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Effect of fly ash and waste glass powder as a fractional substitute on the performance of natural fibers reinforced concrete

Fadi Althoey [a], Osama Zaid [b,*], Ali Majdi [c], Fahad Alsharari [d], Saleh Alsulamy [e], Mohamed M. Arbili [f]

[a] Department of Civil Engineering, College of Engineering, Najran University, Najran, Saudi Arabia
[b] Department of Civil Engineering, Swedish College of Engineering and Technology, 47070 Wah Cantt, Pakistan
[c] Department of Buildings and Construction Techniques Engineering, Al-Mustaqbal University College, 51001 Hillah, Babylon, Iraq
[d] Civil Engineering Department, Jouf University, Sakaka, Jouf 72388, Saudi Arabia
[e] Department of Architecture and Planning, College of Engineering, King Khalid University, Abha 61421, Saudi Arabia
[f] Department of Technical Civil Engineering, Erbil Technical Engineering College, Erbil Polytechnic University, 44001 Erbil, Iraq

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A B S T R A C T

Stockpiling and landfilling of waste glass (WG) is becoming a severe environmental issue around the World as hundreds of tons of WG are dumped on the land. The present research assesses the behavior of WG in a concrete mixture as a partial replacement of sand to attain the optimal percentage of waste glass. Due to the production of ordinary Portland cement (OPC), the natural reserves of limestone are depleting fast, and the production of OPC also leads to a high proportion of carbon dioxide (CO_2), so it is essential to utilize industrial by-products such as fly ash (FA) to replace cement partially. In the current study, the WG is used as a fractional substitute of sand in different proportions (14 %, 15 %, 16 %, 17 %, 18 %, 19 %, 20 %), with 20 % FA as a replacement for OPC, with 2.5 % coconut fibers (CFs) to improve the flexural strength of concrete. Engineering properties such as compressive and flexural strength, water permeability, sorptivity, density, voids ratio, resistance against fire, Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD) spectra were assessed. The outcomes showed that the M4 mixture (WG16-FA20-CFs2.5) had the utmost optimal performance, as 15.8 % and 9.57 % compression strength and flexural strength were improved at the curing of 90 days. During exposure of samples to fire, concrete with 16 % WG lost only 38.7 %, 44.2 % mass and compressive strength at 600 °C, which was the most lowered among other mixtures. Because of the utilization of FA, the concrete's matrix gets denser, leading to improved water-related characteristics of concrete. It was observed that adding more than 16 %, WG led to reduced strength and durability properties of concrete. The current research confirmed that the 16 % WG, 20 % FA, and 2.5 % CFs could be replaced in concrete to produce improved, eco-friendly concrete.

1. Introduction

Using waste materials in construction is becoming increasingly popular to reduce the environmental impact of buildings and use materials that would otherwise go to waste [1,2]. Discarding solid waste materials in forests and cultivable lands has led to a massive proportion of land pollution and other environmental harms [3–5]. One such material that has been gaining attention in recent years is waste glass powder (WGP), which can replace fine aggregate and ordinary Portland cement (OPC) in concrete [6,7]. The percentage of waste glass developed yearly has increased around the globe in recent times [8]. Presently, mostly the waste glass is discarded in landfills in the US (a higher rate among other developed nations), and nearly 97.3 % of discarded glass is dumped in a landfill in Hong Kong [9,10]. In 2018, 135 million tons of discarded glass were produced, of which only 22 % was reutilized or recycled [11]. If the discarded glass isn't appropriately reprocessed for reuse, it becomes a severe environmental issue. To resolve this improper discarding, various procedures have been used to dump

* Corresponding author.
E-mail address: Osama.zaid@scetwah.edu.pk (O. Zaid).

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waste glass (WG) [12] safely. One such method is used by Ibrahim et al. and revealed the potential approach towards using waste glass from broken domestic windows to replace crushed stone aggregates in the concrete mixtures. Szelag et al. [12] also showed an optimistic result by utilizing discarded waste glass from car vehicles as a fractional substitute for aggregates to develop concrete [13,14]. Also, in past studies, waste glass was utilized in developing polymer-based concrete. In their research, Zhang et al. [15] showed that waste glass is equally suitable for different cementitious composites (conventional or polymer-based concrete). This signified that the concrete and construction sector could reduce carbon dioxide outflow and be eco-friendlier [16,17]. As glass is primarily composed of silica (SiO_2), it could be utilized as a fine aggregate (sand) in concrete development. The methods mentioned earlier aim to significantly enhance the amount of utilization of waste glass, which as a result, would lower the atmospheric problems related to landfilling [18,19]. Zhang et al. [20] demonstrated the behavior of concrete by adding a waste glass (WG) of 75 μm to 4.75 mm and 10 mm as a replacement for aggregates. The authors noted a promising result regarding strength and durability characteristics to 20 % substitution [21,22]. When the particle size of WG was lowered by 2 mm, the compressive strength was observed to be enhanced at a 20 % substitution percentage; the enhancement in the compression strength was primarily related to the pozzolanic behavior of WG. Borhan et al. [23] observed lower compression strength at 50 and 100 % replacement ratios. Authors in other studies also observed a reduction in the strength properties of concrete mixtures at a replacement ratio of 7.5 %, 15, and 22.5 % [24–26]. Here, the decline in the mechanical characteristics was generally concerned with the kind, nature and size of waste glass (WG) utilized in these researches [27,28]. The authors in a study also observed that the shape of the WG has a significant influence on the characteristics of concrete as smooth textured particles tend to have good workability, but it has low strength compared to rough textured waste glass particles [11,29].

As observed from the above literature, the implications obtained from the alkali-silica reaction (ASR) also offered to contradict results when WG was utilized in the concrete mixtures [30]. Shao et al. [31] replaced fine aggregates with 30 % waste glass (145 μm – 5 μm) and noticed that as the size of WG was reduced, the impact of ASR was diminished. Xie et al. [32] observed high alkali-silica reaction expansion when 10 % natural fine aggregates are replaced with waste glass (greater than291 μm) in the mixtures as compared to (<291 μm) particles of waste glass. Hussein et al. [33] also observed a rise in ASR reaction when a WG of 100 μm substituted fine aggregates from the river bed at replacements of 25 % and 65 %. Gnappi et al. [34] also observed the same variation by substituting blended colored waste glass (4.7 to 2.4 mm) with 100 % fine aggregates from the riverbed. Opposing the above observations, Du et al. [15] noted a rise in alkali-silica reaction when waste glass's size (0.12 to 2.32 mm) increased with the substitution level of 24 %.

