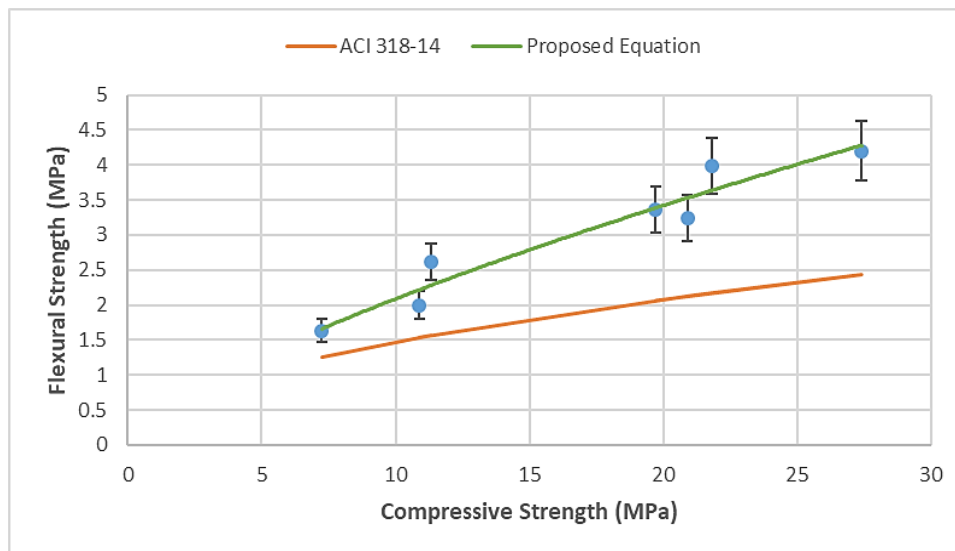


Fig. 15 Measured and calculated flexural strength relative to the corresponding compressive strength of FC mixtures.

respectively. Mass loss decreases proportionally with increasing WMP. The mass loss of specimen of 5% WMP is 10.29 and 14.88% at 300 °C and 600 °C, respectively, which continuously declines as the amount of WMP increases. The lowest mass loss of 7.71 and 12.97% is seen in specimen N30 at 300 °C and 600 °C, respectively.

3.6.2 Compressive strength

Figure 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 is decreased as the temperature is increased relative to the compressive strength at 20 °C. The control specimen shows 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 WMP as a partial cement substitute demonstrate a higher high temperature resistance than that of the control specimen at both 300 °C and

600 °C. The specimens with 5 and 10% WMP content demonstrate the greatest performances when is 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 may lose the adsorbed 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 is 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 is 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 is. Fig. 19 illustrates the relationship between compressive strength and mass loss at 300 °C and 600 °C. It is worth mentioning that the error bar was equal to 10%

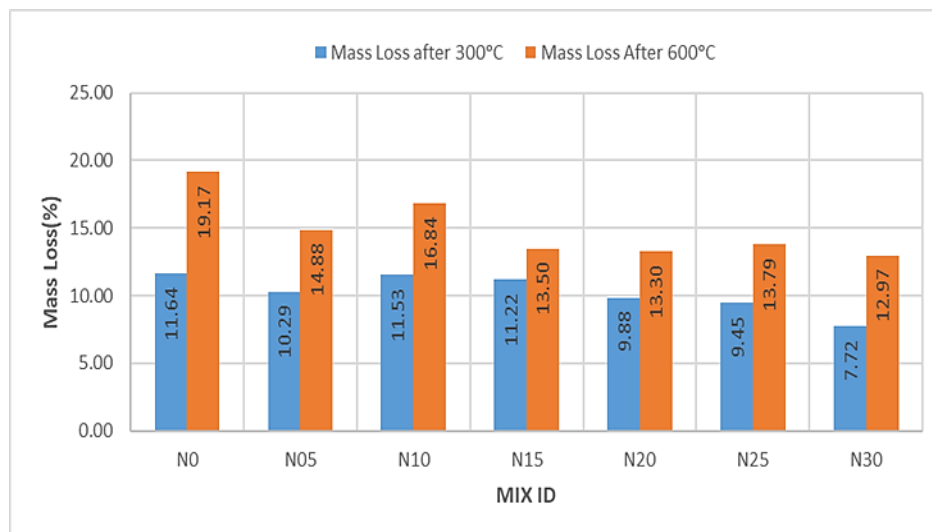


Fig. 16 Mass loss results of FC mixtures at high temperature.

