Journal of Building Engineering 27 (2020) 101003

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Enhancement of strength and transport properties of a novel preplaced aggregate fiber reinforced concrete by adding waste polypropylene carpet fibers

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ARTICLE INFO

Keywords:
Preplaced aggregate fiber reinforced concrete
Two-stage concrete
Transport properties
Strength
Polypropylene carpet fibers

ABSTRACT

Preplaced aggregate concrete (PAC), also known as two-stage concrete (TSC), is a particular type of concrete that is produced by placing coarse aggregates in a form and voids amongst them are then injected with a flowable grout. The preplaced aggregate fiber reinforced concrete (PAFRC) is new developed concrete, with a unique mixture of coarse aggregates and short fibers that are premixed and preplaced in the formwork and injecting grout into the voids of the aggregate mass. The current study develops the concept of a new PAFRC reinforced with waste polypropylene (PP) carpet fibers and investigate its strength and transport properties. Palm oil fuel ash (POFA) was used as partial cement replacement. Six PAFRC mixes with fibers varying from 0 to 1.25% with a length of 30 mm were made by the gravity method. Another six batches with the similar fiber dosages were made, where the pumping method was used to inject the grout into the voids between the aggregates. The results showed that by adding carpet fibers, the compressive strength of PAFRC specimens reduced. However, the PAFRC specimens revealed a notable enhancement in the tensile strength values. Moreover, water absorption, sorptivity, and chloride penetration depth were reduced for POFA-based PAFRC specimens reinforced with carpet fibers. The study revealed that the carpet fibers are potential to be used in PAFRC by developing the transport and strength properties.

1. Introduction

Preplaced aggregate concrete (PAC) is described as concrete manufactured by placing coarse aggregates in the designed forms, subsequently filling the inner voids and openings with a unique mixture of sand and cement in the form of the grout. The PAC method was first described in the 1930s [1,2]. The term PAC refers to a technique of placing the aggregates, rather than a particular kind of concrete [3]. In general, conventional plain concrete is produced by mixing all the components and pouring the matrix into a formwork. However, PAC is made by placing clean, course gap graded aggregates into the designed forms and injecting a flowable cement-based grout, usually with admixtures into the cavities between the aggregates where it hardens to form concrete [4,5]. Since in PAC, segregation of the aggregates is eliminated with the unique placing of aggregates in the formwork, grouting techniques produce concrete with more uniform properties than that of conventional concrete. Therefore, using the PAC method consequences in a denser matrix with higher strength owing to the high pressure and the point-to-point contact of large aggregates [1,6].

In PAC, the method of grouting can be achieved either by pumping or gravity [1,7,8]. In the gravity grouting or penetration technique, the grout which is a mixture of cementing particles and fine aggregates is injected from the top surface of the formwork where coarse aggregates placed earlier and allowed to pass through the aggregate mass to the lowermost of the formwork under the gravity force and filled up the gaps between the aggregates. Nevertheless, the gravity grouting method is suitable for sections with 300 mm depth or lower [9]. In the pumping method, a high-pressure pump used to inject the grout between the

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https://doi.org/10.1016/j.jobe.2019.101003
Received 6 August 2019; Received in revised form 13 September 2019; Accepted 15 October 2019
Available online 16 October 2019
2352-7102/

aggregates through a network of pipes from the bottommost section of formwork. In this method, the pressure used for pumping depends on the size of aggregates as well as the depth of sections. In PAC, the minimum size of coarse aggregates is one of the primary criteria in choosing the appropriate method of grouting. For example, the pumping technique is used for PAC with finer aggregates where the size and amount of voids are smaller, whereas the gravity method is preferred for PAC containing the higher size of aggregates [10–12].

In concrete components, the high rigidity and low tensile strength are the key issues which categorized concrete as a brittle material [13,14]. Preplaced aggregate concrete has shown specifically functional in various applications such as underwater construction, retrofitting the existing concrete structures with massive reinforcement where a good bond is essential for the new concrete to be integrated with components [11]. In addition, PAC can be used to repair the concrete and masonry construction. Consequently, high strength and superior durability performance are required in the applications above for PAC as well as conventional concrete. In this regards, additional constituents are essential to improve the performance of concrete with higher tensile strength and transport properties. Therefore, novel construction materials that can enhance the properties of concrete and better ductility performance are much in demand. Therefore, a possible solution to attain such properties of concrete is by adding short and discontinuous fibers at different volume fraction into the concrete mixture [15,16].

Preplaced aggregate fiber reinforced concrete (PAFRC) is a new composite material made of preplaced coarse aggregates mixed with short fibers at various dosages, and cementing materials mix with fine aggregates in the form of grout to inject into the mixture of preplaced aggregates and fibers. The reinforcement of conventional concrete with various type of fibers such as metallic and polymeric fibers at dosages of 0.1%–2.0% have been established by many researchers [17,18]. In concrete components, short fibers bridging the cracks through a mechanism that restrain cracks opening with an increase in the energy absorption and avoid the quick collapse of concrete components. Several types of research have been carried out to explore the ductility performance of concrete reinforced with short fibers through the impact resistance test. It has been observed that the adding of steel or polymeric fibers noticeably improves the impact resistance of concrete [19,20]. However, PAFRC is a new type of concrete reinforced with fibers.

There is currently a lack of literature on the durability of preplaced aggregate concrete to permeability and chloride diffusion. Recently, the production and development of layered concrete is receiving more attention in order to enhance the strength properties and impact resistance of concrete structures. However, the durability performance of PAC or layered concrete is still mostly unexplored and lacks dedicated researches. In regards to the said matter, Najjar et al. [10] investigated the durability performance of two-stage concrete exposed to sulfate attack. Their results revealed that the two-stage concrete specimens incorporating supplementary cementing materials such as fly ash and silica fume significantly enhance the performance of specimens exposed to sulfate attacks. In conventional concrete, several researchers, for example, Toutanji [21] specified that by adding PP fibers into the mixture, the permeability of concrete specimens improved by providing a grid structure and prevent the entering of liquids into concrete components. Similarly, Mohammadhosseini et al. [22] and Medina et al. [23] stated that fiber-reinforced concrete containing silica fume and fly ash revealed satisfactory durability performance in various aggressive environments.

In the last few decades, several researchers have explored the potential use of waste materials in concrete and their effects on the performance of concrete. In this regard, the production of polymer-based fibers used in carpet and textile industries has been gradually growing, currently beyond 70 million tons annually [24]. In Malaysia, nearly 50 tons of polypropylene fibers used in carpet industries in different forms sent to landfill every year [25]. Though, the option of disposing of wastes is becoming gradually impracticable due to increasing the cost of landfilling as well as the limitations on the available discarding sites [26]. Therefore, the demand to reutilize these waste materials is rising due to the deficiency of landfill sites all around the world and conservation of raw materials. The lower cost of processing than that of existing fibers in the market, hydrophobic nature, and excellent chemical resistance are the main advantages of using industrial waste polypropylene carpet fibers in the production of sustainable construction materials [27].