Currently, eco-friendly high-strength concrete for structural purposes [35,36] is being developed worldwide by utilizing supplementary cementitious materials (SCMs), for instance, granulated blast furnace slag (GBFS), wheat straw ash (WSA), fly ash (FA), and silica fume (SF) etc. [37,38]. Using SCMs, concrete with excellent strength and durability can be achieved [39,40]. Fly ash, a byproduct of coal-fired power plants, is rich in silica and alumina and could substitute up to 30 % of OPC in concrete [39,41]. This replacement reduces energy consumption and greenhouse gas emissions during cement production and improves concrete workability, strength, and durability [42]. In the last two decades, fly ash in the construction section has been significantly amplified. The use of fly ash in concrete has also been found to reduce the permeability of concrete and improve its long-term durability, making it more resistant to aggressive environmental conditions [43]. It has been observed from past studies [44–46] that replacing 20 % fly ash with the OPC has the most optimal influence on the mechanical and physical characteristics of concrete. Pitroda et al. [47] considered different levels of FA for the mechanical characteristics of concrete. The FA was replaced by 10 %, 20 %, 30 %, and 40 % with the OPC by weight. The authors noted that 20 % FA led to enhanced characteristics of concrete than conventional concrete [48]. After 20 % FA, the strength characteristics were lowered by increasing the level of fly ash.

Natural fibers, produced from plants such as wood and leaves and geological processes, are often used to replace steel or synthetic fibers in concrete to improve mechanical, physical and durability performance [49,50]. Bio-based natural fibers comprise jute [51], hemp, sisal, sugar cane, cannabis, bamboo, coconut, and banana [52]. These fibers are favored due to their low cost and availability. Additionally, they are easy to handle in a concrete mixture and can reduce project costs [53]. Coconut fiber is a natural, renewable, and biodegradable material that can provide excellent reinforcement for concrete. Using coconut fibers (CFs) reinforcement in concrete can improve its mechanical properties, such as its tensile strength and flexibility [53,54]. Additionally, using coconut fiber reinforcement could also augment the durability of concrete, making it more resistant to cracking and other forms of damage [55,56]. CFs have the maximum strength among natural fibers, averaging 22 MPa, and have been studied for various applications [57]. Adding just 2 % of coconut fibers to silica fume-modified concrete has been shown to improve flexural strength by 28 %. Researchers are currently focusing on creating concrete employing industrial by-products as a filler and incorporating synthetic and natural fibers. It has also been observed that 2 % coconut fibers can increase flexural strength by 24 % after two weeks of curing [58]. The durability of concrete materials is a significant concern as they are subjected to harsh surroundings throughout their service life [59,60]. Which is a result, it is essential to progress long-lasting concrete that is both strong and cost-effective. Research has shown that the water absorption with WG rises as the amount of WG used in the sample rises. This is due to the high porosity of WG, which affects the permeability of concrete. When the sand was replaced with WG in increments of 25 % up to 100 %, researchers noted that the water permeability of concrete raised as the percentage of WG was raised [29,61]. Similar results were found when WG was introduced to mortar, increasing water permeability [34,62,63].

Previous research has demonstrated the suitability of using discarded glass to replace sand in concrete blends at different levels. The literature review has illustrated that incorporating WG into cement composites as a substitute for fine aggregate has led to improvements in concrete mechanical performance in the range of 10 %-25 %. To achieve improved performance, this study was conducted to determine the optimal substitution ratio (14 %, 15 %, 16 %, 17 %, 18 %, 19 %, and 20 %). The waste glass' particle size gradation employed in this study was chosen based on previous research [64–66], where a waste glass of this size was found to act a vital part in enhancing the behavior of concrete.

Research Significance:

Based on the literature review, there is no clear conclusion about the influence of different proportions of waste glass on the strength and durability characteristics of fly ash-modified coconut fiber-reinforced concrete. The current research aims to determine the optimum substitution ratio of riverbed sand with waste glass (14 %, 15 %, 16 %, 17 %, 18 %, 19 %, and 20 %) while incorporating 20 % fly ash as an OPC replacement and 2.5 % coconut fibers by binder's weight. The authors are aware of the limited research that has thoroughly studied the properties of coconut fiber concrete using an optimal amount of WG as sand with the addition of fly ash. Coconut fibers were chosen among other plant-based fibers because of their high toughness. While waste glass and fly ash have been studied separately, there has been no research on the combination of fly ash and waste glass in natural (coconut) fiber reinforced concrete. The research includes experiments to determine the compressive and flexural strength, density, water absorption, workability, water permeability, fire resistance and sorptivity with a water-to-cement ratio of "0.5″ selected. XRD spectra and FTIR spectroscopy tests were also conducted to analyze the concrete's bond orientation and phase analysis.

2. Materials

2.1. Cement (OPC):

The present study used general-purpose type I ordinary Portland cement per ASTM C150 [28]. The physical characteristics and chemical arrangement of OPC are displayed in Table 1.

2.2. Coconut natural fibers (CFs):

The researchers sourced their coconut fibers (CFs) from a local vendor in Punjab. The study utilized treated coconut fibers, as displayed in Fig. 1. To strengthen the bond between the concrete's matrix and CFs, the CFs were washed with water for 15 min to eliminate dust and other elements. To make the CFs straight, they were combed with a steel comb. After that, the CFs were placed in an oven at 40 °C for eight mins to dry them up and cut to a size of 20–25 mm with a diameter range of 0.15 to 0.25 mm [55]. The treated CFs had a specific gravity of 1.19 and a water absorption rate of 0.31 %. The use of treated CFs will improve the reinforcement binding in concrete, ultimately leading to increased strength.

Table 1
Physical characteristics and chemical arrangement of OPC.

Physical Characteristics	Results	Chemical Arrangement	Percentage
Particle Size	≤ 45 µm	SiO_2	26.9 (%)
Normal consistency	28 %	MgO	2.3 (%)
Fineness	93 %	SO_3	1.9 (%)
Initial setting time	37 mins	CaO	59.7 (%)
Final setting time	465 mins	Fe_2O_3	2.7 (%)
Specific surface	323 m^2/kg	Al_2O_3	5.2 (%)
28 Days Compressive Strength	40 MPa	K_2O	0.4 (%)
Soundness	1.30 %	Na_2O	0.9 (%)

2.3. Fly ash and waste glass:

In the present research, class F (low Ca) fly ash was adopted for use per ASTM C618 [67]. The fly ash in the dark grey color, as presented in Fig. 2a, was procured from a local supplier in Punjab. XRD analysis (see Fig. 2b) was performed to evaluate the chemical arrangement of fly ash (see Table 2). From XRD analysis, high peaks of alumina and silica were observed in the fly ash. Waste glass (see Fig. 3a) was obtained by crushing beverage bottles of a similar color, resulting in glass powder. The powder was then screened through a 650-µm sieve, and the material retained on a 150-µm sieve was used for further analysis. XRD spectra (see Fig. 3b) were performed on the waste glass to determine its crystalline structure, as seen in Figure 3 (b). This analysis showed that the waste glass powder mainly consisted of quartz (SiO_2), making it suitable for use as fine aggregates, as demonstrated in Table 2.

