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Durability and thermal properties of prepacked aggregate concrete reinforced with waste polypropylene fibers

Hossein Mohammadhosseini [a,*], Fahed Alrshoudi [b,**], Mahmood Md Tahir [a], Rayed Alyousef [c,***], Hussam Alghamdi [b], Yousef R. Alharbi [b], Abdulaziz Alsaif [b]

[a] Institute for Smart Infrastructure and Innovative Construction (ISIIC), School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310, Skudai, Johor, Malaysia
[b] Department of Civil Engineering, College of Engineering, King Saud University, Riyadh, 12372, Saudi Arabia
[c] Department of Civil Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, Alkharj, 11942, Saudi Arabia

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ABSTRACT

The prepacked aggregates fiber-reinforced concrete (PAFRC) is an innovative type of concrete composites that recently has gained popularity and pulled the attention of researchers worldwide. The PAFRC components can be manufactured by initially placing the mixture of coarse aggregates with various sizes and shapes and short fibers in the designed molds and then grouted with an especially ready mix mortar. Although prepacked aggregate concrete (PAC) or two-stage concretes have been used widely as construction materials, long-term performance, particularly in aggressive environments, have not been studied. Therefore, the current study investigated the long-term strength properties, resistance against acid and sulfate environments, as well as thermal properties. Two methods of grouting were used, namely, gravity and pumping. For each method, a total of six mixes comprising 30 mm length waste polypropylene (PP) fibers at dosages of 0–1.25% was prepared. The outcomes of the study revealed that the PAFRC specimens obtained a remarkable improvement in the long-term strength values. The findings expose that the rates of sulfate and acid attacks, in terms of mass and strength losses, were controlled significantly by adding PP fibers and POFA into PAFRC specimens. The combination of PP fibers and POFA, which provides a denser microstructure, resulted in the lower depth of carbonation and better performance of PAFRC specimens to delay the time of heat transfer to the middle part of concrete.

1. Introduction

In general, a conventional type of concrete is prepared by mixing all the components, and then, the mixture of fresh concrete is poured in designed formwork. Besides, concrete components may also be manufactured by first packing the coarse aggregate in the designed formwork, and then a special type of mortar in the form of grout injected in between the aggregates. Prepacked aggregate concrete (PAC) or preplaced aggregate concrete, also called two-stage concrete, is a specific sort of concrete which was designated originally in the 1930s [1,2]. This specific method of concreting is produced by initially placing the coarse aggregates with various sizes and shapes, depends on the application, in the preplanned fitments, and then the gaps amongst the aggregate particles poured with a specially prepared mortar in the form of grout [3–6]. This specific technique of concrete construction can be used in the components with complex reinforcement. Prepacked aggregate concrete has demonstrated its ability to especially function in several applications, for example, for repairing the existing structures with massive reinforcement through retrofitting, when a strong bond between the new concrete and the existing components are required, and also underwater construction [7]. Another application of the PAC method is mass concreting like piers and bridge abutment. Moreover, the PAC technique is one of the most preferred methods of concreting underwater, in which aggregate particles with different sizes are preplaced in water, and then a mixture of grout injected into the gaps between the aggregates to replace water [8].

In the PAC method of concrete, the main challenge is to fill up the gaps and voids amongst the aggregate particles to provide a strong bond amongst the aggregates and cement paste. Therefore, the method of grouting, as well as the proper degree of pressure in which the grout should be injected, is essential [3]. The method of grouting and the applied pressure may vary based on the depth of formwork and also the size of aggregates. The applied pressure should be in such a way that it does not interrupt the aggregates or lift them up in the formworks [9]. Besides, in the PAC process, the mortar is prepared in a special type of double drum mixers with high speed, wherein water and cement particles are mixed in one drum, and the sand particles are mixed with the cement paste in the other drum. The mixture of mortar, which used as grout, must be fluid enough to flow consistently into the gaps amongst aggregate [10].

In the PAC technique of concreting, depends on the minimum size aggregates used as well the depth of formworks, the grouting method may vary. Gen-

* Corresponding author.
** Corresponding author.
*** Corresponding author.
E-mail addresses: hofa2018@yahoo.com (H. Mohammadhosseini); Falrshoudi@ksu.edu.sa (F. Alrshoudi); r.alyousef@psau.edu.sa (R. Alyousef)

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erally, in PAC grouting is done by either gravity or pumping methods [11,12]. In the gravity method, the mixture of grout is poured on the aggregates packed in the formworks and allowed to penetrate slowly downwards under its own weight. The gravity method is usually accepted for thin concrete components with a depth of up to 300 mm and larger size of aggregates, for instance, road pavement slab and floor slab. However, with an increase in the depth of sections, the grout cannot completely cross through the entire thickness of formwork. Therefore, in the components with the smaller size of aggregate and deeper sections, the pumping method of grout injection is preferred [3,9]. In this method, a pump with a pressure measuring device is used. The grout is then pumped in between the preplaced aggregates from the bottom of the formworks. The pipes with perforations, which extracted upwards, inject and uniformly distribute the grout mixture into the sections. In this method, the entire depth of the formworks is poured with grout [8,13].

Conventional plain concrete is characteristically categorized as a brittle material, due to the low energy absorption capacity and tensile strength. The formation of cracks and sudden failure may occur in plain concrete when subjected to structural loads, chemical attacks, and thermal deformation [14]. According to Afroughsabet et al. [15], the existence of cracks permit liquids and chemical particles into the concrete components and accelerate the deterioration of concrete structures through carbonation, acid and sulfate attacks, and freezing-and thawing damages [16]. Therefore, to enhance the ductility and durability performance of concrete and prevent the formation of cracks in concrete components, several techniques have been proposed by researchers. In this regard, various methods have been proposed to densify the matrix to reduce the entrance of harmful particles into concrete components, in addition to the enhancement in the strength and durability properties with the inclusion of admixtures have been investigated [17,18]. Nevertheless, these approaches will not help to improve the brittle nature of plain concrete.

As the development of cracks and the existence of pores are the concern of plain concrete exposed to chemical attacks, a technique that enhances the ductility concrete components is desired. For this purpose, several researchers proposed the reinforcement of concrete with short fibers to enhance the performance of concrete under aggressive environments. Behfarnia and Farshadfar [19] and Medina et al. [20] described that by including short fiber into the concrete mix, the brittle nature of concrete enhanced significantly. Besides, Salami et al. [21] and Jaturapitakkul et al. [22] pointed that using pozzolanic materials such as POFA as cementing materials up to a certain level, moderately improved the acid resistance of concrete by reducing the rate of mass loss and strength loss. Therefore, based on the existing literature, the utilization of pozzolanic materials and fibers have been recommended to develop the performance of concrete exposed to chemical attacks. Amongst all recommended fibers, polymeric based fibers such as polypropylene (PP) are more beneficial in contact with acid and sulfate solutions [19].