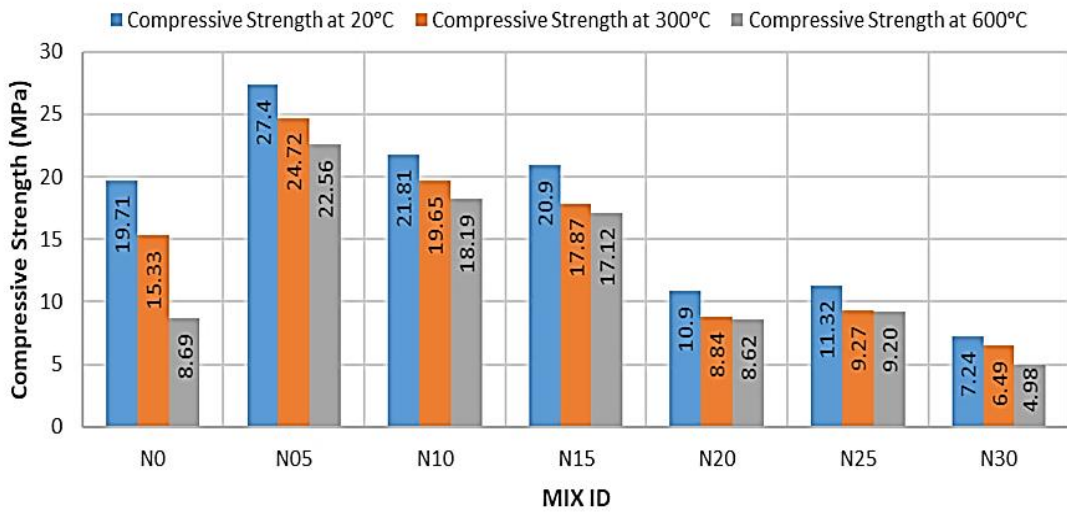


Fig. 17 Measured compressive strength of FC mixtures at high temperature.

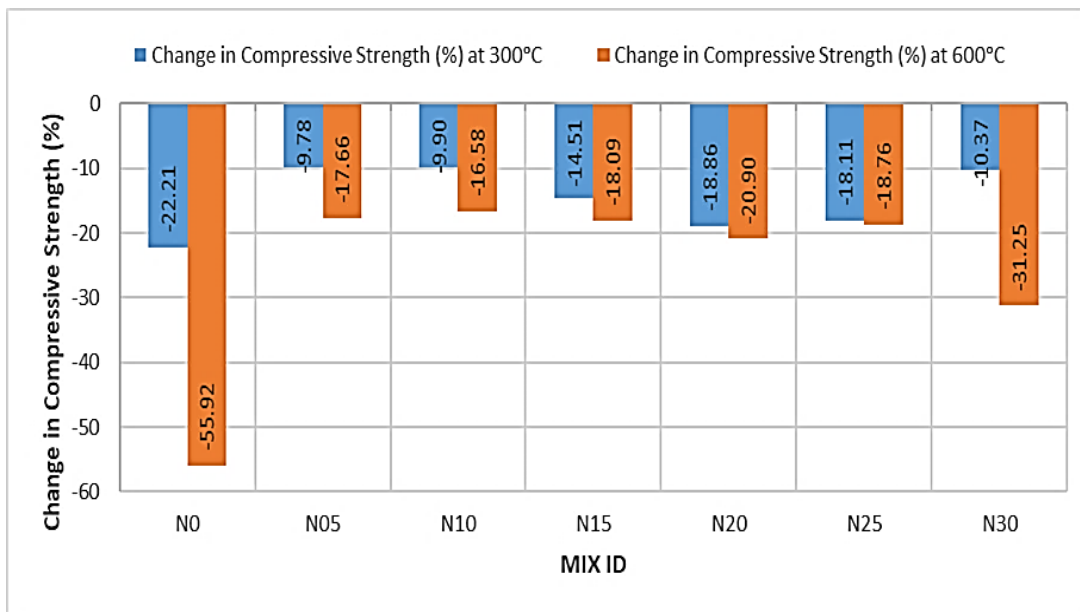


Fig. 18 Compressive strength change of FC mixtures at high temperature.