2.4. Fine and coarse aggregates:

In the present study, the researchers utilized the conventional fine aggregates from the river bed of the Swat river. Also, the researchers used crushed dolomite stone as a coarse aggregate from the Cherat stone quarry. Gradation of fine and coarse aggregates and waste glass is provided in Fig. 4 (a and b). The characteristics of coarse and fine aggregates are displayed in Table 3.

3. Mix designs

The present research prepared the concrete mixtures following *ACI* 221.1 [68]. OPC was substituted with the 20 % fly ash, and 2.5 % CFs (by wt.) was added to the modified mixtures. The fine aggregates were substituted with the WG (by wt.) at different levels (from 14 % to 20 % at 1 % intervals), with the same w/b of 0.50 for all mixtures. The complete details of all the combinations are presented in Table 4. The terminology for all the mixes is planned so that the numeral after the "WG" represents the quantity of WGP as a fractional substitute of fine aggregates, and the numeral after the "CFs" denotes the number of natural coconut fibers. Lastly, the numeral after the word "FA" depicts the quantity of fly ash as a fractional replacement of OPC.

4. Development of concrete specimens and test characterization

The present study used a mechanical mixer with 25 rpm to make fresh concrete. Firstly, OPC, sand, and coarse aggregates were introduced to the mixer and blended for 3 mins, and then 50 % water was included and mixed for 2 mins. Then WG, FA and CFs

Fig. 1. Physical appearance of CFs.

Fig. 2a. Physical appearance of Class F Fly Ash.

were added to the mixer and blended for 4 mins. The freshly mixed concrete was introduced into uniform-size molds into 3 layers, and every layer was tamped with a rod 25 times when the mold was filled with the concrete. The mold was wrapped with polythene sheets to mitigate the moisture coming into contact with the mold. Lastly, after 24 hrs., the samples were removed from the molds and placed in a plastic water tank for curing at room temperature.

ASTM C143 [69] was followed to assess the fresh characteristics of concrete mixtures. For the strength behavior of concrete, for instance, compression strength, 300 mm × 150 mm cylinders were arranged and tried at 7, 28 and 90 days per ASTM C39 [70]. For the flexural behavior of concrete, concrete beams of 600 mm × 150 mm × 150 mm were arranged and tried at the curing of 28 and 90 days per ASTM C78 [71] using a universal testing machine (UTM). ASTM C642 was followed to evaluate permeability, water absorption, and void ratio and concrete cubes of 100 mm were used. During the permeability assessment, a sustained water pressure of 0.65 N/mm^2 was used for the samples for 48 hrs. Water penetration was evaluated after the 48 hrs. water depth. ASTM C1585 was followed to assess the sorptivity of concrete at 28 days using 100 mm discs. In the concrete specimens, a variation in the water capillary was noted for one week regarding the change in the sample's weight. To assess the performance of waste glass concrete against elevated temperature, ISO 834 [72] was followed. This test was performed on concrete specimens cured at 90 days, and the specimens were subjected to fire from 150 °C to 600 °C at the interval of 150 °C. The change in mass loss (%) and the residual compressive strength of the waste glass concrete due to the fire test were assessed. The cube size samples of 150 mm × 150 mm were employed for this test. The electric plus gas fire furnace chamber was used for this test.

Three samples for every mixture ID were tested to maintain uniformity in research results, and their average value was considered the concluding value.

5. Results and discussion

5.1. Workability

In the present research, introducing a superplasticizer was to maintain the required slump values for fresh concrete. The test result for the workability procedure is presented in Fig. 5. From Fig. 5, it could be observed that as the quantity of waste glass increased, the workability tended to reduce with it, which can also be observed from Table 4 as more superplasticizer was required with rising waste glass in the samples. The decline in workability could be ascribed to the sharp angular texture of the WG. Taha et al. [73] noted a lessening in the slump of freshly mixed concrete when they used WG (<5mm) as a partial replacement of fine aggregates. Park et al. [74] also observed almost the same concrete performance when the authors used up to 70 % of waste to replace fine aggregates. In another study [75], the researchers noted an increase in the workability values when they used WG; this could be ascribed to the smooth, rounded shape and low water absorption of waste glass. The reduction in the workability of concrete could also be attributed to the large surface area and high-water absorption of coconut fibers, which can result in lower workability; hence, a superplasticizer is necessary.

5.2. Compressive strength

The concrete's compressive strength with the presence and absence of WG is presented in Fig. 6a. From Fig. 6a, it could be noted that as the proportion of WG was raised from 14 % to 16 % in the mixtures, the compressive strength was noted to rise to 9.8 %, 12.6 %, and 15.8 % in the control mixtures in which the M4 mixture had the highest compressive strength at curing of 7, 28, and 90 days. The enhancement in the concrete's compression could be attributed to the fine size and enhanced hydration of the

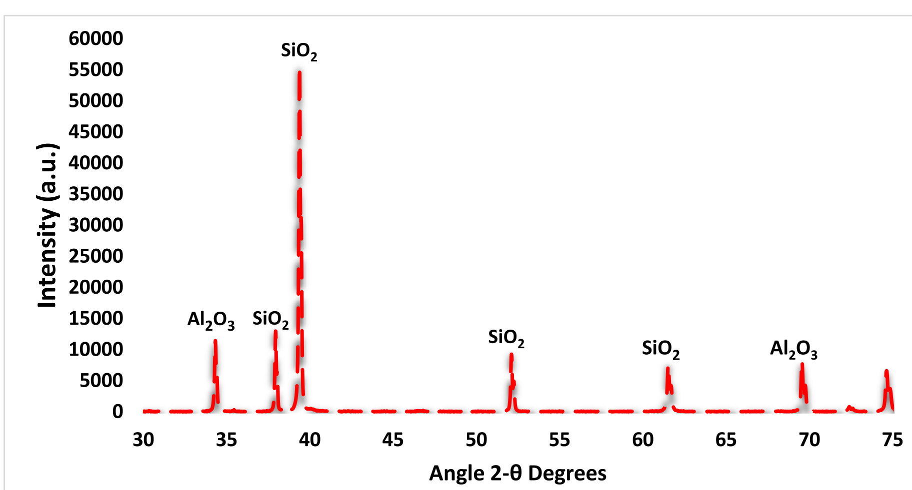

Fig. 2b. XRD spectra of FA.

Table 2
Chemical Arrangement of Fly Ash and Waste Glass.