Besides mechanical properties, the aspects of durability are greatly considered in the assessment of behavior and potential use prepacked aggregate concrete. According to Gruyaert et al. [23], sulfate and acid particles in the liquid form find a way to enter into the cavities in concrete components and chemically react with the hydration products of cement. Rozière et al. [24] also reported that the attack of sulfate particles on calcium aluminate hydrate results in the creation of expansive gypsum and ettringite in the concrete matrix. Besides, Zhou et al. [25] described that acidic rain in the urban area is another serious harm that affects the concrete structures. Acid rain is mostly owing to the burning of fossil fuels and adding CO_2 and H_2SO_4 to the atmosphere in the form of gases. Therefore, these pollutant gases have harmful influences on concrete components when mixed with rain. Consequently, novel construction materials with superior ductility and resistance against chemical attacks are vital to be proposed. Therefore, the addition of various types of short fibers at different dosages, based on the application, can be an alternative solution to attain such enhanced properties in concrete [26]. Accordingly, this study proposed a new prepacked aggregates fiber-reinforced concrete (PAFRC) made by the combination of prepacked aggregates and short fibers and poured with an especially premixed mortar to poured the gaps among the particles in the designed

The thermal poperties of concrete is an essential aspect when considering the amount of heat transfer through conduction [27]. In any concrete structure or building, the amount of heat loss through components has a direct influence on the energy consumption.The essential energy for heating and cooling and the thermal equilibrium of buildings as are significantly reliant on the thermo-physical concrete constituents. Therefore, various parameters such as type and size of aggregates, type of binding materials, and the density of concrete are amongst the most factors which affect the thermal properties of concrete [28]. Khaliq and Kodur [29] stated that the thermal conductivity of concrete reduced with increase in temperature. However, the addition of steel, polypropylene, and hybrid fibers, could significantly delayed the heat transfer into the core of concrete. Consequently, reinforcement of concrete with short fibres is a potential solution to reduce the energy consumption in buildings [30,31]. Besides, PAFRC comprising PP fibres having a good thermal insulation property could b used in such an applications to reduce the energy consumption.

Textile and carpet industries are amongst the industries which produce a vast amount of waste every year. The majority of generated waste in such industries is in the form of fibrous materials. In this regard, about 50 tons of polypropylene (PP) fibers sent to landfills as waste in Malaysia only [32]. Indeed, the option of waste disposal is gradually becoming unviable owing to the increasing cost of landfilling in addition to the limited accessible discarding sites. The demand for reusing solid waste materials is growing owing to the lack of landfill places and the preservation of natural resources. Consequently, the idea of using these fibrous waste materials as fibers in concrete industries has been developed by the researcher. Utilization of waste PP fibers in concrete is beneficial, as these are free of cost, hydrophobic in nature, and high resistance against chemical attacks [33,34]. Moreover, using pozzolanic waste materials as partials cement replacement is another way of reduction in waste generation. Palm oil fuel ash (POFA) is one of the agricultural wastes which has been found as potential pozzolanic material used as supplementary cementing materials in concrete. The production of POFA has been raised up to5 million tons per year in Malaysia, and mostly sent to landfills [35,36]. However, due to the adequate chemical compositions and physical properties, this waste ash can now be used as valuable cementing material to enhance the durability and strength properties of concrete.

Although prepacked aggregate concrete has been used widely as construction materials, long-term performance, particularly in aggressive environments, have not been studied. To date, the long-term performance of prepacked aggregate concrete reinforced with waste PP fibers and using POFA as cementing materials exposed to acid and sulfate solutions, as well as the heat transfer property, have not been investigated yet. Therefore, the current study critically investigated the long-term strength and durability performance of PAFRC, in addition to the thermal properties of PAFRC mixes. The one-year compressive and tensile strengths, carbonation, sulfate, and acid resistance, as well as the thermal resistance of PAFRC specimens, were then assessed.

2. Materials and test methods

2.1. Materials

In this study, a type I cement that complies with the specifications of ASTM C 150–2007 was used. In addition, OPC was substituted by POFA at substitution level of 20%. Initially, the raw palm oil fuel ash particles were collected as waste from the local mill industry. The ash particles were dried at the temperature of 100 ± 5 °C and then sieved to remove the larger particles of over 150 μm. Subsequently, the small size of ash particles was kept in a crushing machine, and the grinding process was continued for about 2 h per each 4 kg of ash. Then, the grounded POFA particles were tested following the specifications of ASTM C618-2015 and BS 3892: Part 1–1992 to achieve the desired properties. The ashes which passed the standard requirements with the desired chemical compositions and physical properties of given in Table 1 were then used as cementing materials. Moreover, sets of trail mix were carried out on the different percentage of POFA content. The results revealed that inclusion of POFA more than

Table 1
Chemical compositions and physical properties of used OPC and POFA.

Composition (%)	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	SO_3	K_2O	LOI	Specific gravity	Blaine fineness (cm^2/g)
OPC	20.40	4.19	62.39	5.20	1.55	2.11	0.005	2.36	3.15	3990
POFA	62.60	8.12	5.70	4.65	3.52	1.16	9.05	6.25	2.42	4930

results and also to reduce the consumption of OPC, 20% POFA content was selected as an optimum to be used in the main experimental work.

The fine and coarse aggregates are the main constituents in the production of PAC. Therefore, in this study, natural river sand with a maximum size of 4.75 mm was used to produce a mixture of the grout. The fineness modulus, specific gravity, and water absorption of sand particles were found as 2.3, 2.6 g/cm^3, and 0.7%, respectively. Moreover, the coarse aggregate particles, which are the main skeleton of PAC, were selected following the specifications of ACI 304.1R-1997. The crushed granite coarse aggregates of 20–38 mm in size, 2.7 g/cm^3 specific gravity, and 0.5% water absorption were employed. The aggregates were cleaned and washed before place in formworks to eliminate any impurities. Additionally, a multi-filament polypropylene type of waste fibers collected from the local carpet industry was used in this study to reinforce the PAC specimens. Initially, the fibers were collected in the form of waste yarns, as shown in Fig. 1a. Then, to use this yarns as fibrous materials in concrete, several tests were carried out on these fibers, and after satisfied the standard requirements, as given in Table 2, the yarns were cut and fabricated in the desired length of 30 mm with an aspect ratio (l/d) of 67, as illustrated in Fig. 1b.

2.2. Mix proportions

In this study, two groups of prepacked aggregate concrete mixes based on the method of grouting were made, i.e. gravity (G) and pumping (P) mix. For each group, six mixes were cast where one is a control mix without any fibers (G0, P0) and other five mixes reinforced with PP fiber volume fractions of 0.25%, 0.50%, 0.75%, 1.0%, and 1.25%. Besides, based on the trial mix results, in all mixes to obtaine a desired properties, OPC was replaced by 20% POAF, and the water/binder (w/b) ratio of 0.5 and cement/sand (c/s) ration of 1/1.15 were kept constant. Table 3 lists the proportions of different components used in the manufacture of PAFRC mixes.

2.3. Sample preparation and test methods

The preparation and manufacture of PAFRC specimens were done in two stages. First, the dry mixture of coarse aggregate particles and PP fibers were placed and packed in the design formworks and molds, and second, the pre-mixed mortar made of blended cement and river sands with adequate flowability in the form of the grout was injected in between the gaps amongst aggregates and fibers, either by gravity or pumping methods. In the grouting process by the gravity method, a PVC pipe with a diameter of 50 mm was placed at the center of the cylindrical molds of size 100 × 200 mm and 150 × 300 mm, and then grout was injected under the gravity force, as illustrated in Fig. 2b. While the grouting process in the pumping method was more complicated. In this method, as illustrated in Fig. 2a, a UPVC pipes of 100 and 150 mm diameter were used as molds. The length of the pipes was varied between 1 and 2 m, based on the number of required samples. After the casting is done, the specimens were cut in the desired length for compressive strength and tensile strength tests as cylindrical specimens of size 100 mm × 200 mm. The arrangement of pipes was then in a formwork made of plywood to prevent the movement during the grouting process. Besides, a pump with a pressure control device was used, which attached to the hopper for the grout injection purpose. To avoid the overflow of grout and also prevent the uplifting of the aggregates, a cap made of plywood was fixed at the top surface of UPVC pipes. The entire process of grouting was monitored to avoid any leakage of grout from the molds as well as prevent the overflow. After the casting process was done, the PAFRC specimens were cured for 24 h at the ambient temperature. The specimens were then removed from the molds and kept in the water tank until the day of testing.