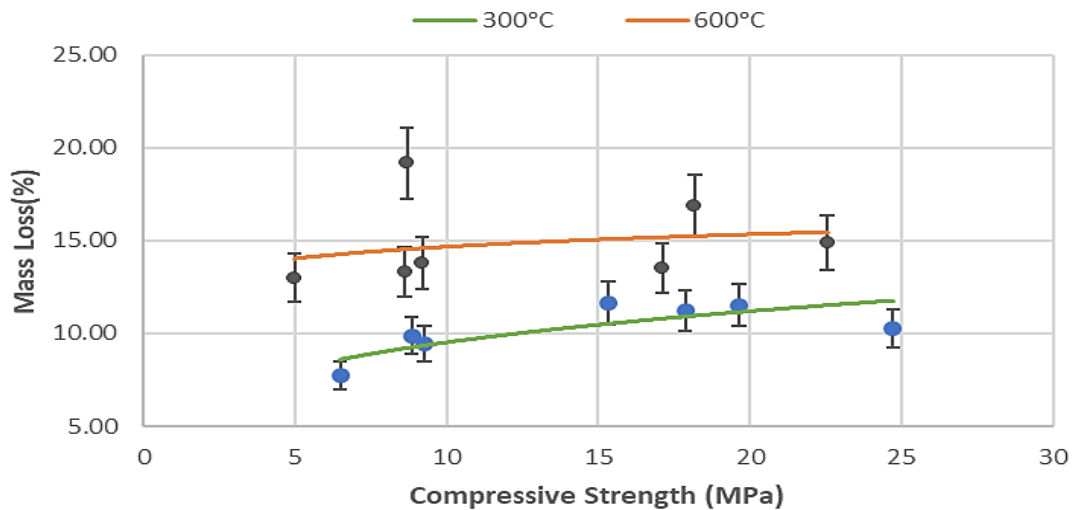


Fig. 19 Mass loss values relative to the corresponding compressive strength of FC mixtures at high temperature.

and all points approximately touched the lines except for one specimen.

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 shows 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 flexural

strength as the WMP content is increasing. For the mixture with 5% WMP, the flexural strength reduction is slightly increased to 21.68 and 33.33% at 300 °C and 600 °C, respectively. All specimens containing different percentages of WMP show almost similar decreases in flexural strength at both temperatures. The specimen with 30% WMP demonstrates 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 flexural 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.