Chemical Arrangement	Fly Ash (%)	Waste-Glass (%)
MgO	2.3	1.55
SO_3	0.2	0.4
Al_2O_3	26.8	3.42
Fe_2O_3	7.3	2.60
K_2O	1.5	0.79
CaO	3.1	11.59
SiO_2	58.7	70.09
Na_2O	0.1	9.56

Fig. 3a. Physical appearance of Waste Glass.

mixture because of the presence of fly ash which offers a filling effect in the matrix. The enhancements in the compression strength at 14 % to 16 % of waste glass could also be ascribed to the pozzolanic nature of waste glass and FA, as observed by other researchers [76,77]. The pozzolanic reaction amid SiO_2, which is present in the waste glass, fly ash, and Ca $(OH)_2$, which exists in the OPC, instigates the development of a dense gel of calcium-silica-hydrate, which results in enhanced compression strength. This could be credited to the introduction of fly ash reducing the density of impervious pores in the matrix, which ultimately augments the concrete's compression strength. The rise in the compression strength could be due to the dense microstructure of the sample's matrix at the ITZ level. An identical research was conducted by the researchers [78] and noted that for 16 % substitution of fine aggregates with a waste glass of 3.5 mm to 195 µm. The researchers noted the improvement in the strength was due to the pozzolanic nature of waste glass, which improved their concrete compression strength by 6.4 % more than the control mixture. In another research, the researchers used fly ash to replace OPC. They noted that due to the introduction of FA, the concrete's microstructure gets dense, leading to improvements in the compression strength of the concrete.

With the inclusion of 17 % waste glass (M5 mixture), the compressive strength was reduced by 1.04 %, 1.26 % and 1.14 % than the M4 mixture, but the compressive strength of the M5 mixture was still higher at all curing levels. Fig. 6a also shows that by introducing 20 % WG in the M8 mixture, the compressive strength of concrete was reduced by 9.9 %, 13.1 %, and 16.49 % than the control sample at 7, 28, and 90 days. The decrease in the strength behavior of concrete can be credited to the reason when the percentage of WG gets higher than 16 %. Some irregular and smooth surface texture of waste glass also enters the concrete matrix, averts the positive impacts of the WG to perform in the matrix, such as WG's pozzolanic behavior and filling capability. In another research, it was noted when more than 18 % WG was added as a substitute for fine aggregates in self-compacting concrete, the compressive strength gets reduced significantly [66]. This lowers the adhesive characteristics of the WG between the binder's paste and the matrix. The lessening in the compression strength is also attributed to the development of voids, which could have formed owing to the finer size of the WG.

Fig. 6b shows that the void ratio increases with the WG's content. Up to 16 % of WG, the filling effect of WG is taking place effectively, and adding WG of more than 16 % resulted in the development of voids. In the present research, the M4 mixture (WG16-FA20-CFs2.5), due to the improved pore filling and pozzolanic behavior of WG and FA, effectively hydrating the matrix render the M4 mixture to be the optimal mix among others.

5.3. Flexural Strength:

The influence of waste glass and FA on coconut fibres reinforced concrete's flexural strength (FS) is presented in Fig. 7a. In the M4 mixture (WG16-FA20-CFs2.5), the flexural strength was improved by 7.73 % and 9.57 % at the curing of 28 and 90 days. Improvement

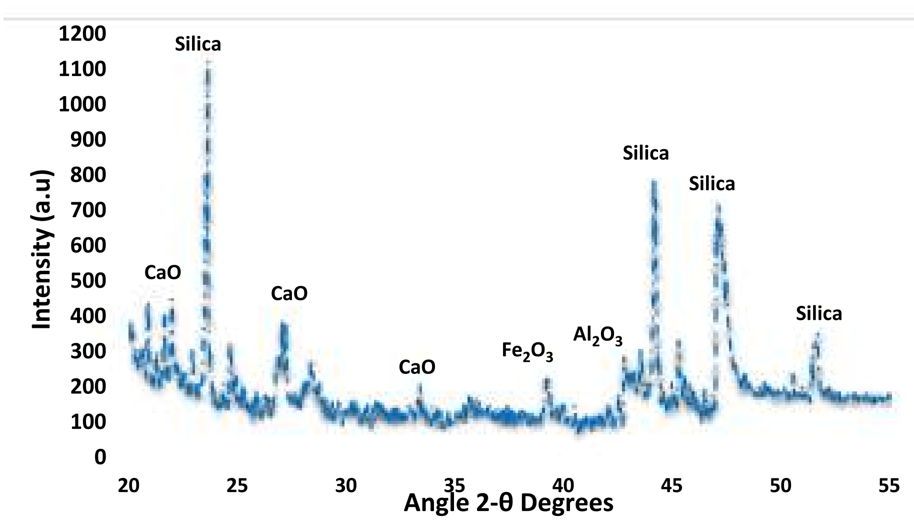

Fig. 3b. XRD spectra of WG.