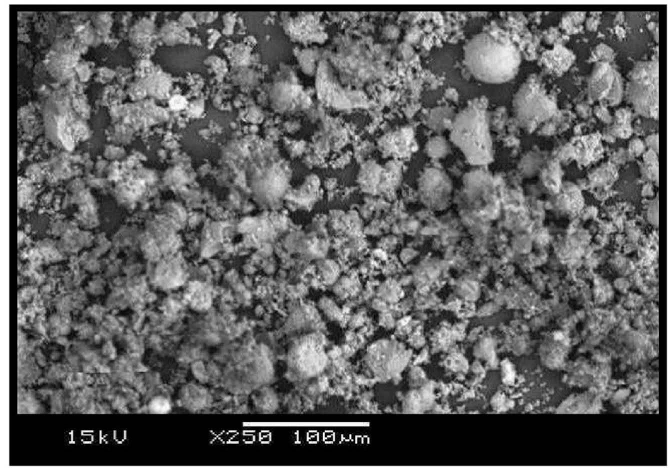

Fig. 1. Scanning electron micrograph of POFA.

In concrete components exposed to chemical attacks, the penetration of disturbance particles into the specimens is one of the main concerns to avoid the deterioration by chemicals. Therefore, the use of pozzolanic materials as partial cement replacement to produce additional hydration products such as C-S-H gels and provide a dense microstructure is well recognized. In regards to the said matter, palm oil fuel ash (POFA) is one of the pozzolanic materials used in a wide range in the production of construction materials [28]. The production of POFA in Malaysia has been reached to about 5 million tons per year, which sent to landfill as waste material [29]. The production rate of POFA is expected to rise with growing the palm trees plantation. According to past researches, the POFA has potential to be used as supplementary cementing materials with high pozzolanic reactivity that can be used in the production of concrete with adequate strength and durability as well as the lower heat of hydration than that of OPC [30,31].

Beside conventional concrete, the aspect of preplaced aggregate

Table 1
Chemical compositions and physical properties of Portland cement and palm oil fuel ash.

Composition	Portland cement (%)	Palm oil fuel ash (%)	Allowable limit
SiO_2	20.40	62.60	
Al_2O_3	5.20	4.65	≤6% (ASTM C150)
Fe_2O_3	4.19	8.12	≤6% (ASTM C150)
CaO	62.39	5.70	
MgO	1.55	3.52	≤6% (ASTM C150)
K_2O	0.005	9.05	
SO_3	2.11	1.16	3–3.5% (ASTM C150)
LOI	2.36	6.25	≤3% (ASTM C150)
Physical properties			
Specific gravity	3.15	2.42	
Blaine fineness (cm^2/g)	3990	4930	≥260 (ASTM C150)
Soundness (mm)	1.0	2.0	

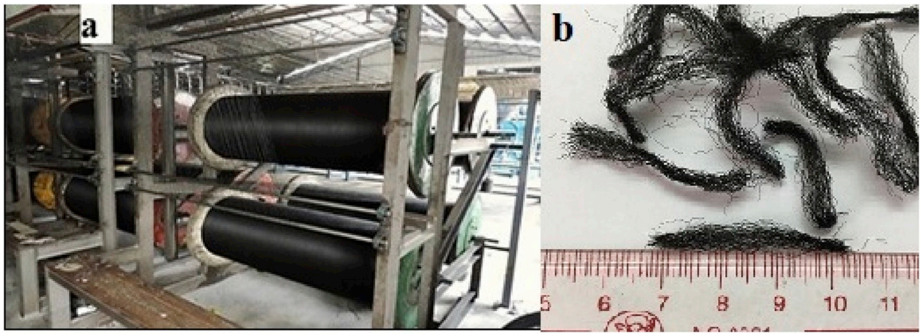

Fig. 2. (a) The yarn used in carpet manufacturing; (b) Fabricated waste carpet fibers used.

concrete is much considered particularly in particular applications. To date and the authors' best knowledge, there is no study on the strength and transport properties of preplaced aggregate concrete containing polypropylene waste carpet fibers and POFA as partial cement replacement. Consequently, as the POFA categorized as pozzolanic material in addition to the local accessibility of industrial carpet waste fibers, the said materials were used in the production of PAC to investigate their effects on the strength and transport properties.

2. Materials and test methods

2.1. Materials

In this research, the type I ordinary Portland cement (OPC) was consumed following ASTM C 150–2007. The palm oil fuel ash was also collected from a palm oil mill located in Johor, Malaysia. Before the ash can be used as a cement replacement, more massive particles were removed, and the carbon content was minimized, and then the ash was kept in the furnace at the temperature of $100 \pm 5\,^{\circ}C$ to evaporate the moisture. Subsequently, the ashes were sieved, and particles passed through a sieve of size 150 μm were kept in a modified Los Angeles abrasion machine and ground for around 2 h per four kg of ashes. Finally, the very fine POFA were collected which conforms to the requirements of BS 3892: Part 1–1992. The obtained POFA can be considered as class C and F, according to the ASTM C618-2015 specifications. A typical electron micrograph of POFA used in this study is demonstrated in Fig. 1. The POFA particles have an extensive range of sizes, but they are relatively spherical. Table 1 displays the chemical and physical properties of Portland cement and palm oil fuel ash used in this study.

The fine aggregate used in this study was uncrushed river sand passed through ASTM sieve No. 14, with a specific gravity of 2.6, 0.70% water absorption, and fineness modulus of 2.3. In preplaced aggregate concrete, as the applied stresses are first transferred to the coarse aggregates and afterward to the hardened grout. Therefore the selection of aggregates in terms of size, shape, and quality is an important issue [1]. According to specifications by ACI 304.1R-1997, in PAC, the coarse aggregate must be washed to remove the surface dust to achieve a great bonding with the injected grout before placed in formwork. Crushed granite of size ranged between 20 and 38 mm, having a specific gravity of 2.7, and water absorption of 0.5% was consumed as coarse aggregates. Besides, to improve the flowability of fresh concrete, superplasticizer at a dosage of 1.0% was used. Carpet fibers were collected as a waste from the ENTEX Carpet Industries SDN. BHD., located in Malaysia. In this study, the multi-filament polypropylene carpet fiber, as shown in Fig. 2a,b was used. The length of fibers was selected as 30 mm and 67 as aspect ratio (l/d) based on the trial tests. Table 2 indicates the common properties of waste polypropylene carpet fibers.