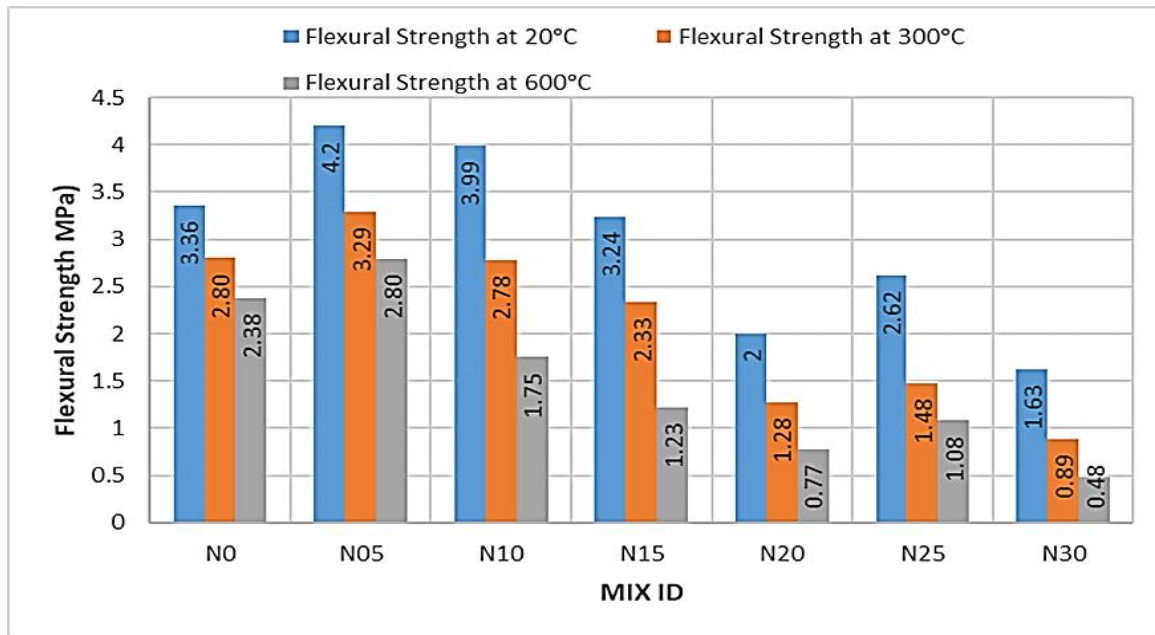


Fig. 20 Measured flexural strength of FC mixtures at high temperature.

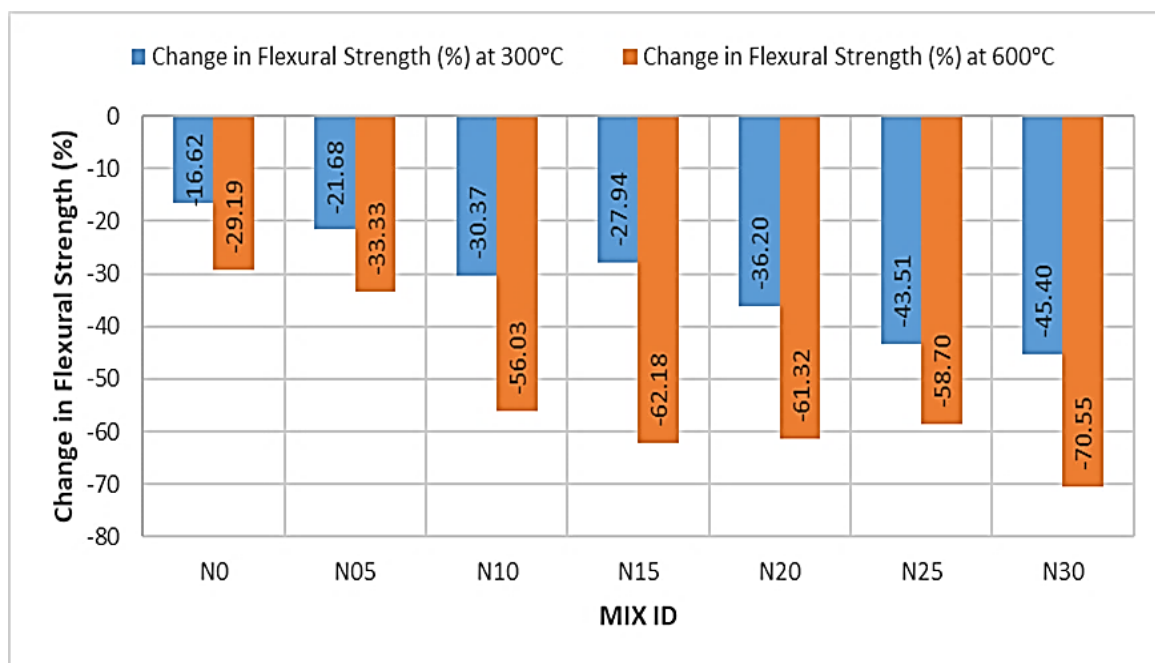


Fig. 21 Flexural strength change of FC mixtures at high temperature.

