

Article

Sustainable Use of Waste Polypropylene Fibers and Palm Oil Fuel Ash in the Production of Novel Prepacked Aggregate Fiber-Reinforced Concrete

Fahed Alrshoudi ^{1,*}, Hossein Mohammadhosseini ^{2,*} , Mahmood Md. Tahir ², Rayed Alyousef ³, Hussam Alghamdi ¹, Yousef R. Alharbi ¹ and Abdulaziz Alsaif ¹

¹ Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 12372, Saudi Arabia; Hsghamdii@ksu.edu.sa (H.A.); Yrharbiii@ksu.edu.sa (Y.R.A.); Aalsaiiff@ksu.edu.sa (A.A.)

² Institute for Smart Infrastructure and Innovative Construction (ISIIC), School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), Skudai, Johor 81310, Malaysia; mahmoodtahir@utm.my

³ Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Alkharj 11942, Saudi Arabia; r.alyouseff@psau.edu.sa

* Correspondence: Falrshoudi@ksu.edu.sa (F.A.); hofa2018@yahoo.com (H.M.)

Received: 26 May 2020; Accepted: 13 June 2020; Published: 15 June 2020



Abstract: This study proposed the prepacked aggregates fiber-reinforced concrete (PAFRC), which is a newly developed concrete, with a unique combination of coarse aggregate and short polypropylene (PP) fiber that is premixed and placed in the formworks. This study aims to investigate the potential use of waste polypropylene fibers and palm oil fuel ash (POFA) in the production of PAFRC to enhance the strength and deformation properties. The compressive strength, impact-resistant, drying shrinkage, and microstructural analysis of PAFRC were investigated experimentally. Six mixes comprising fiber volume fractions from 0–1.25% with a length of 30 mm were cast by gravity technique. Another six mixtures with the same fiber volume fractions were cast using a pump to inject the grout into the formwork. The experimental outcomes exposed that with the addition of PP carpet fiber, the compressive strength of PAFRC decreased. Nevertheless, PAFRC mixes shown a remarkable improvement in the tensile strength. The combination of POFA and PP fibers in PAFRC specimens led to higher impact strength and increasing the ductility of concrete. In addition, the drying shrinkage of PAFRC reduced significantly with the addition of waste PP fibers. It can be concluded that due to the adequate strength and deformation properties, PAFRC is the potential to be used as innovative fiber reinforced concrete in several applications.

Keywords: prepacked aggregate fiber-reinforced concrete; sustainability; strength; deformation; microstructure; waste polypropylene fiber; palm oil fuel ash

1. Introduction

Cleaner and sustainable productions are essential themes of social development all around the world. Utilizing industrial waste and reducing natural resource consumption is the key to achieving cleaner production. Sustainable use of waste materials is an effective way to develop cleaner production by using industrial wastes as raw materials to replace natural resources in the production of construction materials. Among the different concrete constituents, the production of cement is the main source of environmental impacts and greenhouse gas emissions in particular. In the urban regions worldwide, saving energy, lowering carbon dioxide (CO₂) emissions, and disposing of waste arising from the manufacturing of several consumer products remain significant challenges [1–3].

Prepacked aggregate concrete (PAC) is a specific type of concrete that is manufactured by placing different sizes and shapes of coarse aggregates in the formworks, in which the internal cavities and openings are then filled with a mixture of cement and sand in the form of high fluidity grout. The prepacked aggregate concrete technique was first designated in the 1930s [4,5]. The term PAC states to the procedure of insertion the aggregate particles into the formworks, rather than a specific sort of concrete [6,7]. Generally, the traditional type of concrete is manufactured by mixing all the constituents and pouring fresh concrete into designed formworks. Nevertheless, PAC is made by insertion of graded and clean aggregate into the designed formworks and then injecting a grout paste with adequate flowability into the openings amongst the aggregate particles, where it solidifies to form concrete [5]. While in PAC type of concrete, aggregates segregation is reduced with the exclusive packing of aggregate particles in the formworks, grouting methods provide concrete with better performance. Consequently, a denser matrix with higher strength due to the point-to-point interaction of aggregate particles can be made by using a PAC type of concrete [8].