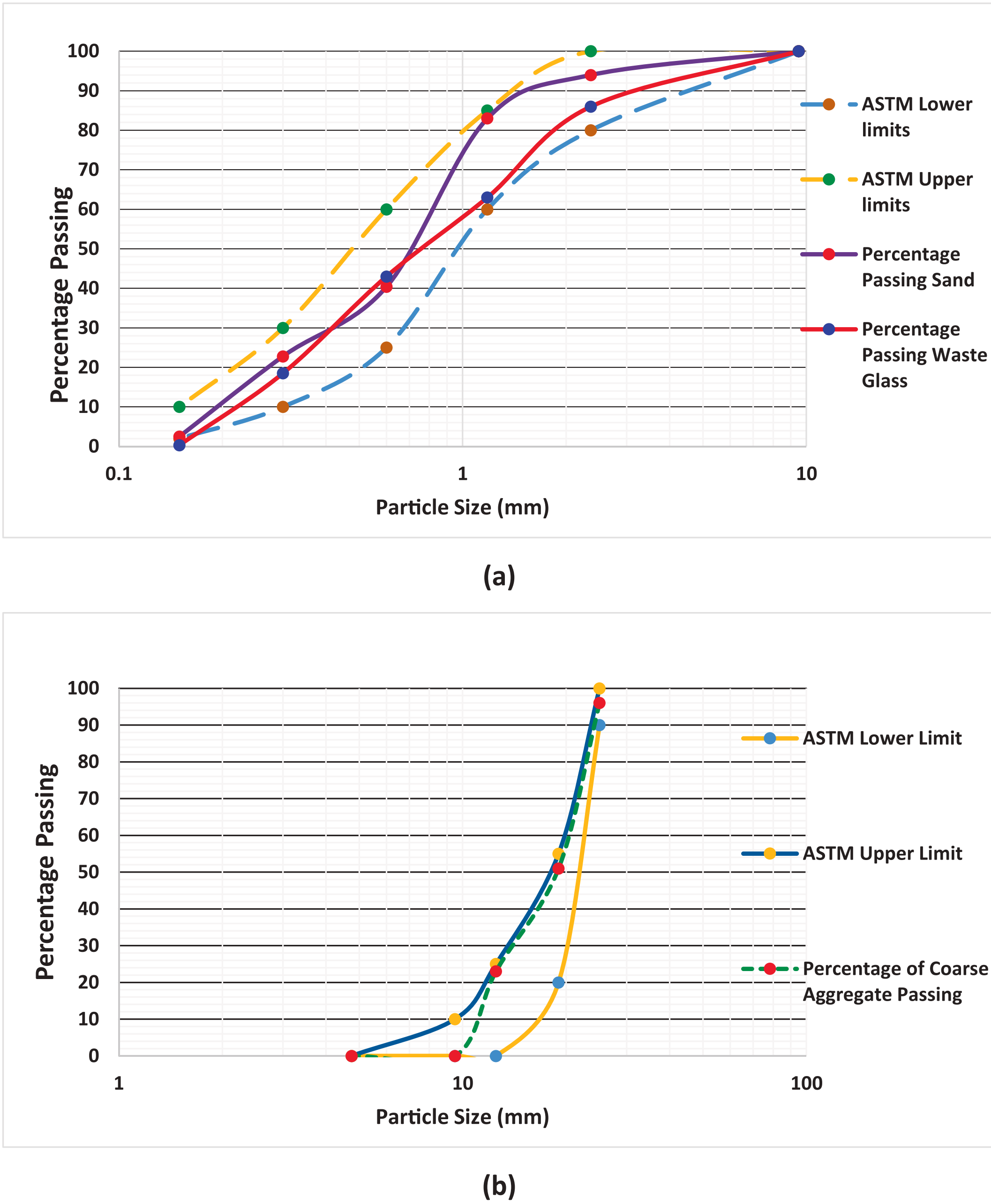

Fig. 4. Gradation of; (a) Fine aggregates and waste glass, (b) Coarse aggregates.

Table 3
Physical characteristics of fine and coarse aggregate.

Physical Properties	Fine Aggregates	Coarse Aggregates
Fineness Modulus	2.59	4.25
Particle Size (mm)	< 4.7 mm	< 20 mm
Bulk Density	1570 kg/m^3	1582 kg/m^3
Moisture Content	1.75 %	1.15 %
Absorption Capacity	4.10 %	2.85 %

in the FS can be attributed to the augmented bonding in the binder's matrix due to the FA at the ITZ level, crack bridging behavior of CFs and the filling effect of the WG. The researchers in a study observed that a rise in the FS is due to the pozzolanic influence of FA in the binder's matrix at the curing of 90 days. The enhancements in the FS can be attributed to the additional binder compounds developed from the chemical reaction of WG and FA with Ca $(OH)_2$, which augments the interfacial transition zone between the fine aggregates and microstructure at the binder's matrix. The tensile cracks in the samples are averted and controlled by the random spread of the coconut fibers in the binder's paste. Due to the presence of the CFs, the growth and propagation of the tensile cracks were mitigated. The existence of the fibers mitigated the flexural and shear cracks and, eventually, the FS. In the M8 mixture, the FS lowered by 6.9 % and 14.21 % more than the control mixture at curing 28 and 90 days. The reduction in flexural strength is primarily ascribed to the development of cracks created due to the sharp edges of WG. This instigates a weak bond amid the particles of WG and the binder's paste at the ITZ level. The above discussion shows that the M4 mixture is an optimal combination among others. The lowered flexural strength past the optimal mix (M4 mixture) could be ascribed to the non-uniformity of

Table 4
Mix design of all combinations (kg/m^3).

Mixture ID	Mixture Description	OPC	FA	Sand	WG	CFs	CA	Water	W/B ratio	CF	SP
M1 Mixture	WG0- FA0-CF0 (Control)	425	0	680	0	8.5	1100	212.5	0.5	0.90	1.4
M2 Mixture	WG14- FA20-CF2.5	340	85	584.8	95.2	10.62	1100	212.5	0.5	0.90	1.45
M3 Mixture	WG15- FA20-CF2.5	340	85	578	102	10.62	1100	212.5	0.5	0.90	1.5
M4 Mixture	WG16- FA20-CF2.5	340	85	571.2	108.8	10.62	1100	212.5	0.5	0.90	1.55
M5 Mixture	WG17- FA20-CF2.5	340	85	654.4	115.6	10.62	1100	212.5	0.5	0.90	1.65
M6 Mixture	WG18- FA20-CF2.5	340	85	557.6	122.4	10.62	1100	212.5	0.5	0.90	1.7
M7 Mixture	WG19- FA20-CF2.5	340	85	550.8	129.2	10.62	1100	212.5	0.5	0.90	1.80
M8 Mixture	WG20- FA20-CF2.5	340	85	544	136	10.62	1100	212.5	0.5	0.90	1.90

OPC – Ordinary Portland Cement, **FA –** Fly ash, **WG –** Waste glass, **CFs –** Coconut fibers, **CA –** Coarse aggregates, **W/B ratio –** Water to binder ratio, **CF –** Compaction factor, **SP –** Superplasticizer

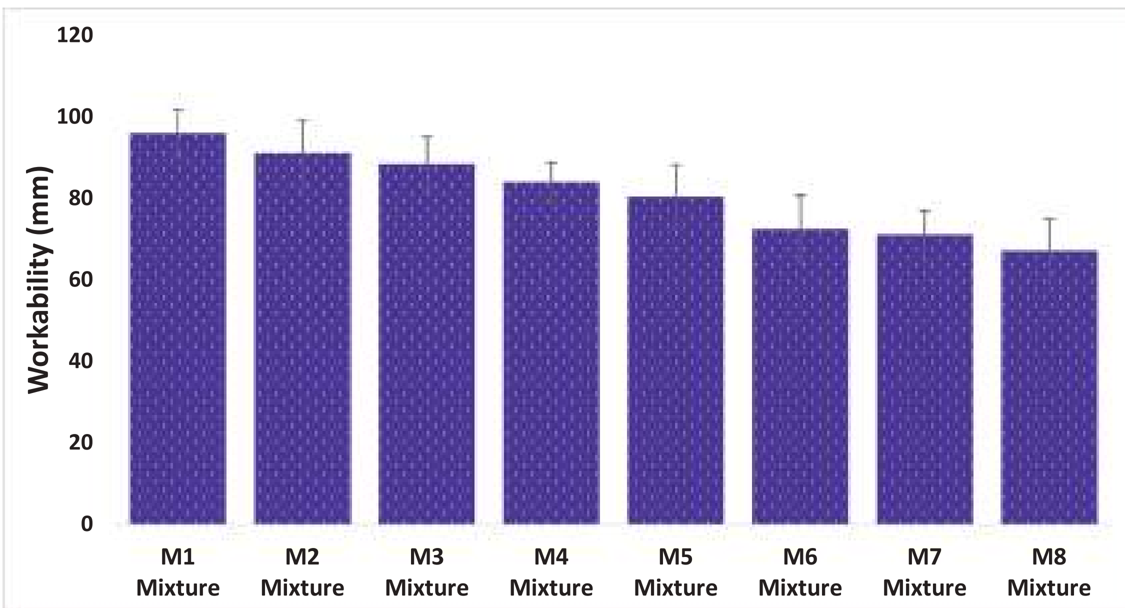

Fig. 5. Workability of fresh samples.