Fig. 1. (a) Waste PP fibers and (b) 30 mm fabricated fibers used.

The compressive strength and tensile strength tests of PAFRC specimens were carried out in accordance with the specifications of ASTM C39M – 18 and ASTM C496-17, respectively, by using cylindrical molds of size 100 mm × 200 mm and 150 mm × 300 mm for both gravity and pumping methods. Besides, cylindrical specimens with the size of 100 × 200 mm were made and subjected to a carbon dioxide (CO_2) prone environment to determine the depth of carbonation following the specifications of the RILEM Committee CPC-18. To indicate the carbonation depth in PAFRC specimens, phenolphthalein solution was sprayed on the split face of specimens. As illustrated in Fig. 3, the carbonated area remained neutral and no changes in the color of concrete, while the color of the un-carbonated area was changed to purple color. The carbonation test was carried out for the ages of 90, 180, and 365 days exposure, and the depth of carbonation was indicated as the distance between the outer edges of specimens to the beginning of purple color and measured by using a digital caliper.

In this study, the immersion method for sulfuric acid and magnesium sulfate in 5% and 10% solutions were adopted, respectively. The immersion procedures were also followed by the methods proposed by Monteny et al. [37] and Sideris et al. [38], who used 10% $MgSO_4$ solution and 5% H_2SO_4 solution in their studies for conventional concrete. Overall, 36 cylindrical specimens of size 100 × 200 mm were made for each sulfate and acid tests. After 24 h of casting, the PAFRC specimens were kept in a water tank for 28 days. Then, the specimens removed from the water tank and prepared for immersion. The PAFRC specimens were dried, and the mass in the saturated surface dry (SSD) condition was measured as the initial mass of specimens. The specimens were then submerged in $MgSO_4$ solution with 10% concentration for sulfate resistance test, and H_2SO_4 solution of 5% concentration for sulfuric acid resistance

Table 2
Properties of fabricated waste PP fibers.

Waste PP fiber	Length (mm)	Diameter (mm)	Density (kg/m^3)	Melting point (°C)	Tensile strength (MPa)	Reaction with water
Multi-filament polypropylene	30	0.45	910	170	400	Hydrophobic

Table 3
The ratios of constitutions used in the production of PAFRC mixes.

Mix	Water (kg/m ^{3})	Cement (kg/m ^{3})	POFA (kg/m ^{3})	Fine Aggregate (kg/m ^{3})	Coarse Aggregate (kg/m ^{3})	V_f (%)
P0	186	304	76	545	1320	0
P1	186	304	76	545	1320	0.25
P2	186	304	76	545	1320	0.50
P3	186	304	76	545	1320	0.75
P4	186	304	76	545	1320	1.00
P5	186	304	76	545	1320	1.25
G0	186	304	76	545	1320	0
G1	186	304	76	545	1320	0.25
G2	186	304	76	545	1320	0.50
G3	186	304	76	545	1320	0.75
G4	186	304	76	545	1320	1.00
G5	186	304	76	545	1320	1.25

Fig. 2. Methods of grouting in PAC and their setup: a) Pump b) Gravity.

test for 365 days. The pH values of the solutions were controlled and fixed as 2.5 and 8.5 for sulfuric acid and magnesium sulfate solutions, respectively.

Subsequently, the immersed test specimens were removed after 365 days and cleaned by using a dry towel and left in a testing room for about 1 h. To evaluate the variation in the mass of specimens, the mass of all PAFRC specimens were measured and noted as the residual mass after one-year immersion. The percentage of loss in the mass of samples was calculated by using Eq. (1):

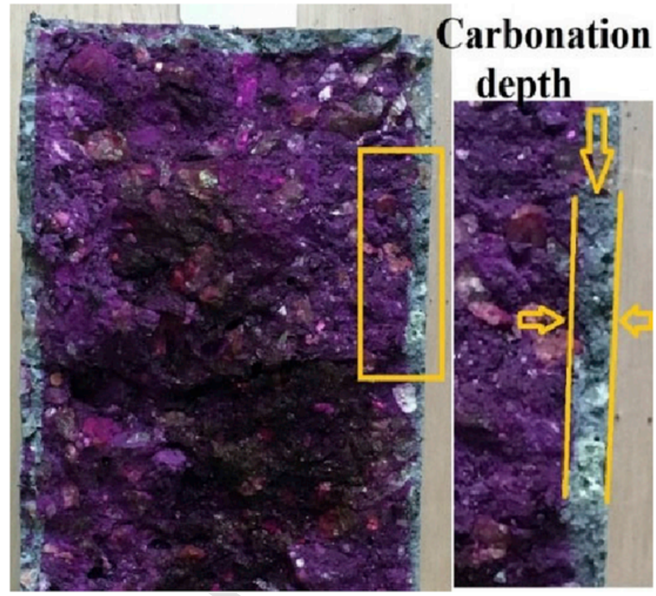

Fig. 3. The indication of carbonation depth by using phenolphthalein solution.

$$ML_t = \frac{M_t - M_i}{M_i} \times (100) \tag{1}$$

where ML_t is the mass change after 365 days exposure, M_t is the residual mass after the exposure period (gr), and M_i is the original mass before immersion (gr).

In this study, the losses in the strength of concrete specimens after exposure to acid and sulfate solutions were evaluated in terms of strength loss factor (SLF) by using Eq. (2) as follow:

$$SLF = \frac{F_{cw} - F_{cr}}{F_{cw}} * \ 100\% \tag{2}$$

where F_{cw} is the compressive strength of water-cured companion specimen, and F_{cr} is the residual compressive strength after 365 days of exposure in acid and sulfate solutions.

Finally, PAFRC specimens were tested for heat transfer by using cylindrical specimens of 150 × 300 mm. Type K thermocouples were used, which were located at the center of the molds. The molds were then filled with aggregate particles, and the grout was subsequently injected into the molds using polypropylene foam lid through the drilled hole. To prevent the direct contact of PPAFRC specimens with water and also the entrance of water into the specimens, all PAFRC specimens were wrapped and tight with thin plastic sheets and kept in the boiler water tank (Fig. 4a). Besides, a PVC pipe of 2 cm in diameter was used to cover the thermocouple (Fig. 4b). The thermocouples were attached to

Fig. 4. The setup of a heat transfer test: a) boiler tank; b) PAFRC specimen.

Fig. 5. TDS type data logger to record the temperature.

a data logger, as revealed in Fig. 6. The PAFRC samples were then placed in the boiler tank with the initial temperature of 30 °C. The boiling process was started, and the temperature of water increased gradually. The temperatures and their respective times were recorded until the temperature of water reached to100 °C. Then the temperature kept constant at 100 °C, and the time that each specimen reach 100 °C was recorded (see Fig. 5).

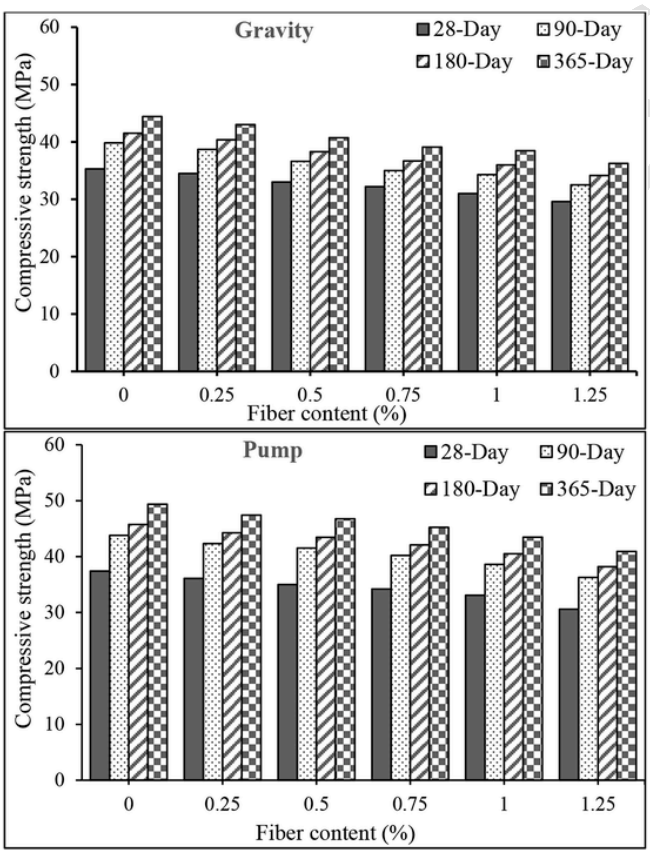

Fig. 6. Long-term compressive strength of PAFRC specimens.