In prepacked aggregate concrete, the grouting can be attained by gravity or pumping methods [4–6]. Generally, the minimum size of aggregates used in PAC is one of the main factors in selecting the suitable technique of grouting. For instance, in PAC with the smaller size of aggregates and the lower amount of voids, the pumping technique is favored, while for PAC, comprising the larger size of aggregate particles and the bigger size of cavities, the gravity method is favored [5,9]. In the gravity method, the top surface of the formworks used to inject the grout, as aggregates were placed previously, and the grout mixture move across the aggregates from top to the lowermost of the formworks under the gravity force, and consequently, fills up the openings amongst the aggregate particles. This gravity grouting technique is appropriate for formwork sections up to 300 mm depth [5,6]. In the method of pumping, a controlled-pressure pump used to inject the mixture of grout into the spaces amongst the aggregates by using a pipe from the lowest section of the formworks. In the pumping method, the magnitude of the pressure for the injection process selected based on the size of the aggregate particles used and also the depth of the formworks.

In recent years, the manufacture and growth of layered concrete are getting more attention to increase the impact strength and energy absorption of concrete components. In regards to the said matter, Mastali et al. [10] investigated the effects of steel fibers on the strength and impact resistance of layered two-stage concrete slabs. Their findings showed that the reinforcement of concrete with three layers of steel fibers of up to 4% enhanced the impact strength of concrete with higher energy absorption capacity, as compared to that of non-fibrous plain concrete. Similarly, Murali and Ramprasad [11] stated that the inclusion of steel fibers of up to 2% in all layers of concrete significantly enhanced the performance of layered slabs under the drop weight method. In addition, Ong et al. [12] researched the impact resistance of concrete slabs reinforced with steel fibers, polyolefin, and polyvinyl alcohol fibers. The results of their study confirmed that the addition of various fibers resulted in better performance under impact loads with higher energy absorption capacity.

PAC is the potential type of concrete to be used as a repairing material in masonry and concrete construction. PAC is also applicable in structures, where placement by conventional techniques is very difficult, such as massive concrete [11]. Furthermore, due to the lower volume variations and comparatively lesser heat of hydration in PAC than that of conventional concrete, it has the potential to be used in mass concrete, such as dams and tunnels, in which cold joints, creep, shrinkage and thermal cracks are the key concerns [13]. Given its high brittleness and low tensile strength, concrete is considered brittle material. Hence, the greater impact strength is essential in different uses for PAC and conventional concrete. In concrete components, the development of cracks in various sizes causes significant problems relating to strength and durability performance. In most cases, the formation of cracks noticeably reduces the lifespan of concrete structures by allowing harmful particles to enter into the concrete components [14,15]. Therefore, the assessment of strains and exploration of cracks development over time is essential to develop the durability of concrete in long periods [16,17].

Accordingly, to improve the properties of concrete structures with superior ductility, novel construction materials are essential to be developed. Relatedly, a promising solution to enhance the concrete performance is the addition of short fiber at various dosages into the mixtures [18]. Prepacked aggregates fiber-reinforced concrete (PAFRC) is a novel construction material made of the combination of coarse aggregates with different sizes and short fibers placed in formworks, and cementing material mix with sand is injected to the gaps among the particles in the form of the grout. Therefore, due to the existence of fibers and unique methods of casting, the proposed PAFRC can be a good solution to improve the performance of concrete components. Many researchers have discovered the possible use of solid wastes in construction materials, particularly concrete or mortar, and their influences on the mechanical properties. In this regard, the manufacture of polymer-based fibers utilized for the manufacturing of carpets and textiles has been steadily rising, at present more than 70 million tons yearly [19,20]. In Malaysia, approximately 50 tons of polypropylene fiber used in the carpet industry in various forms are discarded to landfills annually [21]. Palm oil fuel ash (POFA) is waste ash, which is used as supplementary cementing material (SCM) in the construction materials [22,23]. The production of POFA in Malaysia reaches approximately 5 million tons per year, and this is sent to landfills as waste [24]. The manufacturing rate of POFA is estimated to grow with the increasing of palm trees plantations. According to past research, POFA can be used as SCMs in concrete with satisfactory durability and mechanical properties [25].