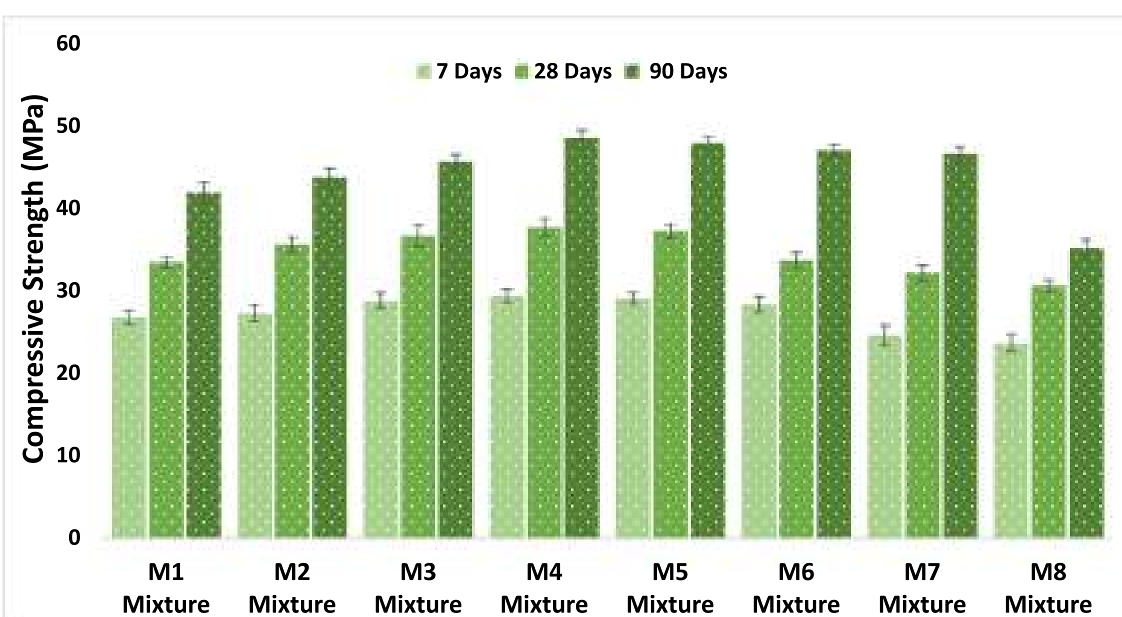

Fig. 6a. Compressive strength of concrete.

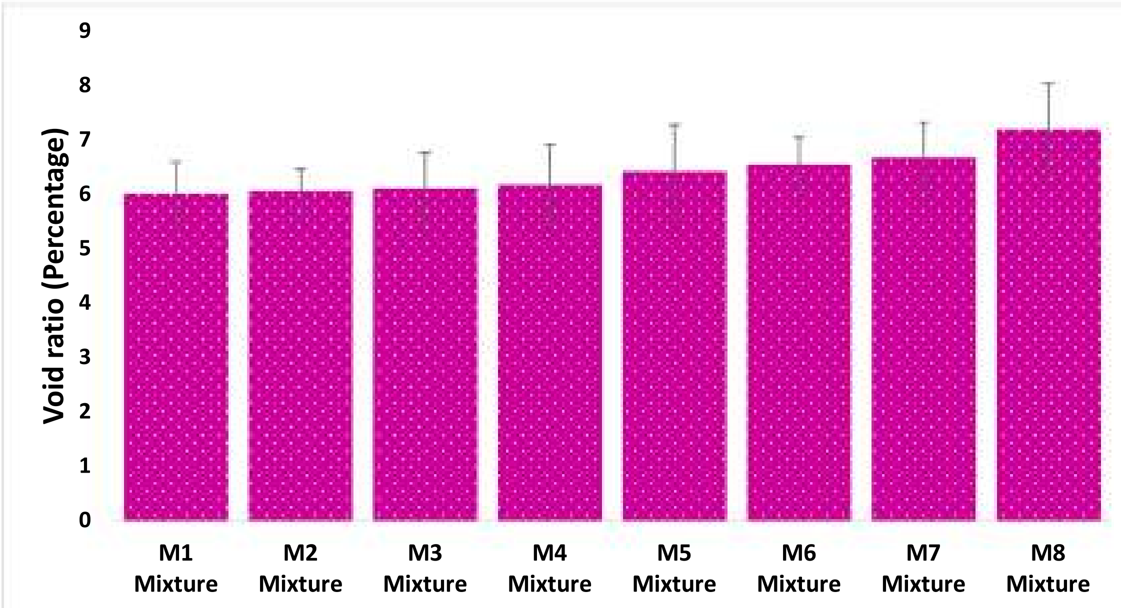

Fig. 6b. Void ratio of concrete.

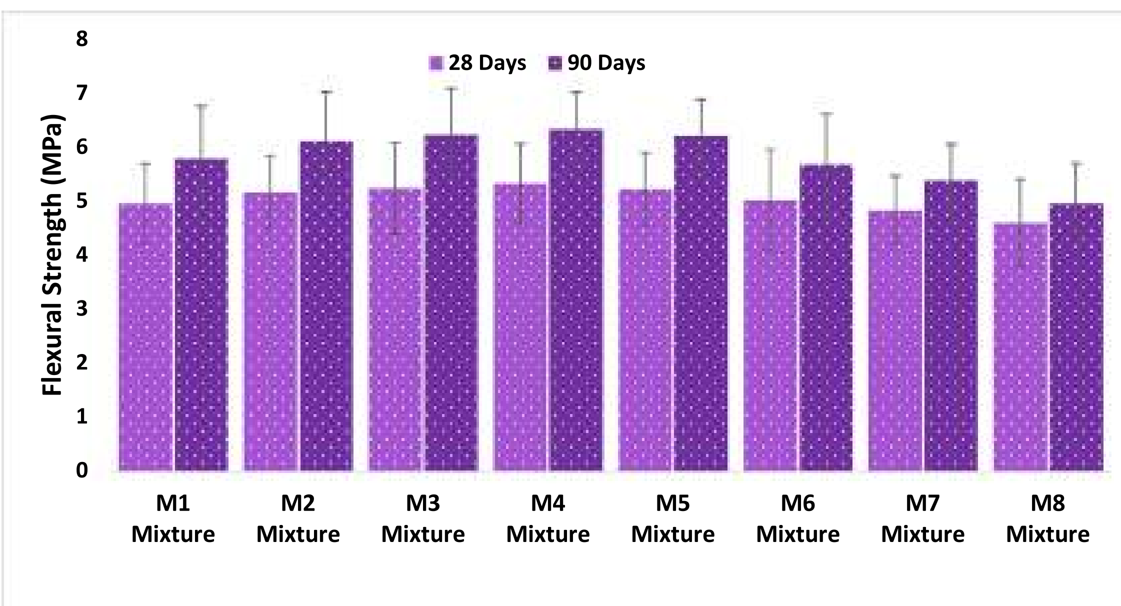

Fig. 7a. Flexural strength of concrete.

the concrete mix because of adding high content of the waste glass. Fig. 7a presents the statistical co-relation between compression and flexural strength at the curing of 28 days. A firm co-relation is noted between compression and flexural strength, with the value of R-square (98.78 %) approaching the unity, which shows the accuracy of experimental results.Fig. 7b.