2.2. Mix proportions

The various contents of used materials in the concrete mix compositions are displayed in Table 3. Overall, twelve preplaced aggregate concrete mixes were prepared in this study. The water/binder (w/b) ratio of 0.5 and cement/sand (c/s) ratio of 1/1.15 were kept for all mixes. In this study, two groups were designed, namely gravity (G) and pumping (P) groups. For each group, one batch was made as a control without any fibers, i.e., G0 and P0 for gravity and pumping methods, respectively. In addition, for each group, five PAFRC mixes were made were reinforced with PP carpet fibers at the dosages of 0%, 0.25%, 0.50%, 0.75%, 1.0%, and 1.25% namely G1-G5 and P1-P5 for gravity and pump methods, respectively. In all mixes, OPC was replaced by 20% POFA.

2.3. Sample preparation

The preparation of PAFRC was carried in two stages. First, placing the mixture of coarse aggregates and PP carpet fibers in the designed formworks, and second, injecting the grout by gravity and pump methods into the molds to fill up the gaps amongst the aggregate particles. In order to obtain a uniform mixture, the coarse aggregates and carpet fibers were dry mixed for about 2 min and then placed in the formwork. In this study, the cylindrical samples of size 100×200 mm and 150×300 mm were used for gravity methods, as illustrated in Fig. 3a. In addition, in the pumping method, the unplasticized polyvinyl chloride (UPVC) pipes with 100 mm and 150 mm diameters were used as a mold and placed in a designed plywood formwork base (Fig. 3b). A detailed schematic of the designed formwork for pumping method is illustrated in Fig. 4. A plywood cap was used on the top of the UPVC tubes to preventing the lifting of aggregates during the grout injecting process. Also, a mild steel cone with a steel ball was attached to the platform under the tube which acts as a one-way valve to ensure the consistent flowing of grout mixture through the section of the tube.

The grout, which was the mixture of blended cement and fine aggregates, were prepared by using an electric mixer. The mixing process was about 5 min to get the required consistency. Subsequently, the flowable grout was placed into the grout hopper with continuously stirring for the entire grouting process, to prevent the segregation of particles in the grout. In this study, as shown in Fig. 3b, a hand pump with pressure controlling device was connected to the hopper for the

Table 2
General properties of waste polypropylene carpet fibers.

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

Table 3
The proportions of the various constituents used in the concrete 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 (%)
	[a]G0	186	304	76	545	1320	–
Gravity	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
	[b]P0	186	304	76	545	1320	–
Pump	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

[a] Gravity method.
[b] Pumping method.

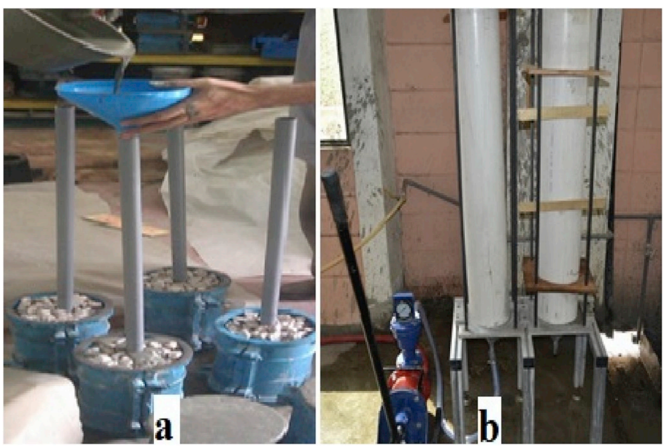

Fig. 3. Grouting methods of PAFRC: a) Gravity; b) Pumping.

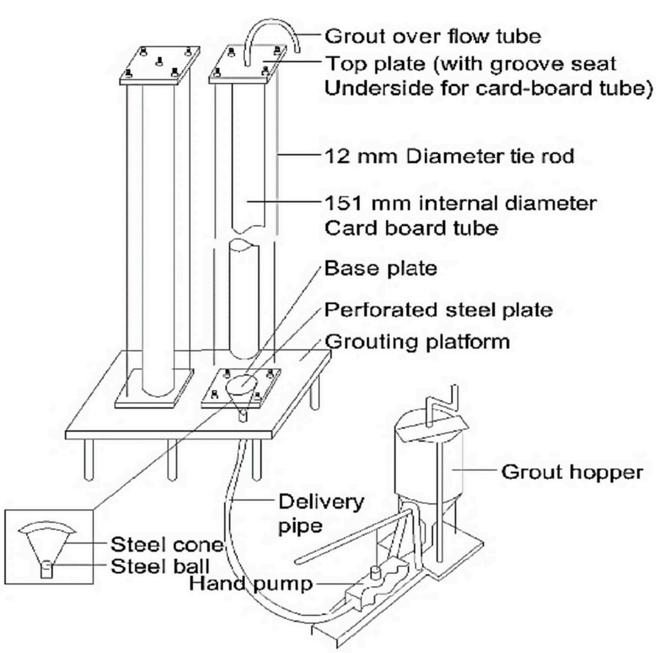

Fig. 4. Schematic process of grouting by pumping method.

grout injecting purpose into the tubes and formworks. Besides, in the gravity method, the grout mix was injected through a PVC pipe having a diameter of 5 mm under gravitational force into the cylindrical molds, as revealed in Fig. 3a. While casting PAFRC specific care was taken to assure that the grout was not leaked out. After casting was done, the specimens were cured in a room temperature of 20 ± 5 °C for 24 h. Then the samples were demolded and kept in water tank for 28 and 90 days prior to testing.

2.4. Testing methods

The fresh properties of grout in terms of grout fluidity (sec) and bleeding (%). To assess the influence of POFA on the consistency of grout, the flow characteristics of the grout was studied in accordance with ASTM C939-16. In addition, the bleeding of the grout was evaluated by pouring 800 ± 10 ml of fresh grout mixes inside a 1000 ml glass graduate following the specification of ASTM C940-16. To evaluate the compressive strength and splitting tensile strength of PAFRC specimens, cylindrical samples of size 100 mm × 200 mm were prepared, cast, and tested in accordance with ASTM C39M-18 and ASTM C496M-17, respectively. In addition, concrete disks of size 100 mm × 50 mm following the specifications of ASTM C1585-13 were prepared and tested for the sorptivity test as illustrated in Fig. 5. Before the test, the concrete disks were placed in an oven at a temperature of 50 ± 2 °C consistently for 72 h. Succeeding, the concrete disks were placed in a sealable container for 15 days in order to control the moisture content. After 15 days, the specimens were out, and the initial mass was recorded to the adjacent of 0.01 g. The average of three recorded values was then used for each concrete batch.