3. Results and discussion

3.1. Compressive strength

The PAFRC specimens were tested for compressive strength at the ages of up to 365 days, and the outcomes ate demonstrated in Fig. 6. The obtained results indicated that the addition of PP fibers results in a slight reduction in the compressive strength of PAFRC specimens, particularly at an early age. However, the findings exposed that the obtained compressive strengths for PAFRC specimens at the ages beyond 180 days are higher due to the existence of POFA. The reinforcement of PAFRC specimens for the gravity method resulted in the reduction of compressive strength values. For example, at the age of 28 days, the compressive strength values of 34.5, 33, 32.2, 31, and 29.6 MPa were noted for the mixes reinforced with 0.25%, 0.5%, 0.75%, 1%, and 1.25% fibers, correspondingly, which are slightly lower than that of 35.3 MPa noted for the plain prepacked aggregate concrete mix without any fibers (G0). Similarly, for the same fiber dosages, the PAFRC specimens of pumping method obtained the compressive strengths of 36.1, 35, 34.2, 33.1, and 30.6 MPa, respectively, which are slightly lesser than that of 37.4 MPa recorded for plain mix (P0) at the age of 28 days. The reduction in the compressive strength could be attributes to the existence of air voids in the matrix which are increased by adding fibres at higher dosages and disturbed the distribution of grout between the aggregates, and therefore, effects of air voids in reduction of strength was more effective, compared to arresting the further crack openings.The findings indicate that the compressive strengths of pumping method specimens are comparatively higher than those strength values recorded for the specimens of gravity method. However, the lower strength values of the early ages could be due to the existence of POFA. Due to the pozzolanic nature of POFA, the hydration rate was slow at 28 days, and consequently, caused in lower strength [39].

Nonetheless, at the ultimate ages of 180 days and beyond, owing to the existence of POFA, the strength values were found to be greater than those recorded at an early age. For instance, at the curing period of 365 days, the compressive strength values of 49.4, 47.5, 46.7, 45.2, 43.5, and 40.9 MPa were noted for the pumping method PAFRC mixes comprising 0%, 0.25%, 0.5%, 0.75%, 1%, and 1.25%, correspondingly. The obtained strength values are comparatively higher than those values of 44.4, 43, 40.7, 39.1, 38.4, and 36.2 MPa, which recorded for specimens of the gravity method with the same fiber contents, respectively. It could be seen that the pumping method specimens revealed advanced strengths, as related to those of the gravity PAFRC specimens for the similar fiber contents. It could be due to the good penetration of grout by the pump into the cavities amongst the aggregate particles and fibers, which consequences in providing a denser matrix and, therefore, higher strength values [40,41].

Moreover, the obtained results of the compressive strength were found to be higher than those of recorded at the early ages. It could be attributed to the pozzolanic nature of POFA, which contains a large volume of reactive SiO_2. With the existence of moisture, along the time, this reactive SiO_2 chemically reacts with the released CH, which is the hydration product of OPC, and for extra C–S–H gels in the matrix. Consequently, these supplementary hydration products, which are due to the pozzolanic action of POFA, filled up the cavities and porosity in the matrix and resulted in a dense microstructure. These denser microstructures then result in enhanced strength and durability performance of concrete [42]. Fig. 7 displays the SEM image of POFA-based paste in PAFRC specimens at the age of 365 days. The homogeneous distribution of hydration products such as C–S–H gels is shown in the SEM image, which filled up the cavities in the matrix and provided a solid microstructure.

3.2. Tensile strength

The findings of one-year water cured PAFRC specimens tested for tensile strength are demonstrated in Fig. 8. The outcomes revealed that the addition of PP fibers significantly improved the tensile strength of both gravity and pumping method PAFRC mixes. It was observed that at the age of 28 days, by the inclusion of 0.25%, 0.5%, 0.75%,

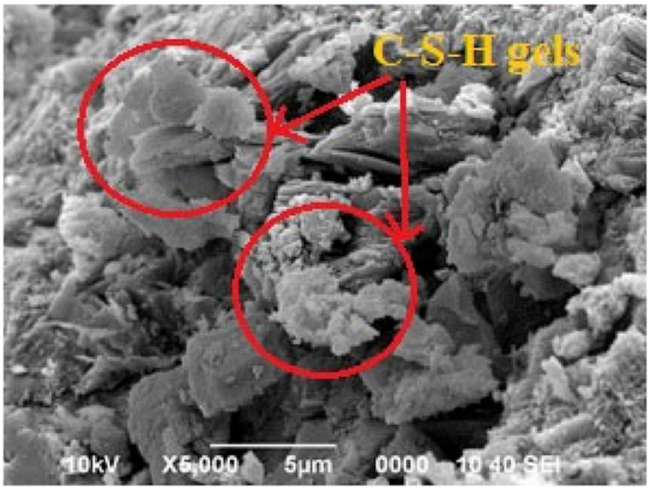

Fig. 7. SEM images of POFA-based pastes cured in water for 365 days.

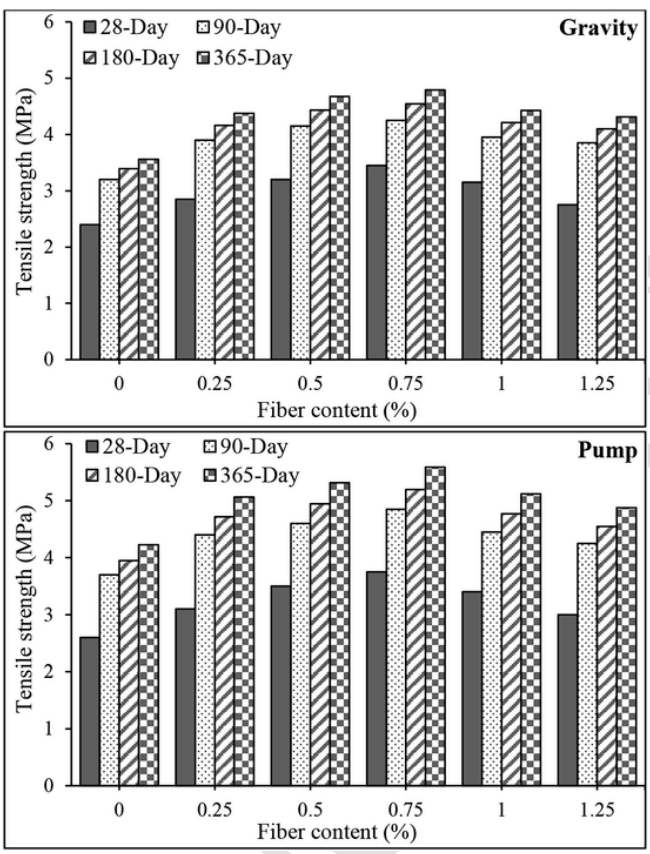

Fig. 8. Long-term tensile strength of PAFRC specimens.