5.4. Hardened Density:

Fig. 8 presents the influence of introducing WG, CFs and FA on the concrete's (bulk and apparent) density. Fig. 8 shows that the M4 mixture (WG16-FA20-CFs2.5) has the highest density among other mixtures, which signifies a low number of pores. The M4 mixture had 6.3 % and 8.1 % more bulk and apparent density than the control specimen. The improvement in the concrete's hardened density signifies impervious packed pores, which improves the compression strength of concrete. Adding more than 16 % WG, the density gets to reduce slowly, as the M5 mixture (WG17-FA20-CFs2.5) had 1.91 % and 2.36 % less bulk and apparent density than the M4 mixture, but it was still higher than the control mixture. Among all the mixtures, the M8 mixture (WG20-FA20-CFs2.5) had the lowermost density with 5.62 % and 7.74 % less hardened (bulk and apparent) density than the reference mixture (WG0-FA0-CFs0). The reduction of concrete's hardened density due to adding higher WG than the optimal amount is also ascribed to the specific gravity (SG) of waste glass particles, as the SG of WG

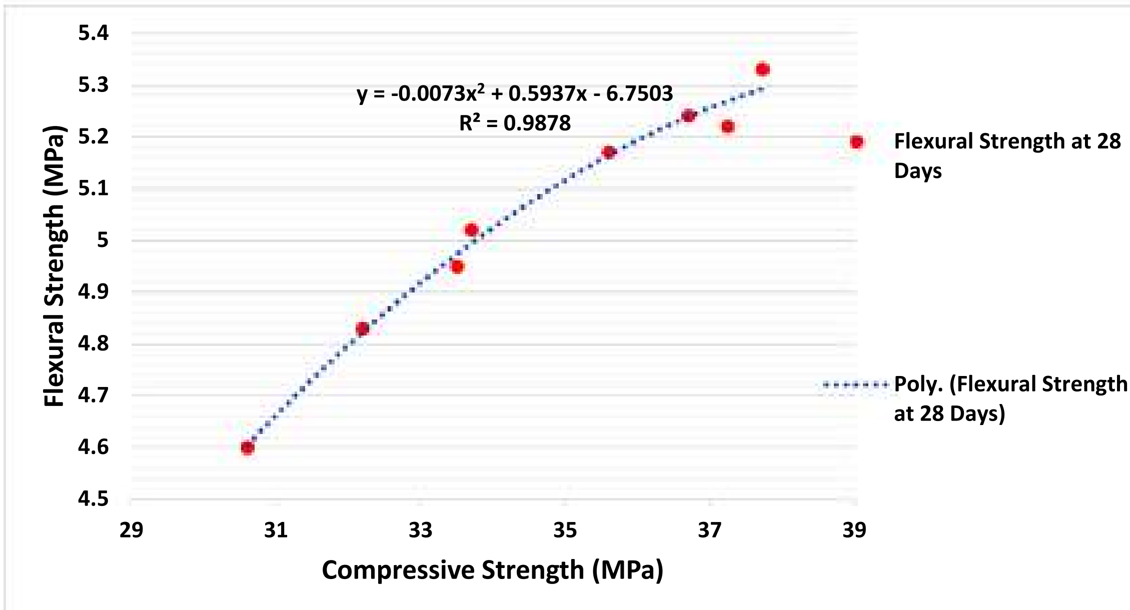

Fig. 7b. Relation between flexural and strength.

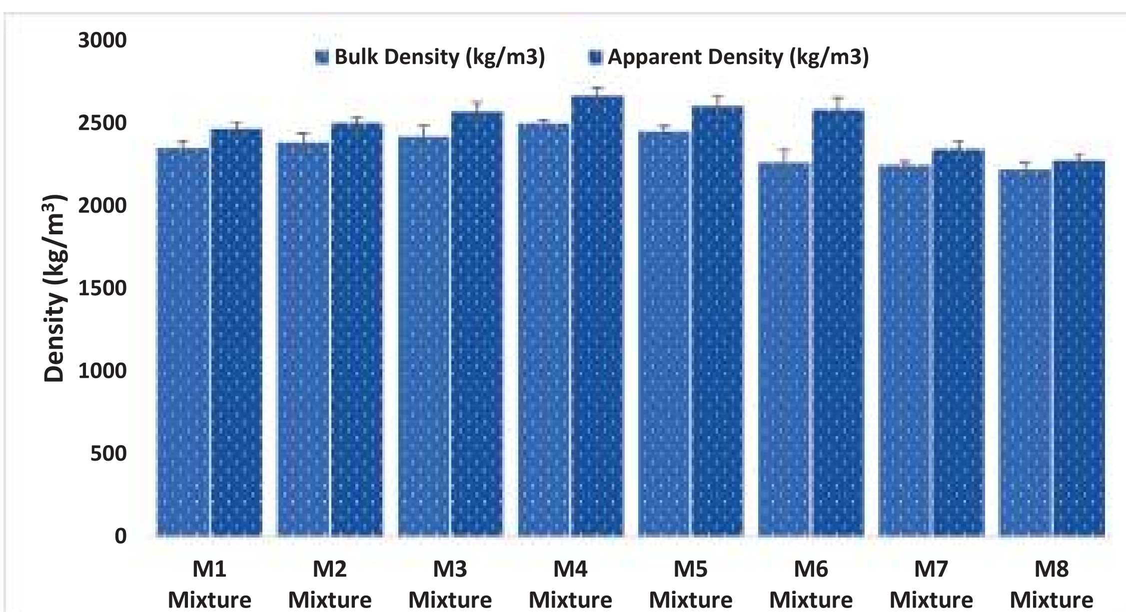

Fig. 8. Hardened Density of samples.

is 2.39, which is lower than the sand's SG (2.64). The researchers in research [25] observed that introducing more WG led to concrete blocks with continuously low density as due to the addition of WG, their concrete density lowered by more than 7.41 % than the control mixture. A similar trend of reduced density of cement mortar was also observed in another research [79], in which waste glass from different sources was utilized as a replacement for sand; the authors credited the lowered density to low specific gravity and low-density particles of waste glass.