Prepacked aggregate concrete is a unique construction process, and it has been investigated for its mechanical properties. Nevertheless, there is a lack of study on the deformation and strength behavior of prepacked aggregate concrete reinforced with waste carpet fibers and also containing POFA. Given the quarrel as mentioned above, the purpose of this work was to inspect the mutual effects of waste polypropylene fiber and POFA on the strength and deformation properties of new prepacked aggregate concrete, as well as the microstructural analysis. As the construction of PAC requires unique skills and experience that most workers do not have, the current paper offers beneficial information on the manufacturing of PAFRC that can help both engineers and workers. The consumption of waste polypropylene (PP) fiber and POFA in the manufacture of PAFRC could be beneficial in both environmental and economic points of view.

2. Materials and Methods

2.1. Materials

Following the specifications of ASTM C 150-2007, type I ordinary Portland cement (OPC) was used in the current study. The raw ashes were collected from a palm oil mill located in Johor, Malaysia. POFA was dried and sieved to eliminate larger materials such as unburned particles, and subsequently, the ashes were kept in a furnace at the temperature of 100 ± 5 °C to vaporize moisture. Afterward, the ash was sieved, and constituents that lesser than 150 μm were kept in a Los Angeles milling device to grind each 4 kg of POFA for about two hours. Besides, the particles that remained on the 150 μm sieve were put in a furnace and heated up to 800 °C to reduce the carbon content. The materials were then reprocessed. Then, the grounded fine ashes, which adapted to the requirements of ASTM C618-2015 and BS 3892: Part 1-1992 specifications, were collected and used as partial cement replacement. Table 1 shows the physical properties and chemical compositions of the used OPC and POFA.

Uncrushed natural river sand, with a size of smaller than 4.75 mm, a fineness modulus of 2.3, 2.6 g/cm³ specific gravity, and 0.7% water absorption, was used to make the grout mixture. In this study, the coarse aggregates, which are the main components of PAC were the crushed granite type with size ranged between 20–38 mm, with 0.5% water absorption, and a specific gravity of 2.7 g/cm³. According to ACI 304.1R-1997 specifications for PAC, before placing the aggregates in the formwork, the particles must be clean and wash to eliminate the impurities such as dust. It would help to attain a better bond between the aggregates and injected grout. Moreover, to achieve the better flowability of the fresh grout mixture, a polymeric base superplasticizer at a dosage of 1.0% was used. In this

research work, industrial waste carpet fibers from ENTEX Carpet Industries Sdn. Bhd., located in Malaysia, was collected and used as a fibrous material. The multi-filament type of PP fibers was used. Besides, the fiber's length was selected as 30 mm according to the size of the coarse aggregates with an aspect ratio (l/d) of 67. The common engineering properties of carpet fibers are given in Table 2.

Table 1. Characteristics of used palm oil fuel ash (POFA) and ordinary Portland cement (OPC).

Composition	OPC (%)	POFA (%)
SiO ₂	20.40	62.60
Al ₂ O ₃	5.20	4.65
Fe ₂ O ₃	4.19	8.12
CaO	62.39	5.70
MgO	1.55	3.52
K ₂ O	0.005	9.05
SO ₃	2.11	1.16
LOI	2.36	6.25
<i>Physical properties</i>		
Specific gravity	3.15	2.42
Blaine fineness (cm ² /g)	3990	4930
Soundness (mm)	1.0	2.0

Table 2. Common properties of used waste polypropylene (PP) fibers.

Waste Carpet 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

2.2. Mix Proportions

The mix proportions of different constituents used in the production of PAFRC are illustrated in Table 3. In this study, a total of 12 batches were made in two groups, i.e., gravity (G) and pumping (P) groups. In addition, the water/binder (w/b) and cement/sand (c/s) ratios were kept constant as 0.5 and 1/1.15, respectively, for all mixes. For all PAFRC mixes, OPC was substituted by 20% POFA. In each group, one mix was cast as a control mix without any fiber, namely P0 and G0 for pumping and gravity methods, correspondingly. Besides, five PAFRC mixes were prepared for each group, in which carpet fibers were added at the volume fractions of 0.25%, 0.50%, 0.75%, 1.0%, and 1.25%, i.e., P1 to P5 and G1 to G5 pumping and gravity injection techniques, correspondingly.