of gravity method exhibit tensile strength values of 2.85, 3.2, 3.45, 3.15, and 2.75 MPa, respectively, which all are higher than that of 2.4 MPa recorded for the plain mix without any fibers (G0). Besides, the higher tensile strength values of 3.1, 3.5, 3.75, 3.4, and 3 MPa were noted for the same fiber dosages, respectively, in pumping method specimens, which are higher than that of 2.6 MPa recorded for the plain mix (P0). Furthermore, at the ultimate ages, due to the existence of POFA with high pozzolanic activity, PAFRC specimens attained enhanced tensile strengths than those of an early age values. At the age of 365 days, the tensile strength values of 3.6, 4.4, 4.7, 4.85, 4.45, and 4.3 MPa were noted for the gravity method PAFRC mixes comprising 0%, 0.25%, 0.5%, 0.75%, 1%, and 1.25% PP fibers, correspondingly. However, the higher strength values of 4.2, 5.1, 5.3, 5.6, 5.15, and 4.9 MPa were noted for the pumping method PAFRC samples with the same fiber contents, respectively. This strength enhancement attribute to the addition of high modulus PP fibers. The fibers are effectively improving the lateral bond within the concrete core and bridging the micro-cracks up to a reliable limit [21]. Besides, the results obtained in this study shows that with the presence of PP fibres, the failure mode was generally ductile in nature. In addition, it was found that further increases in PP fibers beyond 0.75% resulted in lower tensile strength. This phenomenon could be due to the existence of fibres at higher dosages which prevented the well-distribution of grout mixture throughout the formwork, and therefore, increase in the matrix porosity and lower tensile strength.

Besides, Fig. 9 displayed the distribution of fibers in the matrix in addition to the interfacial transition zone among fiber and cement paste in the concrete matrix after one-year water curing. The SEM image reveals a robust bond among fibers and blended cement paste. This strong bonding between fibers and paste provides a reliable solid microstructure in the matrix, which results in a reduction in the crack formation at the interface zone. Consequently, a lower volume of cracks caused in the strength development and high ductility of PAFRC specimens. In the study conducted by Mastali et al. [43], they specified that the addition of PP fibers at various dosages considerably enhanced the tensile strength of layered concrete (see Fig. 10).

3.3. Carbonation depth

In this study, the PAFRC specimens were exposed to natural outdoor carbonation for up to 365 days, and depths of carbonation were measured, and results are illustrated in Fig. 11. Generally, carbonation propagation is the procedure of CO_2 diffusion into the concrete components of the environment. The depth of carbonation in concrete increases with a rise in the rate of CO_2 transmission, as well as the penetration depth [44]. In addition to the environmental issues, the existence of cracks and a network of pores in concrete components as a passageway for CO_2 diffusion led to an increase in the depth of carbonation [45]. Therefore, it is expected that the inclusion of fibers into the concrete can provides a grid network in the matrix, which reduce the development of cracks through the anti-cracking nature of the fiber, and consequently, reduce the capillary of concrete and depth of carbonation, as stated by Zhang and Shao [46].

The results of the carbonation test revealed that by the inclusion of waste PP fiber to the PAFRC mixes up to a certain dosage, reduce the carbonation depth. It can be seen that at the age of 90 days, the addition of PP fibers at dosages of 0, 0.25%, 0.5%, 0.75%, 1%, and 1.25% to the gravity method PAFRC specimens results in the carbonation depths of 0.33, 0.31, 0.26, 0.36, 0.45, and 0.61 mm, respectively. However, at the same day of testing, the lower depths of carbonation were noted for the pumping method PAFRC specimens as 0.16, 0.14, 0.1, 0.12, 0.2, and 0.25 mm for the same fiber dosages, respectively. Moreover, with an increase in the diffusion period, the depth of carbonation increased. For example, at 365 days of diffusion, the carbonation depths of 1.1, 0.92, 0.8, 1.06, 1.25, and 1.6 mm were noted for the gravity method PAFRC mixes comprising 0, 0.25%, 0.5%, 0.75%, 1%, and 1.25% PP fibers, correspondingly. Whereas, the carbonation depths of 0.85, 0.7, 0.63, 0.74, 0.98, and 1.15 mm were obtained for the same fiber contents in pumping method specimens. At best, with the addition of 0.5% PP fibers, the carbonation depth reduced by about 26% as associated with that of the control mix (P0).

It can be seen that the depths of carbonation were relatively lesser in the PAFRC samples of the pumping method than those specimens of gravity method. The denser matrix of specimens poured by the pump and lower volume of voids results in a smaller depth of carbonation [3]. To the author's best knowledge, there is no literature on the carbonation depth of PAFRC reinforced with PP fibers; however, the outcomes of the current study are similar to the results described by Gupta et al. [47]. They stated that the polypropylene fibers are the potential to decrease the carbonation depth of conventional fiber reinforced concrete by providing a grid network in the matrix and reduced the porosity, and therefore, prevent the diffusion of disturbance gas and other constituent parts.

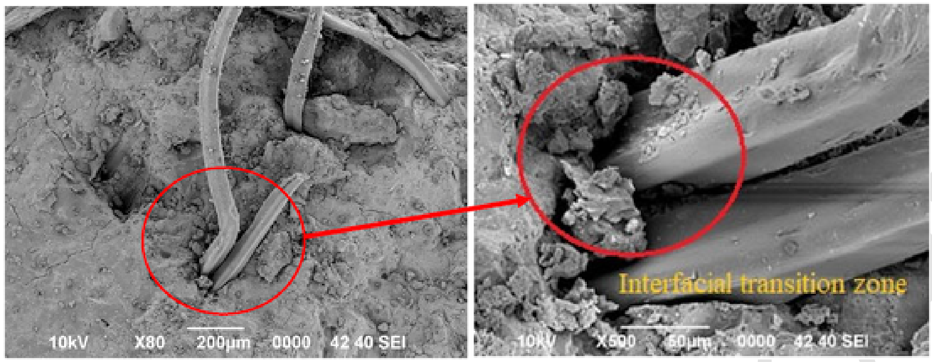

Fig. 9. Distribution of PP fibers and the interfacial transition zone between paste and fiber cured in water for 365 days.

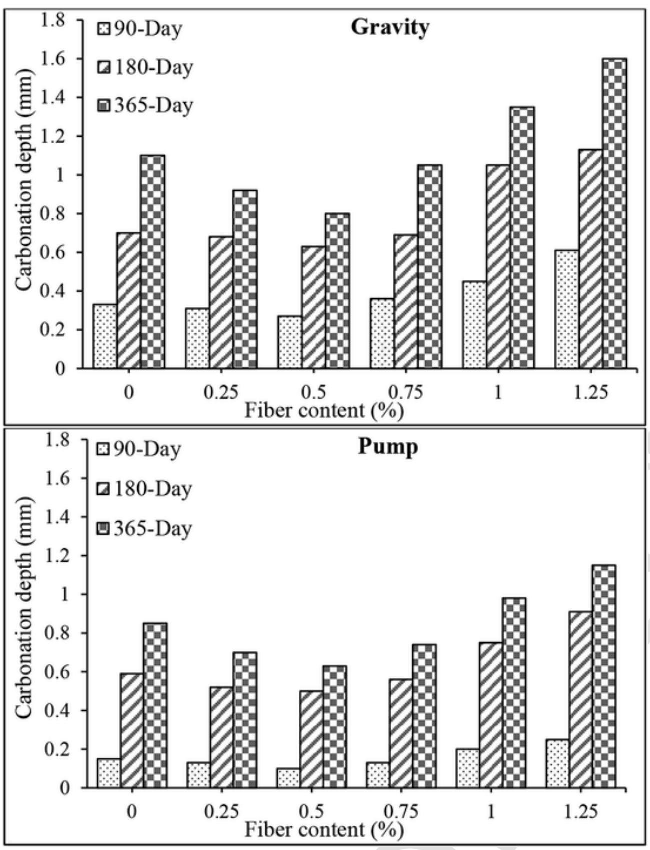

Fig. 10. Carbonation depth of PAFRC specimens.