5.5. Water absorption

Fig. 9a presents the influence of introducing WG, CFs and FA on the concrete's water absorption. Fig. 9a depicts that as the amount of WG increased, the specimens' water absorption also raised. For the M8 mixture (WG20-FA20-CFs), the water absorption increased to 5.56 % from the control specimen, though the control specimen had a water absorption of only 2.21 %. The increase in the water absorption could be credited to the high surface area of FA, the porous nature of coconut fibers and rounded particles and the smooth texture of WG, which instigates the opening and propagation of cracking and develops voids in the concrete's matrix. This could lead to a reduction in the bonding among the aggregates, WG and binder's paste. The high proportion of voids and cracks in the matrix make channels for outside water or chemicals to infiltrate the concrete's specimen. The statistical co-relation between water absorption and voids ratio is presented in Fig. 9b. from Fig. 9b, it can be observed that voids ratio and water absorption are closely co-related. Their regression coefficient value (R-square) is near 1, showing the test outcomes' accuracy.

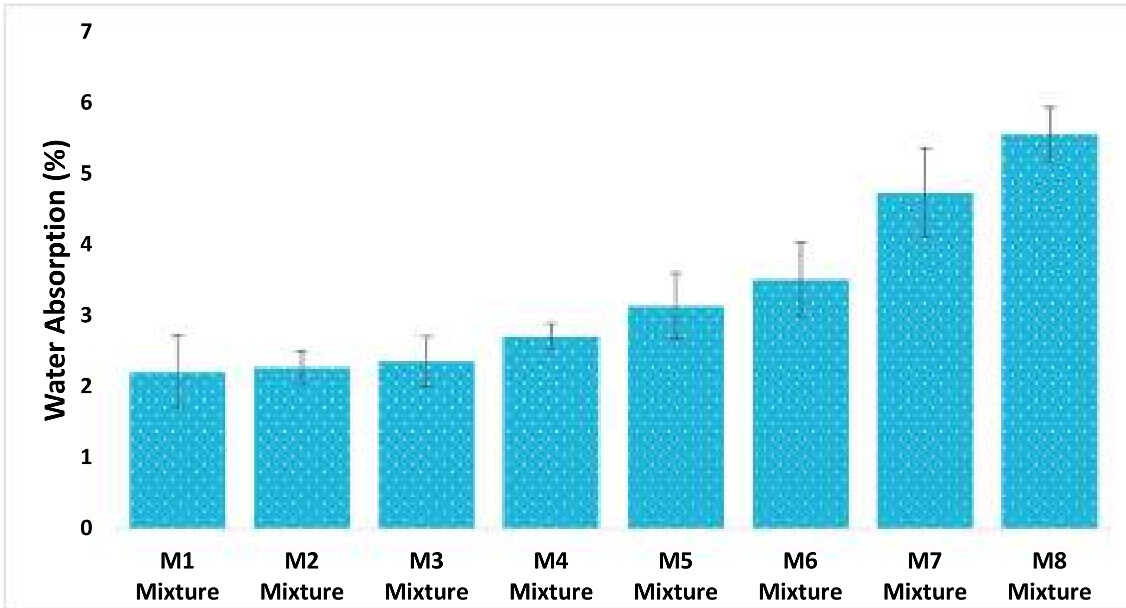

Fig. 9a. Water absorption of concrete samples.

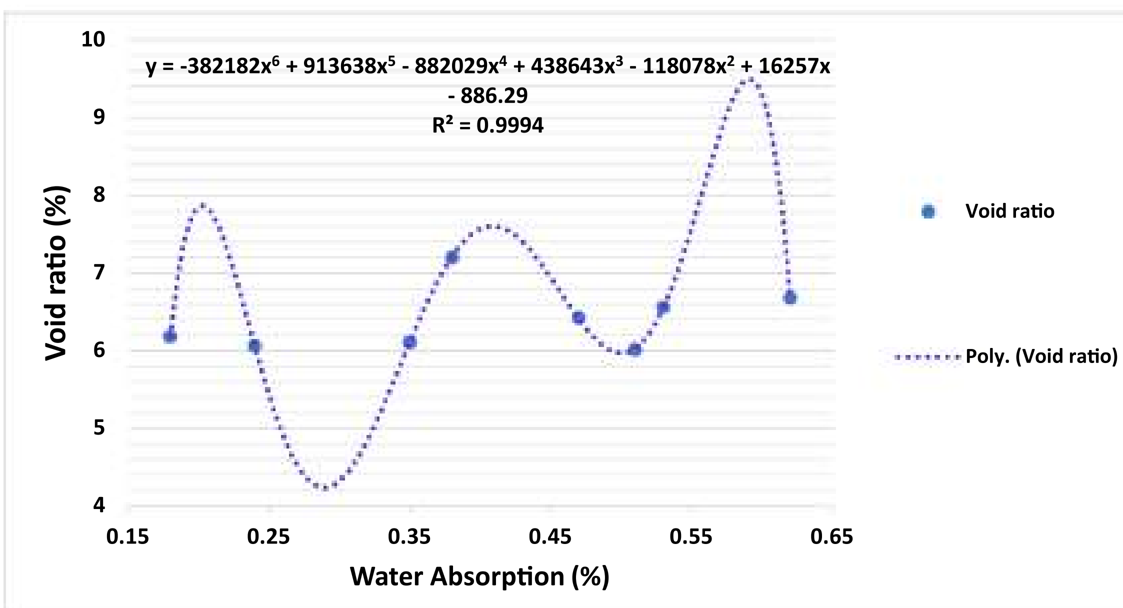

Fig. 9b. Statistical analysis between water absorption and void ratio.

5.6. Permeability of concrete:

The concrete's permeability was assessed in respect of the depth of water penetration. In Fig. 10a, the values of concrete's permeability due to the introduction of CFs, FA, and WG are present. It can be observed from Fig. 10a that by introducing waste glass from 14 % to 20 %, infiltration of the depth of water increases from 45 mm to 63 mm to the control mixture; the control mixture had a penetration of water of 23.5 mm. The increased permeability in the concrete with more WG can be attributed to the development of voids amid the interface of WG and the binder's paste, which allows the water to pierce into the specimen of a large capacity. The statistical analysis among permeability, water absorption and voids ratio are presented in Fig. 10b. A strong co-relation in Fig. 10b among the above parameters was observed with the value of R-square more than 84 % and 99 % for water absorption and void ratio, respectively. This result conforms with the past study, where the researchers utilized WG as sand in a cementitious composite and observed similar permeability results due to the addition of waste glass.

5.7. Behavior of waste glass concrete against elevated temperature:

The WG concrete's mass loss after being subjected to heating conditions up to 600 °C is presented in Fig. 11a. Stability in the mass loss was observed for WG concrete up to 300 °C, while the