In this study, to assess the depth of chloride penetration of PAFRC specimens reinforced with carpet fibers, cylindrical specimens similar to the tensile strength test of 100 × 200 mm were prepared and tested. After casting, the concrete specimens were then cured in water for 28 days. Once the curing period is done, the cylinders were immersed in a 5% sodium chloride (NaCl) solution. The exposure periods were designed for 7, 28, and 90 days. Three samples were prepared for each PAFRC batch at the end of exposure time and split the cylindrical specimens into two parts along the length. Then, the freshly exposed faces of the specimens were sprayed with 0.1 N silver nitrate ($AgNO_3$) solution to observe the penetration depth. As shown in Fig. 6, directly after spray the $AgNO_3$ solution, the outer portions of the samples were brighter owed to the silvery deposit of silver chloride (AgCl), which indicates the penetration depth, although the internal portions were darker, owing to the existence and consequence of silver hydroxide (AgOH) [32].

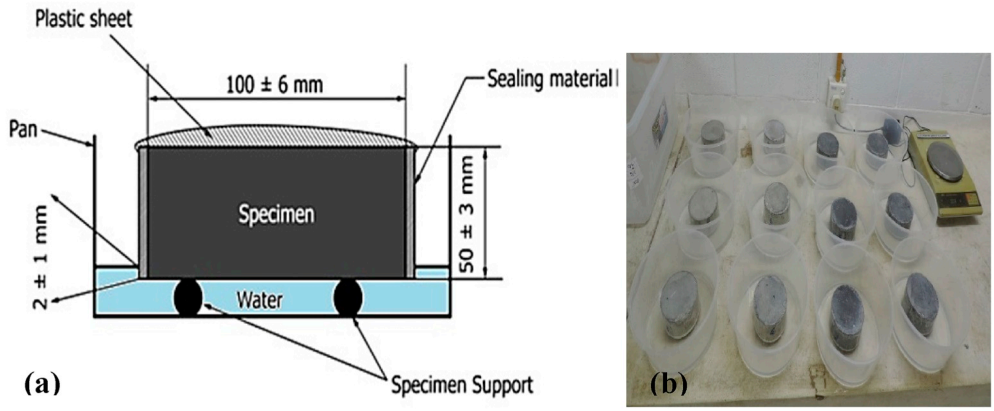

Fig. 5. (a) The procedure of sorptivity test; (b) concrete disk specimens used.

Fig. 6. The depth of chloride penetration depth measurement.

Table 4
Fresh properties of the grout.

Mix	Grout fluidity (sec)	Bleeding (%)
OPC	15.2	10.4
20% POFA	13.1	8.7

3. Results and discussion

3.1. Fresh properties of grout

In PAC, assessing the consistency of grout mixture is vital as it has a direct influence on voids penetrability and pumpability. In this study, the flow cone method was used for measuring the flowability of the grout. The effects of the POFA replacement on the grout consistency was investigated, and the results are given in Table 4. It can be seen that the inclusion of POFA at replacement level of 20% significantly increase the flowability of the grout. At the constant w/b of 0.5 and c/s of 1.15, the 20% POFA replacement resulted in higher grout fluidity. This is to note that the grout fluidity of POFA mixture was recorded as 13.1 s, which is lower than that of 15.2 s recorded for OPC mixture. It indicates that the POFA-based grout is more flowable than that of OPC grout. It could be due to the finer particle size of POFA than those of OPC particles [9] and also the relatively spherical shape of the POFA particles, as shown in Fig. 1. In addition, the results of a bleeding test for OPC and POFA grout mixtures are shown in Table 4. It can be seen that the POFA-based grout obtained a lower bleeding percentage as compared to that of OPC grout. The bleeding capacity of grout, which is the proportion of the bleed water to mixing water was recorded as 8.7% for POFA-based grout, which is comparatively lower than that of 10.4% recorded for OPC grout. This indicates that the replacement of POFA with finer particle size can absorb more water in the mix and reduce the bleeding.

3.2. Compressive strength

The experimental results of compressive strength for PAC and PAFRC

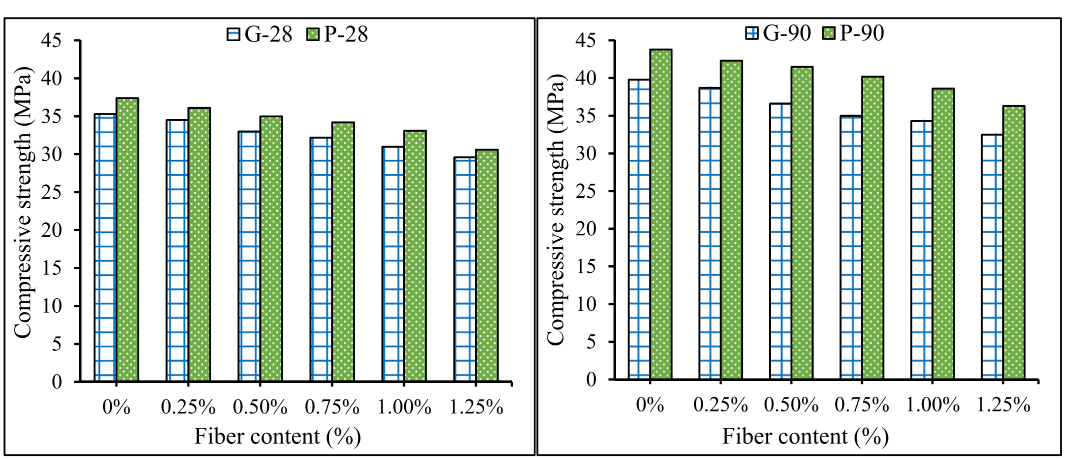

Fig. 7. Compressive strength of PAFRC mixes vs. fiber content.

specimens are illustrated in Fig. 7. The results show that the compressive strength of PAFRC mixtures decreased by increasing fibers content. It can be seen that there is a significant increase in the compressive strength of pumping method specimens with respect to gravity method specimens. Comparing the compressive strength values of cylindrical specimens at the age of 28-day for control PAC mixes without any fibers, the strength of pumping method specimens was about 6% higher than that of gravity method. Moreover, by adding PP carpet fibers to the PAFRC at the dosages of 0.25%, 0.5%, 0.75%, 1% and 1.25%, the cylindrical compressive strength of gravity method specimens decreased by about by 2.3%, 6.5%, 8.8%, 12.2% and 16.1%, respectively, as associated with control plain mix. Similarly, in pumping method specimens with the same fibers volume fractions, the compressive strength values decreased by approximately by 3.4%, 6.4%, 8.5%, 11.4%, and 18%, respectively. The decrease in the compressive strength of PAFRC specimens might be due to the presence of cavities in the matrix, which are increased by the inclusion of fibers at high dosage. Higher fiber content induces balling effect by fibers, voids formation, and clustering, consequently making the matrix weaker and prone to crack. It, therefore, reduce the amount of grout injected between the mixture of coarse aggregates and fibers and tends to the reduction in compressive strength of concrete [11].