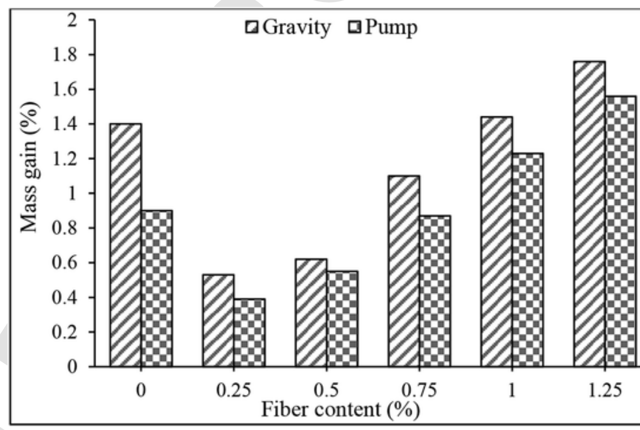

Fig. 11. Variation in the mass of PAFRC specimens exposed to sulfate solution.

3.4. Sulfate resistance

In this study, the PAFRC specimens were exposed to 10% $MgSO_4$ solution for 365 days, and the influence of sulfate attack on the variation in the mass of concrete specimens after one-year immersion was assessed. In this regard, the mass of PAFRC specimens before and after one-year immersion were recorded. From the obtained results, it can be detected that all of the PAFRC specimens were suffered by the sulfate attack and consequences in the mass gain through absorption of the sulfate constituent parts after one-year exposure.

As revealed in Fig. 11, it can be seen that the masses of plain PAC mixes of gravity (G0), and pumping (P0) methods were gained by about 1.4% and 0.9%, respectively. Nevertheless, the reinforcement of PAFRC mixes with PP fiber at dosages of 0.25%, 0.5%, 0.75%, 1%, and 1.25% resulted in the mass gain by 0.53%, 0.62%, 1.1%, 1.44%, and 1.76%, respectively, for the gravity method. However, a lower rate of mass gain was noted for the pumping method PAFRC specimens where the gain in masses was recorded as 0.39%, 0.55%, 0.87%, 1.23% for the same fiber dosages, respectively. The outcomes exposed that the addition of PP fibers up to 0.75% resulted in a significant reduction in the mass gain of PAFRC specimens. Nevertheless, a further rise in the fiber content results in a higher rate of mass gain in the samples immersed in a sulfate solution. The lower percentage of mass gain in the pumping PAFRC samples might be owing to the development of a grid structure in the matrix by fibers, which banned the diffusion and disruption of harmful constituents into the matrix. Therefore, the combination of PP fibers and in PAFRC specimens under sulfate environment is beneficial to provide a dense microstructure and filled up the holes by superior pozzolanic action [48–50].

In addition, the effect of sulfate exposure on the performance of PAFRC specimens in terms of compressive strength was assessed. The residual compressive strength values of PAFRC specimens after one-year exposure in 10% $MgSO_4$ solution were measured, and the results are illustrated in Fig. 12. It can be seen that the PAFRC specimens exposed to sulfate solution were suffered, and the compressive strength was negatively affected; whereas, the companion PAFRC samples cured in water gained their strength with continued hydration process.

The results indicated that the rate of strength losses in the PAFRC specimens of gravity technique was higher than those of pumping technique mixes for all fiber dosages. For example, the strength losses of 10.2, 7.1, 5.5, 9.2, 12.3, and 14 MPa were noted for gravity method PAFRC specimens comprising 0, 0.25, 0.5, 0.75, 1, and 1.25% PP fiber, correspondingly. Although in the pumping method PAFRC mixes with the same fiber dosages, relatively lesser strength losses of 8.5, 6.1, 4.2, 9.1, 11.2, and 13.1 MPa were noted, respectively. The losses in the strength of PAFRC mixes could be owed to the long-term immersion of specimens in the $MgSO_4$ solution, which slow down the hydration process as compared to those companion specimens cured in water. Moreover, the formation of cracks in the plain PAC specimens as a result of sulfate attack leads to accelerate the loss in strength of concrete. Nevertheless,

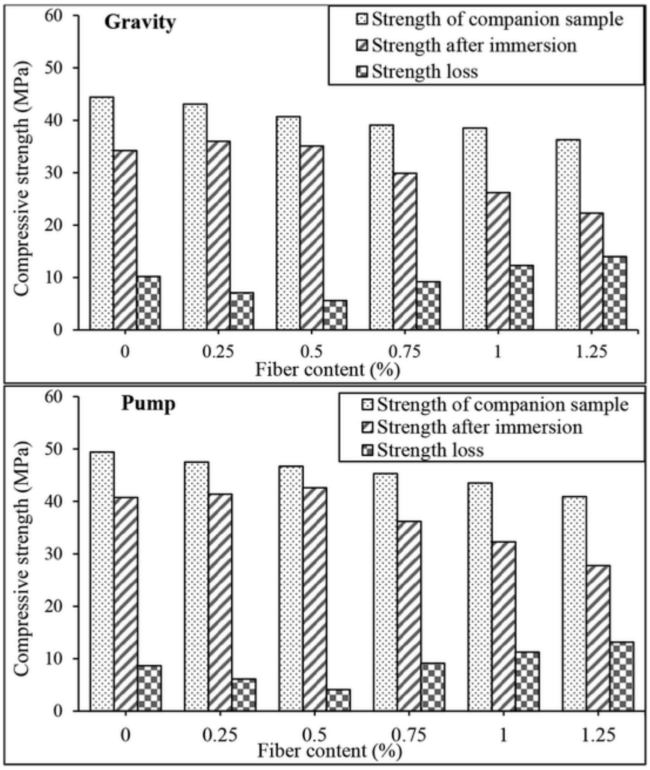

Fig. 12. Residual compressive strength of PAFRC specimens exposed to sulfate solution.

the PP fibers and POFA together helped to minimize the development of cracks and prevented the spalling of PAFRC specimens. As there is a lack of literature on the performance of prepacked aggregate concrete at the sulfate environment, the outcomes of this study are comparable to those results stated by Al-Rousan et al. [51] on the potential use of PP fibers to enhance the sulfate resistance of conventional fiber reinforced concrete.

Moreover, in this study, the strength loss factor (SLF) of PAFRC specimens owing to the deterioration by sulfate attack was assessed. The outcomes of SLF after one-year exposure in sulfate solution are revealed in Fig. 13. The SLF developed for all PAFRC mixes, which signifies the negative effect of sulfate attack on the strength of PAFRC samples after 365 days of exposure. It can be seen that the SLF values noted for the gravity method PAFRC samples are relatively greater than those obtained for pumping method PAFRC samples. It is interesting to note that the lower SLF value of about 9% was found for the PAFRC mix reinforced with 0.5% PP fibers (P0), which indicates the superior performance of pumping method PAFRC specimens under sulfate attacks.