4. Conclusions

In this investigation, a series of FC mixtures, with varying waste marble Powder (WMP) content, were examined in order to test their workability, wet and dry density, compressive strength, splitting tensile strength, and flexural strength for investigating the influences of WMP utilized 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 WMP as cement substitution affects the workability of the FC mixture, as water requirement increases while the WMP 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 WMP as cement substitution decreases the density of all FC specimens. WMP has a lower specific gravity than cement, so adding WMP to the mixture reduces the density of specimens relative to the control specimen without WMP. The lowest density was gained for the specimen with 30% WMP which was 25.54% lower than the control specimen at 28 days.
- 3) The addition of WMP 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% WMP 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 WMP increases the characteristics of the transition zone (TZ) that surrounds the aggregate.
- 4) The addition of WMP as cement substitution up to 15% would increase the splitting tensile strength of FC specimens. At 28 days, the specimen with 5% WMP 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 WMP on compressive strength is similar to the trend observed in the tensile strength of WMP-containing mixtures.
- 5) The addition of WMP 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% WMP 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 shows 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% is seen in the specimen with 30% WMP content at 300 °C and 600 °C, respectively. Accordingly, it could be concluded that the mass loss reduces as WMP 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 WMP as partial cement substitution reveal a less compressive reduction than the control specimen. The specimen that contained 5% WMP demonstrates the greatest high temperature performance, with a compressive strength decrease of 9.78 and 9.90%, while the control specimen demonstrates 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% WMP 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 utilization of the WMP 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 WMP show satisfactory performance at temperatures of 300°C and 600°C. Furthermore, utilizing WMP as a cement substitute reduces the cement content. Cement is an expensive component, and utilizing WMP 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.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

References

- [1] B. Kado, S. Mohammad, Y. Huei Lee, P. Ngian Shek, M. Aida Ab Kadir, Effect of curing method on properties of lightweight foamed concrete, *International Journal of Engineering & Technology*, 2018, 7, 927, doi: 10.14419/ijet.v7i2.29.14285.
- [2] R. Andrew, Global CO₂ emissions from cement production, *Earth System Science Data*, 2018, doi: 10.5194/essd-2018-90.
- [3] Z. Prošek, V. Nežerka, P. Tesárek, enhancing cementitious pastes with waste marble sludge, *Construction and Building Materials*, 2020, 255, 119372, doi: 10.1016/j.conbuildmat.2020.119372.
- [4] A. Khodabakhshian, J. de Brito, M. Ghalehnavi, E. Asadi Shamsabadi, Mechanical, environmental and economic performance of structural concrete containing silica fume and marble industry waste powder, *Construction and Building Materials*, 2018, 169, 237-251, doi: 10.1016/j.conbuildmat.2018.02.192.
- [5] K. K. Das, E. S. S. Lam, H. H. Tang, Partial replacement of