However, at the curing period of 90-day, concerning the outcomes attained in PAFRC samples, a significant rise in compressive strength values were perceived in both gravity and pumping method specimens. As 20% POFA replaced OPC, the concrete strength tended to improve with the curing period for all fiber dosages. It might be owing to the higher fineness of POFA particles as well as the higher pozzolanic reactivity of POFA at ultimate ages, which results in the development of concrete strength [33]. It is interesting to note that, the results of PAFRC for pumping method specimens revealed the greater compressive strength relating to the gravity method specimens for the same fiber volume fractions. The attained findings of this study are in agreement with the outcomes reported by Murali and Ramprasad [11], who stated the effects of the fibers on the compressive strength of layered two-stage concrete slabs.

The microstructural analysis of grout paste used in OPC and POFA-based PAFRC mixes in terms of scanning electron microscopy (SEM) was conducted to attain a comprehensive consideration of the effects of POFA on the hydration procedure and strength development of the PAFRC. Fig. 8 illustrates SEM images of specimens at 90 days curing in water. The existence and homogeneous spreading of C-S-H gels for OPC and POFA specimens are shown. In the mixes containing POFA, due to the consumption of $Ca(OH)_2$ throughout the hydration procedure, mainly at ultimate curing times, the development of strength of concrete was significantly higher than that of OPC mixes. Following Eq. (1) and Eq. (2), while Portland cement is mixed with water, a calcium silicate hydrate (C-S-H) is formed, and subsequently, calcium hydroxide (CH) released. This chemical reaction is relatively speedy. On the other hand, once POFA is added to the mixture, the reactive silica (SiO_2) of POFA reacts with released CH in the hydration process to create extra C-S-H gels in the presence of water. However, the reaction is comparatively slow and then resulting in slow strength development as well as the lower heat of hydration [34].

$$\text{Hydration reaction: } C_2 \text{ or } C_3S + H_2O \text{ primary C-S-H gel} + Ca(OH)_2 \quad (1)$$

$$\text{Pozzolanic reaction: } Ca(OH)_2 + SiO_2 \text{ (POFA)} + H_2O \text{ secondary C-S-H gel} \quad (2)$$

3.3. Splitting tensile strength

As mentioned earlier, the evaluation of splitting tensile strength of PAFRC specimens was carried out using eighty-four cylindrical specimens of size 100 mm × 200 mm. The tensile strength of PAFRC samples was recorded and illustrated in Fig. 9. The results revealed that reinforcement of PAC with PP carpet fibers tends to increase the tensile strength values. It can be observed that by adding fibers and rise in fiber volume fractions, the tensile strength of PAFRC mixes was noticeably higher than those plain PAC without any fibers for both gravity and pumping methods.

As illustrated in Fig. 9, reinforcement of plain PAC specimens of gravity method resulted in an increase of 21.9%, 29.7%, 32.8%, 23.4% and 20.3% in tensile strength of PAFRC specimens with PP carpet fibers of 0.25%, 0.5%, 0.75%, 1% and 1.25%, respectively, with reference to G0 mix at the age of 90-day. Besides, for the same fiber dosages, an incensement of 18.9%, 24.3%, 31%, 20.3% and 15% in tensile strength of pumping method PAFRC specimens were recorded. Additionally, the obtained values of the tensile strength of pumping method PAFRC specimens were comparatively higher than those of gravity method specimens whereas; the maximum tensile strength was measured as 4.85 MPa for mix P3 with 0.75% fibers, which is 51.5% and 31% higher than those plain mixes of G0 and P0, respectively. This enhancement in tensile strength of PAFRC specimens might be due to arresting cracks in specimens by PP carpet fibers under indirect tension. The higher PP carpet fiber content acts a crucial role in restricting the formation of cracks, and therefore, increasing the splitting tensile strength of PAFRC. Mastali et al. [17] also found that adding fibers and increasing the fiber dosages into the concrete mixture significantly enhance the tensile strength of layered concrete.

3.4. Sorptivity and water absorption

The measured values of water absorption test for PAFRC specimens are illustrated in Fig. 10. Based on the obtained results, the addition of PP carpet fibers leads to a reduction in water absorption of both gravity

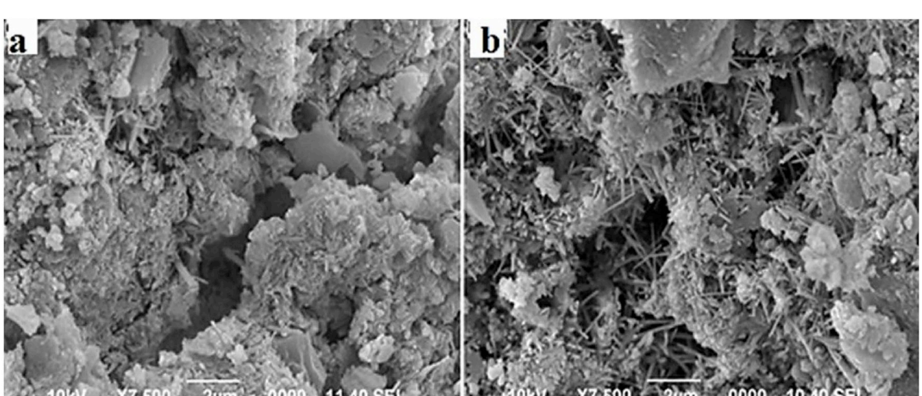

Fig. 8. SEM images of (a) OPC and (b) POFA grouts used in PAC at 90 days.