2.3. Sample Preparation

Unlike conventional concrete, the preparation and production of PAFRC were carried out in two steps. Initially, mixing and placing of coarse aggregates with various sizes and 30 mm length PP fibers in the formworks, and then, the mixture of cement and sand as a grout was injected by the pumping and gravity techniques into the formworks to fill up the cavities between the aggregates and fibers. Cylindrical samples of size 100 × 200 mm and 150 × 300 mm were used for gravity specimens, and the mixture of cement and sand with adequate fluidity was injected under gravitational force through PVC pipes of 5 mm in diameter into the mold, as demonstrated in Figure 1b. Conversely, in the pumping technique, the UPVC pipes with different diameters of 100 mm and 150 mm were cut in the desired length and used as a mold. The pipes then placed and fixed in a pre-designed formwork base to avoid any movement during the grout injection process, as illustrated in Figure 1a. A mild steel cone with a steel ball was connected under the tube on the platform to act as a one-way valve

during the grouting and control the steady flow of grout over the tubes. Besides, a cap of plywood was attached to the top of the tubes to prevent the uplifting of the coarse aggregates particles throughout the grout injection procedure.

Table 3. The mix proportions of the materials used in the prepacked aggregates fiber-reinforced concrete (PAFRC) mixture.

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	-
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	-
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 </td <td>76</td> <td>545</td> <td>1320</td> <td>1.00</td>	76	545	1320	1.00
G5	186	304	76	545	1320	1.25

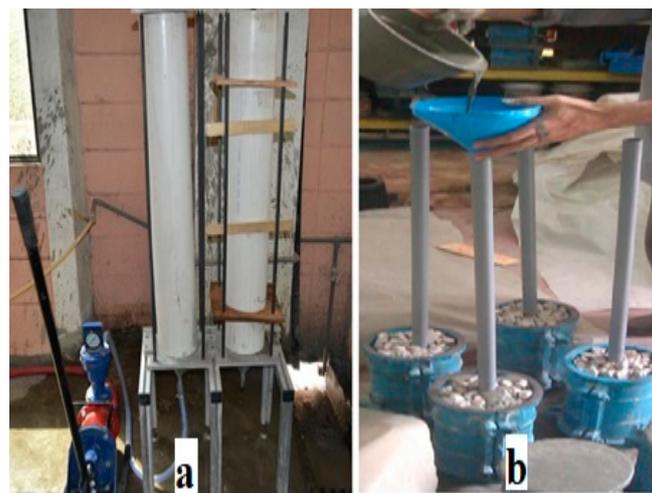


Figure 1. Grouting techniques of PAFRC: (a) Pumping; (b) Gravity.

In this study, a mix of blended cement and river sand was made as grout by using an electric mixer for approximately five minutes. Afterward, the grout with adequate flowability was transferred into the hopper with constant stirring for the whole filling procedure to control the flowability of the grout mixture. Moreover, a pump with a device to control the pressure was attached to the hopper for the injection of grout between the aggregates, as revealed in Figure 1a. During the casting process of PAFRC specimens, precise care was taken to ensure that the mixture of cement and sand did not leak out from the formworks. Besides, for each batch of the concrete and specified test, three samples were made and tested, and the average value was recorded and presented in this paper. Once casting of specimens was complete, the PAFRC samples were cured at ambient temperature for 24 h. After 24 h, the specimens were removed from the formworks and retained in a water tank containing normal tap water before testing in the room temperature of 20 ± 5 °C.

2.4. Testing Methods

The cylindrical compressive strength test was done on the samples of size 100 mm × 200 mm, and tested according to ASTM C39M-18. Besides, scanning electron microscopy (SEM) and X-Ray

Diffraction (XRD) were used to inspect the morphology and microstructure of the grout paste samples. The impact strength of PAFRC specimens was attained, following the specifications of ACI 544.2R-1999. Three concrete disk specimens with 64 mm thickness and 150 mm diameter for each batch were cut from the cylindrical specimens of size 150 × 300 mm and exposed to impact load induced by steel hammer mass of 4.45 kg repeatedly released from a height of 457 mm on a stainless steel ball with a diameter of 63.5 mm located on the top surface of the center of the samples (Figure 2). The number of blows for the first crack and failure of specimens to occur was noted as the first crack impact resistance (N1) and ultimate impact resistance (N2), respectively. The deformation of PAFRC specimens was recorded in terms of shrinkage values. Shrinkage test was also conducted on the cylinders of size 100 mm × 200 mm following the specifications of ASTM C512-2010 for 180 days, as shown in Figure 3. The tested specimens were placed in a room with a fixed temperature and humidity of 20 ± 2 °C and $65 \pm 5\%$, respectively.