- cement by ground granulated blast furnace slag and silica fume in two-stage concrete (preplaced aggregate concrete), *Structural Concrete*, 2021, **22**, 466-473, doi: 10.1002/suco.201900494.
- [6] Y. Zhang, D. Chen, Y. Liang, K. Qu, K. Lu, S. Chen, M. Kong, Study on engineering properties of foam concrete containing waste seashell, *Construction and Building Materials*, 2020, **260**, 119896, doi: 10.1016/j.conbuildmat.2020.119896.
- [7] R. Kumar, Partial replacement of cement with marble dust powder, *International Journal of Engineering Research and Applications*, 2015, **5**, 106-114, doi: 10.1016/j.engstruct.2013.11.426.
- [8] A. Ergün, Effects of the usage of diatomite and waste marble powder as partial replacement of cement on the mechanical properties of concrete, *Construction and Building Materials*, 2011, **25**, 806-812, doi: 10.1016/j.conbuildmat.2010.07.002.
- [9] B. Demirel, The effects of waste marble dust applying as a fine sand on the mechanical properties of concrete, *International Journal of Physical Sciences*, 2010, **5**, 259-267, doi: 10.32388/p09nlv.
- [10] E. Tugrul Tunc, Recycling of marble waste: a review based on strength of concrete containing marble waste, *Journal of Environmental Management*, 2019, **231**, 86-97, doi: 10.1016/j.jenvman.2018.10.034.
- [11] A. Yunusa, M. A. Onugba, A. O. Austyns, C. U. Ojih, A. E. Oni, The use of waste marble dust as partial replacement for cement in concrete, *Current Journal of Applied Science and Technology*, 2022, 39-46, doi: 10.9734/cjast/2022/v41i831684.
- [12] S. Firat, J. M. Khatib, G. Yilmaz, A. T. Comert, Effect of curing time on selected properties of soil stabilized with fly ash, marble dust and waste sand for road sub-base materials, *Waste Management & Research*, 2017, **35**, 747-756, doi: 10.1177/0734242x17705726.
- [13] F. Gameiro, J. de Brito, D. Correia da Silva, Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry, *Engineering Structures*, 2014, **59**, 654-662, doi: 10.1016/j.engstruct.2013.11.026.
- [14] K. Vardhan, R. Siddique, S. Goyal, Influence of marble waste as partial replacement of fine aggregates on strength and drying shrinkage of concrete, *Construction and Building Materials*, 2019, **228**, 116730, doi: 10.1016/j.conbuildmat.2019.116730.
- [15] M. Singh, P. Lamba, A. Srivastava, D. Bhunia, Long Term Effect of Partially Replacing Cement by Waste Marble Slurry in Concrete Congress on Technical Advancement 2017. Duluth, Minnesota. Reston, VA: American Society of Civil Engineers, 2017, **7**, 65-76, doi: 10.1061/9780784481035.007.
- [16] A. Tiwari, S. Singh, R. Nagar, Comparative assessment of effects of sand & cement replacement in concrete by marble dust & in turn deriving an optimum design mix for concrete paver blocks, *Conference: Global Stone Technology Forum*, 2015, 17-18.
- [17] R. Bansal, R. Bansal, Partial replacement of cement with waste marble powder with m25 grade, *International Journal of Technical Research and Applications*, 2015, **3**, 202-205, doi: 10.22214/ijraset.2019.4079.
- [18] A. Talah, F. Kharchi, R. Chaid, Influence of marble powder on high performance concrete behavior, *Procedia Engineering*, 2015, **114**, 685-690, doi: 10.1016/j.proeng.2015.08.010.
- [19] A. Rana, P. Kalla, L. J. Csetenyi, Sustainable use of marble slurry in concrete, *Journal of Cleaner Production*, 2015, **94**, 304-311, doi: 10.1016/j.jclepro.2015.01.053.
- [20] F. Memon, A. Yousfani, D. Ladher, N. Jarwar, Effect of marble dust as a partial replacement of cement on fresh and hardened properties of concrete, *Conference: International Conference on Sustainable Development in Civil Engineering*, 2017, **2**, 16-20.
- [21] S. Zhang, K. Cao, C. Wang, X. Wang, J. Wang, B. Sun, Effect of silica fume and waste marble powder on the mechanical and durability properties of cellular concrete, *Construction and Building Materials*, 2020, **241**, 117980, doi: 10.1016/j.conbuildmat.2019.117980.
- [22] ACI 213R-14; Guide for Structural Lightweight-Aggregate Concrete. *American Concrete Institute (ACI): Farmington Hills, MI, USA*, 2014.
- [23] R. Allouzi, A. Qatawna, T. Al-Kasasbeh, Lightweight foamed concrete mixture for structural use, *Materials*, 2020, **117**, 99-109, doi: 10.14359/51722405.
- [24] ASTM Standard C494; Specification for Chemical Admixtures for Concrete. *ASTM International: West Conshohocken, PA, USA*, 2017.
- [25] ASTM Standard C144.; Standard Specification for Aggregate for Masonry Mortar. *ASTM International: West Conshohocken, PA, USA*, 2018.
- [26] BS EN 1008:2002; Mixing Water for Concrete. Specification for Sampling, Testing and Assessing the Suitability of Water, Including Water Recovered from Processes in the Concrete Industry, as Mixing Water for Concrete. *British Standards Institute: London, UK*, 2002.
- [27] ASTM Standard C495; Standard Test Method for Compressive Strength of Lightweight Insulating Concrete. *ASTM International: West Conshohocken, PA, USA*, 2009.
- [28] ASTM Standard C1437; Standard Test Method for Flow of Hydraulic Cement Mortar. *ASTM International: West Conshohocken, PA, USA*, 2007.
- [29] ASTM Standard C642; Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. *ASTM International: West Conshohocken, PA, USA*, 2022.
- [30] BS EN 12390-3; Testing hardened concrete - Compressive strength of test specimens. *British Standards Institute: London, UK*, 2019.
- [31] ASTM Standard C496/C496M; Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. *ASTM International: West Conshohocken, PA, USA*, 2017.
- [32] ASTM C 78; Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). *ASTM International: West Conshohocken, PA, USA*, 2002.
- [33] BS EN 1881-118; Testing Concrete - Method for Determination of Flexural Strength. *British Standards Institute: London, UK*, 1983.