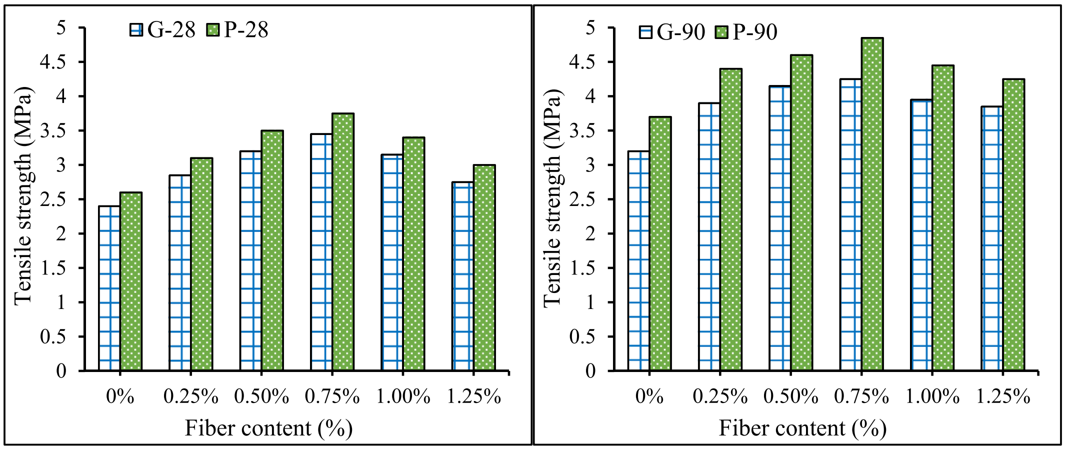

Fig. 9. Tensile strength of PAFRC mixes with different fiber volume fractions.

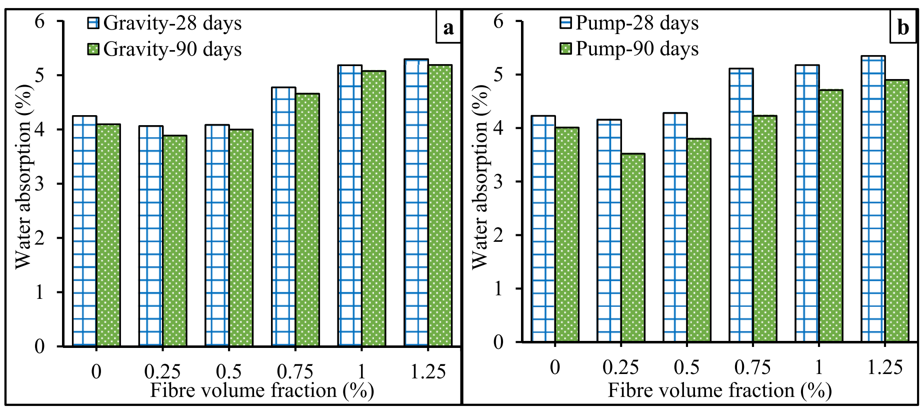

Fig. 10. The variation in water absorption of PAFRC specimens for (a) gravity method; (b) pumping method.

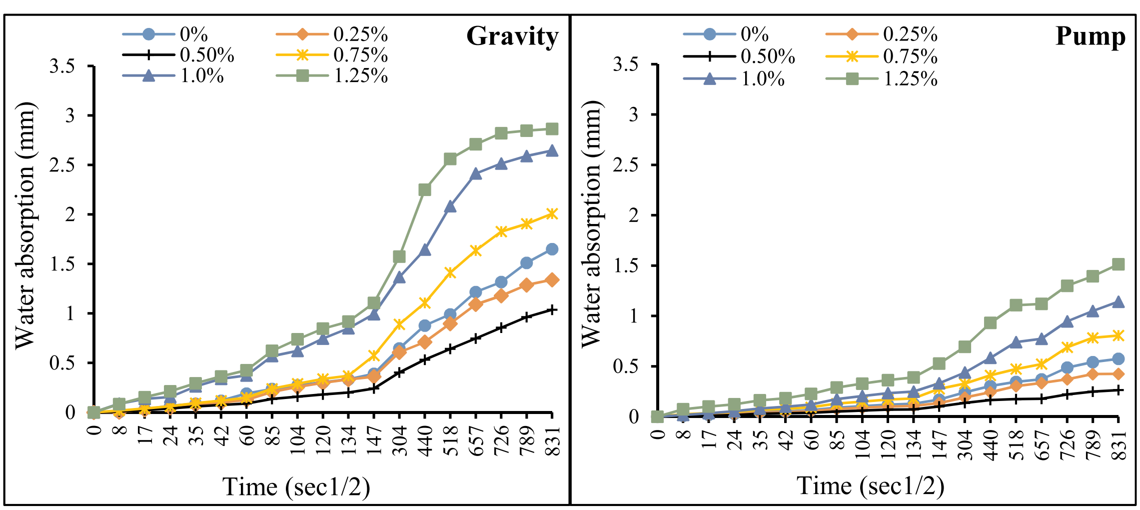

Fig. 11. Water absorption vs. square root of time for gravity and pumping methods PAFRC specimens.

and pumping group specimens. The minimum water absorption was measured as 3.52% for pumping method PAFRC mix reinforced with 0.25% carpet fibers at the curing period of 90-day, which is comparatively lower than that values recorded for plain PAC mix. This improvement could be due to the bridging action of carpet fibers by providing a grid structure and prevent the entry of water into the PAFRC specimens. In addition, the high pozzolanic activity of POFA at longer curing periods resulted in the formation of additional hydration products such as C-S-H gels which make the matrix denser and prevent the entry of water into the concrete [35]. In general, the pumping group PAFRC specimens obtained lower water absorption values than those of gravity group specimens. However, the rate of water absorption was gradually increased by increasing in the fiber volume fractions. The higher water absorption in specimens with higher fiber content could be

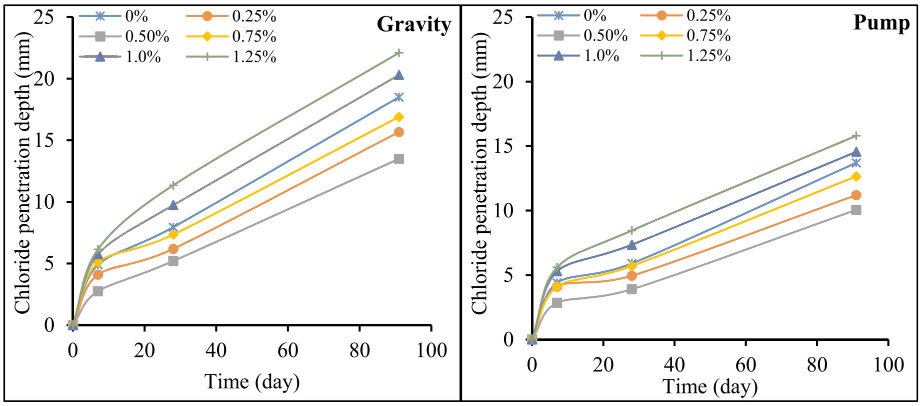

Fig. 12. Effects of carpet fibers on the chloride penetration depth for (a) gravity method and (b) pumping PAFRC specimens.

owed to the balling effects by fibers, which interrupted the proper injection of grout into the voids, and therefore initiated the pores in the matrix.