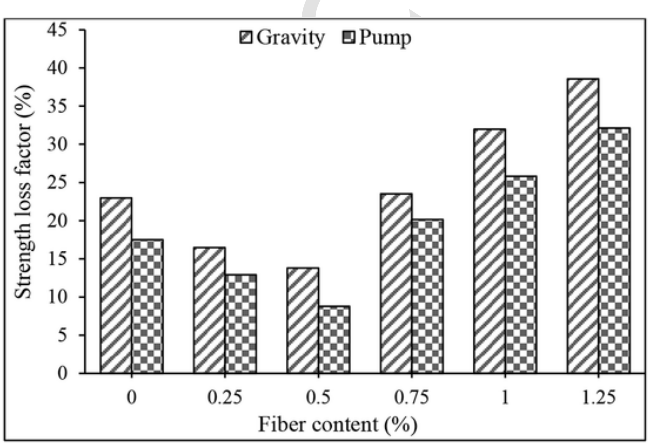

Fig. 13. Strength loss factors of PAFRC specimens exposed to sulfate solution.

3.5. Acid resistance

In this study, to assess the effects of the acid solution on the PAFRC specimens, the variation in the mass of PAFRC samples after one-year exposure to 5% H_2SO_4 solution was recorded and illustrated in Fig. 14. It can be seen that all PAFRC specimens followed a trend of mass loss after one-year immersion. The obtained results revealed that the gravity method PAFRC specimens loss their masses at a higher rate than those of pumping PAFRC specimens. It indicates that the gravity method PAFRC specimens washed out at a higher rate during the exposure period. The reinforcement of gravity method PAFRC samples comprising fibers at dosages of 0.25, 0.5, 0.75, 1, and 1.25% resulted in the mass losses of 13.85%, 10.3%, 8.13%, 7%, and 5.5%, correspondingly, which all are lesser than that of 19.18% recorded for a plain mix without fibers (G0). While comparatively lower mass loss values were noted for pumping method PAFRC specimens. For example, the mass losses of 11.1%, 8.4%, 6.1%, 4.1%, and 3.5% were recorded for the same fiber dosages, correspondingly, which are relatively lesser than that of 16.4% measured for the plain mix (P0). The lower percentage of mass loss in the PAFRC specimens containing PP fibers might be owing to the linking action of PP fibers and arrest the aggregates and cement past particles and, therefore, prevent the spalling and washed out the specimens exposed to the acid solution [17].

Moreover, the residual compressive strength of PAFRC specimens after 365 days immersion in the H_2SO_4 solution was measured, and the results are revealed in Fig. 15. The results indicate that the long-term exposure in acid solution, remarkably affect the strength of concrete. It can be observed that the percentage of strength loss, which is the difference between the strength of the water-cured specimens and those exposed to the acid solution, decreased with an increase in the fiber dosages. Besides, the rate of strength loss was found to be greater in the gravity method PAFRC specimens than that of pumping method specimens. For gravity method mixes comprising 0.25%, 0.5%, 0.75%, 1%, and 1.25% fiber, the strength losses were obtained as 27.54, 25.1, 23.6, 21.8, and 21.3 MPa, respectively, which are all lower than that of 31.1 MPa recorded for plain mix (G0), that signifies the positive effect of fibers in controlling the strength loss in an acidic environment. Whereas, relatively lower strength losses of 25.7, 23.1, 21.8, 20.6, and 20.3 MPa were noted for pumping method PAFRC specimens containing the same fiber volume fractions, respectively, which are lower than that of 28.8 MPa noted for a plain mix without any fibers (P0).

The enhanced performance of PAFRC specimens containing PP fibers under acid attacks might be owing to the linking action of PP fibers, which banned the crack formation and, consequently, reduce the spalling of samples. Furthermore, the existence of POFA, which contains lower CaO content as compared to OPC, as CaO quickly dissolves in acid, resulted in the lower rate of washing out in the PAFRC specimens [18]. Therefore, the combination of PP fibers and POFA leads to enhance the durability performance of PAFRC specimens exposed to acidic environments.

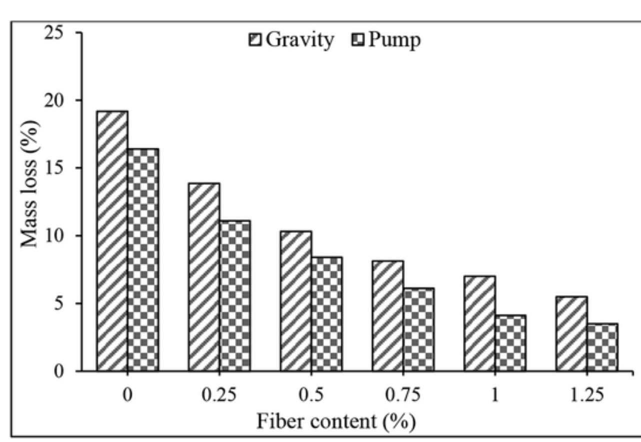

Fig. 14. Mass loss of PAFRC specimens exposed to the acid solution.

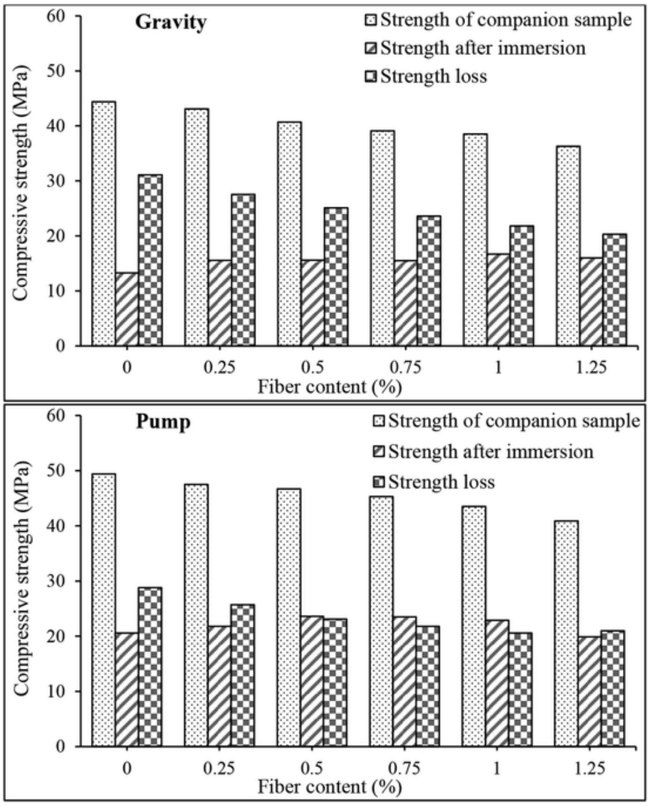

Fig. 15. Residual compressive strength of PAFRC exposed to the acid solution.

Additionally, the SLF values of PAFRC mixes containing PP fibers after one-year exposure in acid solution were measured and revealed in Fig. 16. As mentioned earlier, the combination of POFA and fibers significantly enhanced the performance of PAFRC specimens under the acid attacks. Due to the linking action of fibers, which connect the aggregates and cement particles and prevent the spalling of specimens, in addition to the formation of extra C–S–H gels through the pozzolanic activity of POFA, the SLF values were remarkably lower in the reinforced PAFRC mixes as related to those of plain prepacked aggregate concrete specimens. It was also observed that the pumping method specimens performed better in terms of SLF than that of gravity method, which is the result of well distribution of grout into the gaps between the aggregates and fibers, and consequently, provide a denser microstructure and superior performance against acid attack [52].