- [34] A. O. Mashaly, B. A. El-Kaliouby, B. N. Shalaby, A. M. El-Gohary, M. A. Rashwan, Effects of marble sludge incorporation on the properties of cement composites and concrete paving blocks, *Journal of Cleaner Production*, 2016, **112**, 731-741, doi: 10.1016/j.jclepro.2015.07.023.
- [35] İ. B. Topçu, T. Bilir, T. Uygunoğlu, Effect of waste marble dust content as filler on properties of self-compacting concrete, *Construction and Building Materials*, 2009, **23**, 1947-1953, doi: 10.1016/j.conbuildmat.2008.09.007.
- [36] D. Kumar, Ashish, Feasibility of waste marble powder in concrete as partial substitution of cement and sand amalgam for sustainable growth, *Journal of Building Engineering*, 2018, **15**, 236-242, doi: 10.1016/j.job.2017.11.024.
- [37] O. Gencel, C. Ozel, F. Koksall, E. Erdogmus, G. Martínez-Barrera, W. Brostow, Properties of concrete paving blocks made with waste marble, *Journal of Cleaner Production*, 2012, **21**, 62-70, doi: 10.1016/j.jclepro.2011.08.023.
- [38] R. Rodrigues, J. de Brito, M. Sardinha, Mechanical properties of structural concrete containing very fine aggregates from marble cutting sludge, *Construction and Building Materials*, 2015, **77**, 349-356, doi: 10.1016/j.conbuildmat.2014.12.104.
- [39] A. A. Aliabdo, A. Elmoaty M Abd Elmoaty, E. M. Auda, reuse of waste marble dust in the production of cement and concrete, *Construction and Building Materials*, 2014, **50**, 28-41, doi: 10.1016/j.conbuildmat.2013.09.005.
- [40] A. Shirule, A. Rahman, D. Rakesh, Partial replacement of cement with marble dust powder, *International Journal of Advanced Engineering Research and Studies*, 2012, **3**, 175-177, doi:10.22214/ijraset.2017.10359.
- [41] M. R. Jones, A. McCarthy, Preliminary views on the potential of foamed concrete as a structural material, *Magazine of Concrete Research*, 2005, **57**, 21-31, doi: 10.1680/mac.2005.57.1.21.
- [42] E. K. K. Nambiar, K. Ramamurthy, Influence of filler type on the properties of foam concrete, *Cement and Concrete Composites*, 2006, **28**, 475-480, doi: 10.1016/j.cemconcomp.2005.12.001.
- [43] H. F. W. Taylor, *Cement Chemistry*, 3rd ed.; Academic Press, London, 1991, 322-322, doi: 10.1002/nadc.19910390317
- [44] M. A. O. Mydin, Y. C. Wang, Mechanical properties of foamed concrete exposed to high temperatures, *Construction and Building Materials*, 2012, **26**, 638-654, doi: 10.1016/j.conbuildmat.2011.06.067.
- [45] H. Y. Wang, The effects of elevated temperature on cement paste containing GGBFS, *Cement and Concrete Composites*, 2008, **30**, 992-999, doi: 10.1016/j.cemconcomp.2007.12.003.

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