The outcomes of the sorptivity test on PAFRC disk specimens are shown in Fig. 11. Concerning the recorded results, the reinforcement of preplaced aggregate concrete specimens by carpet fibers results in enhanced permeability with lower water absorption rate. It can be observed that with fiber contents of up to 0.5% for both gravity and pumping method specimens, the water absorption of PAFRC specimens reduced significantly. Besides, it was detected that the rate of absorption was comparatively lower in the pumping specimens than those of gravity method specimens. Moreover, the measured values for the sorptivity test show that the lower water absorption of PAFRC specimens is highly related to the replacement of POFA by 20%. It could be attributed to the growth of additional C-S-H gels in the matrix owing to the pozzolanic nature of POFA. These extra gels fill up the voids and microspores in the concrete and therefore, provides a dense microstructure and lower permeability of concrete [36].

3.5. Chloride diffusion

In this study, the chloride diffusion depth was inspected by immersion of PAFRC cylindrical specimens in 5% chloride solution, and the results are illustrated in Fig. 12. The reinforcement of preplaced aggregate concrete by carpet fibers with the presence of POFA at replacement level of 20% provided a grid and dense structure in the matrix which has a significant effect towards decreasing the chloride penetration into concrete as well as a reduction in the development of microcracks [37]. The outcomes of the test revealed that the depth of penetration in those mixes reinforced with PP carpet fibers at the dosages of 0.25%, 0.5%, and 0.75% was noticeably reduced for both gravity and pumping methods. The chloride penetration depth was recorded as 13.5 mm for gravity method specimens reinforced with 0.5% fibers, which is about 27% lower than that of the recorded value of 18.5 mm for plain PAC without any fiber. Besides, the lower penetration depths were recorded for pumping method mixes for the same conditions. At the age of 90-day, the penetration depth of 10.05 mm has noted for pumping method specimens reinforced with 0.5% fibers, which was relatively lower than that of the measured value of 13.7 mm for plain PAC mix without any fiber. However, a further increase in fiber dosage increased the permeability of concrete and therefore, increased the depth of penetration.

By comparing the depth of chloride penetration for PAFRC specimens, it can be seen that the incorporation of POFA and fibers into the preplaced aggregate concrete caused to a breakdown of bigger voids in the matrix and therefore, filled up the cavities through the formation of additional hydration products. It is owing to the finer particle size of POFA as compared to that of OPC particles in addition to the high pozzolanic activity of POFA. During the pozzolanic reaction of POFA, a significant amount of calcium hydroxide ($Ca(OH)_2$) involved in the pozzolanic reaction and react with active SiO_2 of POFA results in the formation of extra C-S-H gel [38]. This additional hydration produces, therefore provide a dense microstructure in the concrete matrix and reduce the amount of porosity and consequently, lower depth of chloride penetration.

4. Conclusions

This study pioneers the viability of reinforcing the preplaced aggregate concrete (PAC) by waste polypropylene carpet fibers and proposed a new preplaced aggregate fiber reinforced concrete (PAFRC). The mechanical and transport properties of PAFRC specimens were explored. The following conclusions could be drawn based on the experimental and analytical results:

- The substitution of OPC by 20% POFA resulted in the higher flowability of grout in addition to the lower bleeding.
- The compressive strength of PAFRC cylindrical specimens decreased by adding PP carpet fibers and rise in the fiber dosages. Due to the slow pozzolanic activity of POFA, the development in the compressive strength of PAFRC specimens was slightly lower than that of OPC-based plain PAC mix at the early ages. Though, at 90-day, the compressive strength values were higher than those of OPC mix. The rate of strength improvement was more notable in the pumping method PAFRC specimens as compared to those of gravity method specimens.
- Regardless of the reduction in compressive strength of PAFRC specimens reinforced with PP carpet fibers, significant enhancement in splitting tensile strength of PAFRC specimens for both gravity and pumping groups were attained for fiber dosages up to 0.75%. However, beyond the 0.75% fibers, the tensile strength reduced due to the loss of fluidity as a result of higher fibers content, which in turn likely produced lower compaction degree.
- The addition of carpet fibers and POFA enhanced the water absorption and sorptivity properties of PAFRC specimens, which was owing to the growth of extra C-S-H gels by hydration of POFA and bridging action of fibers.
- A considerable reduction in the depth of chloride penetration was observed in PAFRC specimens reinforced with carpet fibers. The reduction was more significant in the pumping method specimens.
- The new method of reinforcement of preplaced aggregate concrete has provided a way to move from conventional fiber reinforced concrete (FRC) to new preplaced aggregate fiber reinforced concrete (PAFRC) that provide new thoughts for the upcoming types of FRC.

Declaration of competing interest

There is no conflict of interest.

Acknowledgments

This research was financed by Universiti Teknologi Malaysia (UTM) through grant No. Q.J130000.21A2.04E11. The authors also extend their appreciation to the International Scientific Partnership Program ISPP at King Saud University for funding this research work through ISPP-127.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2019.101003.