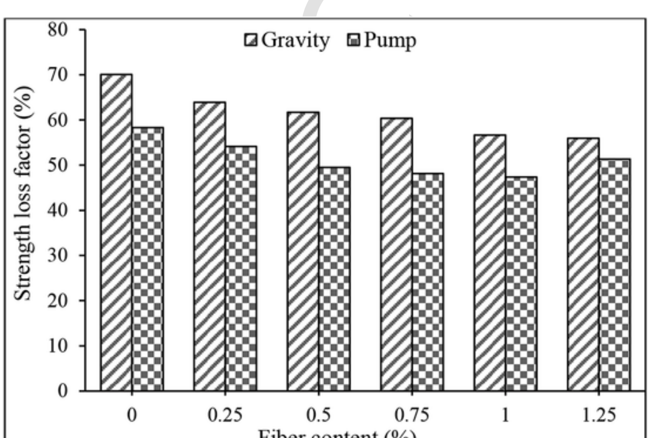

Fig. 16. Strength loss factors of PAFRC specimens exposed to the acid solution.

3.6. Heat transfer

Heat transfer is the process where heat transfers from a high-temperature body to low temperature body. In the thermodynamic points of view, heat transfer is the movement of heat throughout the boundary of the system owing to temperature difference amongst the surrounding and system. The heat transfer process will be continued until there is no difference between the temperatures of two bodies, which called thermal equilibrium [53]. In this study, the heat transfer test was carried out through the boiling water, which considered as the hot body and PAFRC specimens as cold bodies. Therefore, while boiling water in the temperature-controlled tank, the mid-depth temperature of PAFRC specimens was recorded by using a thermocouple, and the variations in the temperature of the water and concrete specimens were measured until both temperatures reached to 100 °C. The variation in the temperatures of water and the center of PAFRC specimens along with time is illustrated in Fig. 17.

As revealed in Fig. 17, the temperature of water reached to 100 °C after 21.5 h from the test was initiated. Besides, the mid-depth temperatures of control plain specimens without any fibers, reached to100 °C after 22.2 and 23 h after the test was initiated for gravity method and pumping method specimens, respectively. However, with the reinforcement of PAFRC specimens with PP fibers, the time in which mid-depth temperature of specimens to reach at 100 °C increased. On the other hand, the existence of fibers delays the heat transfer process. For example, for the gravity technique PAFRC specimens containing 0.25%, 0.5%, and 0.75% PP fibers, the mid-depth temperatures reached to 100 °C after 24, 27, and 29 h after the test was started. Whereas, a comparatively lower rate of heat transfer was noted for the pumping method specimens. For instance, the mid-depth temperatures of PAFRC specimens reached to 100 °C after 25, 28, and 31 h after the test was started, for the same fiber dosages, respectively. Besides, the influence of fiber at higher dosages was more significant on the delay of the time at which the inner temperature of PAFRC specimens reached the 100 °C. The thermal insulation nature of PP fibers, as well as the pozzolanic activity of POFA, which provides a denser mi-

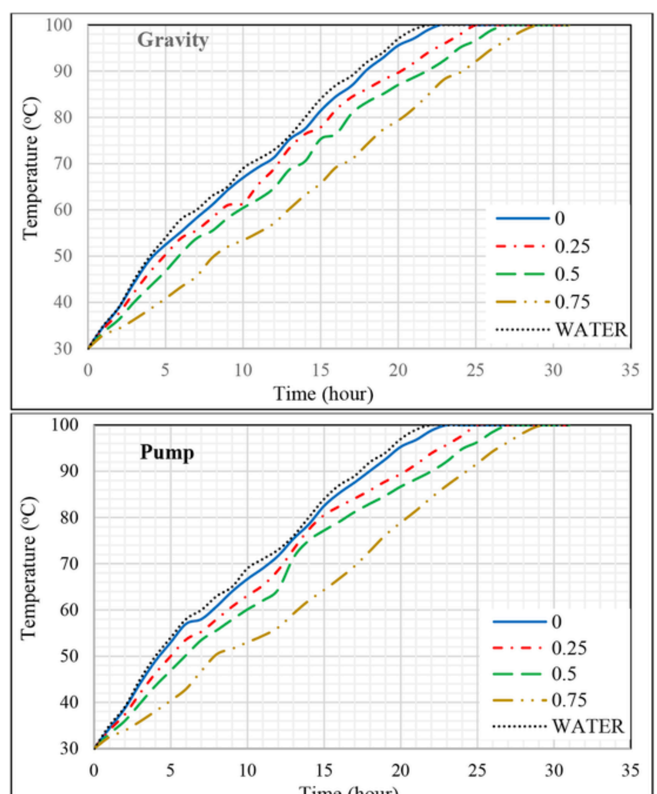

Fig. 17. Effects of PP fibers on the heat transfer property of PAFRC mixes in the boiled water.

crostructure, resulted in the better performance of PAFRC specimens to delay the time of heat transfer to the middle part of concrete [27,54]. Therefore, based on the obtained results, it can be detected that the PAFRC specimens containing POFA and waste PP fibers are potential to be used as insulated concrete components with a lower rate of heat transfer.

4. Conclusions

Considering the developing in the novel construction materials such as concrete, which is vulnerable in the aggressive environment, the current study proposed a new prepacked aggregate concrete reinforced with polypropylene fibers, and critically investigated the long-term strength properties, the resistance against sulfuric acid and magnesium sulfate solutions, in addition to the heat transfer property. The following are the conclusions made based on a visual inspection and experimental results:

- The inclusion of waste PP fibers slightly reduced the compressive strength of PAFRC mixes. However, due to the pozzolanic nature of POFA, the long-term strength values of up to 50 MPa were noted after one year of curing in water.
- The tensile strength of all PAFRC specimens enhanced significantly by adding waste PP fibers. The maximum tensile strength of 5.6 MPa was noted for the PAFRC mix comprising 0.75% fibers poured by a pump at the age of 365 days.
- The reinforcement of PAFRC mixes with PP fiber up to 0.75%, results in the reduction of carbonation depth. After 365 days of exposure to outdoor CO_2, the lowest depth of carbonation was obtained for the PAFRC mix of pumping method comprising 0.5% PP fiber as 0.63 mm, which is about 26% lesser than that of 0.85 mm recorded for the plain PAC mix.
- PAFRC specimens revealed an enhanced performance in the resistance against sulfate attacks as the consequence of PP fibers and POFA. The combination of POFA and fibers was attributed to the creation of a grid network and dense matrix to escape the entering of destructive particles into the matrix and crack formation. Moreover, the lower rate of mass gain and strength losses were detected for PAFRC specimens exposed to sulfate solution.
- PAFRC specimens performed an adequate level of acid resistance. The primary consequence of the existence of PP fibers and POFA in the matrix was attributed to the dilution effect of pastes owing to the replacement of OPC by POFA, which decreased the existing amount of $Ca(OH)_2$ content for reaction with acid and formation of gypsum. PP fibers also prevent reduced the rate of washing out and prevent the spalling of specimens. Also, a lower rate of mass and strength losses were perceived for the reinforced PAFRC mixes.
- The combination of PP fibers and POFA, which provides a denser microstructure, resulted in the better performance of PAFRC specimens to delay the time of heat transfer to the middle part of concrete.
- Based on the obtained results, it can be detected that the PAFRC specimens comprising POFA and waste PP fiber are potential to be used as structures with massive reinforcement through retrofitting and concrete components exposed to aggressive environments as well as insulated concrete components with a lower rate of heat transfer.

CRediT authorship contribution statement

Hossein Mohammadhosseini: Conceptualization, Formal analysis, Investigation, Writing - original draft, preparation, Writing - review & editing, Writing - review & editing. **Fahed Alrshoudi:** Conceptualization, Formal analysis, Resources, Writing - review & editing. **Mahmood Md Tahir:** Conceptualization, Supervision. **Rayed Alyousef:** Methodology, Investigation, Resources. **Hussam Alghamdi:** Methodology. **Yousef R. Alharbi:** Validation, Data curation, Visualization. **Abdulaziz Alsaif:** Validation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2020.101723.

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