References

[1] M.F. Najjar, A.M. Soliman, M.L. Nehdi, Critical overview of two-stage concrete: properties and applications, Constr. Build. Mater. 62 (2014) 47–58.
[2] A.S.M.A. Awal, Creep recovery of preplaced aggregate concrete, J. Mater. Civ. Eng. 4 (3) (1992) 320–325.
[3] H.S. Abdelgader, How to design concrete produced by a two-stage concreting method, Cement Concr. Res. 29 (3) (1999) 331–337.
[4] A.S.M.A. Awal, Manufacture and Properties of Pre-packed Aggregate Concrete, Master thesis, University of Melbourne, Australia, 1984.
[5] M.F. Omidi, A.M. Rajabi, H.S. Abdelgader, M. Kurpińska, K. Wilde, Effect of coarse grain aggregate on strength parameters of two-stage concrete, Mater. Budowlane. 559 (2019) 1–3.
[6] H.S. Abdelgader, A.S. El-Baden, H.A. Abdurrahman, A.S.M.A. Abdul Awal, Two-stage concrete as a sustainable production, MATEC Web Conf. 149 (2018), 02009.
[7] H.S. Abdelgader, J. Górski, Concrete repair using two-stage concrete method, Mater. Budowlane. 8 (2015) 66–68.
[8] S. Swaddiwudhipong, J. Zhang, S.L. Lee, Preplaced grouting process in concrete construction, J. Mater. Civ. Eng. 15 (6) (2003) 567–576.
[9] H. Mohammadhosseini, A.S.M.A. Awal, A.R.M. Sam, Mechanical and thermal properties of preplaced aggregate concrete incorporating palm oil fuel ash, Sādhanā. 41 (10) (2016) 1235–1244.
[10] M.F. Najjar, M.L. Nehdi, A.M. Soliman, T.M. Azabi, Damage mechanisms of two-stage concrete exposed to chemical and physical sulfate attack, Constr. Build. Mater. 137 (2017) 141–152.
[11] G. Murali, K. Ramprasad, A feasibility of enhancing the impact strength of novel layered two stage fibrous concrete slabs, Eng. Struct. 175 (2018) 41–49.
[12] H.S. Abdelgader, A.A. Elgalhud, Effect of grout proportions on strength of two-stage concrete, Struct. Concr. 9 (3) (2008) 163–170.
[13] M. Hsie, C. Tu, P.S. Song, Mechanical properties of polypropylene hybrid fiber-reinforced concrete, Mater. Sci. Eng. A 494 (1–2) (2008) 153–157.
[14] V. Corinaldesi, G. Moriconi, Use of synthetic fibers in self-compacting lightweight aggregate concretes, J. Build. Eng. 4 (2015) 247–254.
[15] T. Henriksen, S. Lo, U. Knaack, A new method to advance complex geometry thin-walled glass fibre reinforced concrete elements, J. Build. Eng. 6 (2016) 243–251.
[16] H. Mohammadhosseini, A.S.M.A. Awal, Physical and mechanical properties of concrete containing fibers from industrial carpet waste, Int. J. Res. Eng. Technol. 2 (12) (2013) 464–468.
[17] M. Mastali, M.G. Naghibdehi, M. Naghipour, S.M. Rabiee, Experimental assessment of functionally graded reinforced concrete (FGRC) slabs under drop weight and projectile impacts, Constr. Build. Mater. 95 (2015) 296–311.
[18] V.R. Ramkumar, G. Murali, N.P. Asrani, K. Karthikeyan, Development of a novel low carbon cementitious two stage layered fibrous concrete with superior impact strength, J. Build. Eng. 25 (2019) 100841.
[19] H. Mohammadhosseini, M.M. Tahir, Durability performance of concrete incorporating waste metalized plastic fibres and palm oil fuel ash, Constr. Build. Mater. 180 (2018) 92–102.
[20] M. Nili, V. Afroughsabet, The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete, Constr. Build. Mater. 24 (6) (2010) 927–933.
[21] H.A. Toutanji, Properties of polypropylene fiber reinforced silica fume expansive-cement concrete, Constr. Build. Mater. 13 (4) (1999) 171–177.
[22] H. Mohammadhosseini, N.H.A.S. Lim, A.R.M. Sam, M. Samadi, Effects of elevated temperatures on residual properties of concrete reinforced with waste polypropylene carpet fibres, Arabian J. Sci. Eng. 43 (4) (2018) 1673–1686.
[23] N.F. Medina, G. Barluenga, F. Hernández-Olivares, Enhancement of durability of concrete composites containing natural pozzolans blended cement through the use of Polypropylene fibers, Compos. B Eng. 61 (2014) 214–221.
[24] A.S.M.A. Awal, H. Mohammadhosseini, Green concrete production incorporating waste carpet fiber and palm oil fuel ash, J. Clean. Prod. 137 (2016) 157–166.
[25] H. Mohammadhosseini, M.M. Tahir, A.R.M. Sam, N.H.A.S. Lim, M. Samadi, Enhanced performance for aggressive environments of green concrete composites reinforced with waste carpet fibers and palm oil fuel ash, J. Clean. Prod. 185 (2018) 252–265.
[26] A. Sotayo, S. Green, G. Turvey, Carpet recycling: a review of recycled carpets for structural composites, Environ. Technol. Innov. 3 (2015) 97–107.
[27] H. Mohammadhosseini, A.S.M.A. Awal, J.B.M. Yatim, The impact resistance and mechanical properties of concrete reinforced with waste polypropylene carpet fibres, Constr. Build. Mater. 143 (2017) 147–157.
[28] N.H.A.S. Lim, H. Mohammadhosseini, M.M. Tahir, M. Samadi, A.R.M. Sam, Microstructure and strength properties of mortar containing waste ceramic nanoparticles, Arabian J. Sci. Eng. 43 (10) (2018) 5305–5313.
[29] E. Khankhaje, M.W. Hussin, J. Mirza, M. Rafieizonooz, M.R. Salim, H.C. Siong, M. N.M. Warid, On blended cement and geopolymer concretes containing palm oil fuel ash, Mater. Des. 89 (2016) 385–398.
[30] C. Chandara, K.A.M. Azizli, Z.A. Ahmad, S.F.S. Hashim, E. Sakai, Heat of hydration of blended cement containing treated ground palm oil fuel ash, Constr. Build. Mater. 27 (1) (2012) 78–81.
[31] H. Mohammadhosseini, N.H.A.S. Lim, M.M. Tahir, R. Alyousef, H. Alabduljabbar, M. Samadi, Enhanced performance of green mortar comprising high volume of ceramic waste in aggressive environments, Constr. Build. Mater. 212 (2019) 607–617.
[32] F. He, C. Shi, Q. Yuan, C. Chen, K. Zheng, AgNO3-based colorimetric methods for measurement of chloride penetration in concrete, Constr. Build. Mater. 26 (1) (2012) 1–8.
[33] N.H.A.S. Lim, M.A. Ismail, H.S. Lee, M.W. Hussin, A.R.M. Sam, M. Samadi, The effects of high volume nano palm oil fuel ash on microstructure properties and hydration temperature of mortar, Constr. Build. Mater. 93 (2015) 29–34.
[34] K. Muthusamy, J. Mirza, N.A. Zamri, M.W. Hussin, A.P.A. Majeed, A. Kusbiantoro, A.M.A. Budiea, Properties of high strength palm oil clinker lightweight concrete containing palm oil fuel ash in tropical climate, Constr. Build. Mater. 199 (2019) 163–177.
[35] H. Mohammadhosseini, M.M. Tahir, M.I. Sayyed, Strength and transport properties of concrete composites incorporating waste carpet fibres and palm oil fuel ash, J. Build. Eng. 20 (2018) 156–165.
[36] O. Karahan, C.D. Atiş, The durability properties of polypropylene fiber reinforced fly ash concrete, Mater. Des. 32 (2) (2011) 1044–1049.
[37] M. Balonis, B. Lothenbach, G. Le Saout, F.P. Glasser, Impact of chloride on the mineralogy of hydrated Portland cement systems, Cement Concr. Res. 40 (7) (2010) 1009–1022.
[38] P. Chindaprasirt, S. Rukzon, V. Sirivivatnanon, Resistance to chloride penetration of blended Portland cement mortar containing palm oil fuel ash, rice husk ash and fly ash, Constr. Build. Mater. 22 (5) (2008) 932–938.