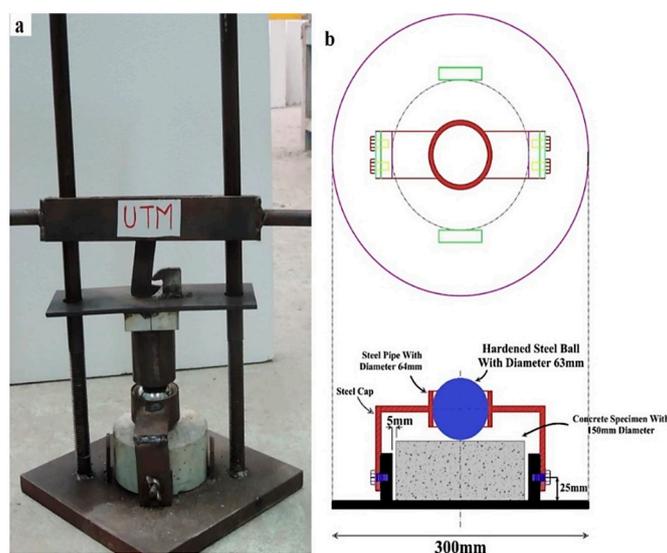


Figure 2. (a) The drop weight impact resistance device; (b) The test setup.

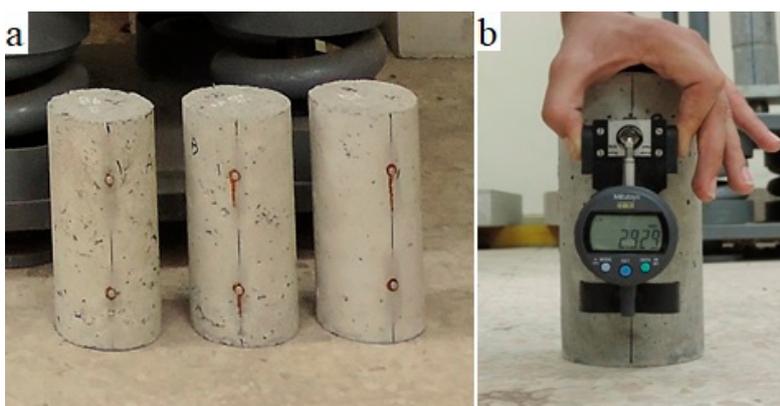


Figure 3. (a) PAFRC specimens used for drying shrinkage; (b) A digital comparator meter.

3. Results and Discussion

3.1. Compressive Strength

Figure 4 illustrates the outcomes of the compressive strength test for PAFRC mixtures. It could be seen that the cylindrical compressive strength of PAFRC mixes dropped with the addition of fibers. The obtained results revealed higher strength values of the specimens injected by the pumping method than those specimens of gravity technique. Relating the strength values for control PAC mix without

any fibers at the age of 28 days, the strength value of the pumping method mixture was around 7% greater than that of the gravity method specimens. The lower strength values at the age of 28 days could be accredited to the slow rate of hydration of POFA at an early age [26]. Reinforcement of PAFRC specimens by carpet fibers of 0.25%, 0.5%, 0.75%, 1%, and 1.25%, reduced the strength values of gravity technique mixes by about 2.3%, 6.5%, 8.8%, 12.2%, and 16.1%, correspondingly, as related with control mix without any fiber (G0). Likewise, in the specimens of pumping technique with the same fiber content, the cylindrical compressive strength dropped by 3.4%, 6.4%, 8.5%, 11.4%, and 18%, correspondingly. The drop in the strength values of PAFRC with carpet fibers could be owing to the existence of holes in the samples, which were raised by the adding of short fiber at high volume fractions. Indeed, higher dosages of fibers induce balling effect, pores development, and clustering, subsequently, reduce the strength and disposed to cracks. It, consequently, decreases the volume of grout mixture amongst the fibers and aggregate particles, and thus, leads to the drop in the strength values of PAFRC [27,28].

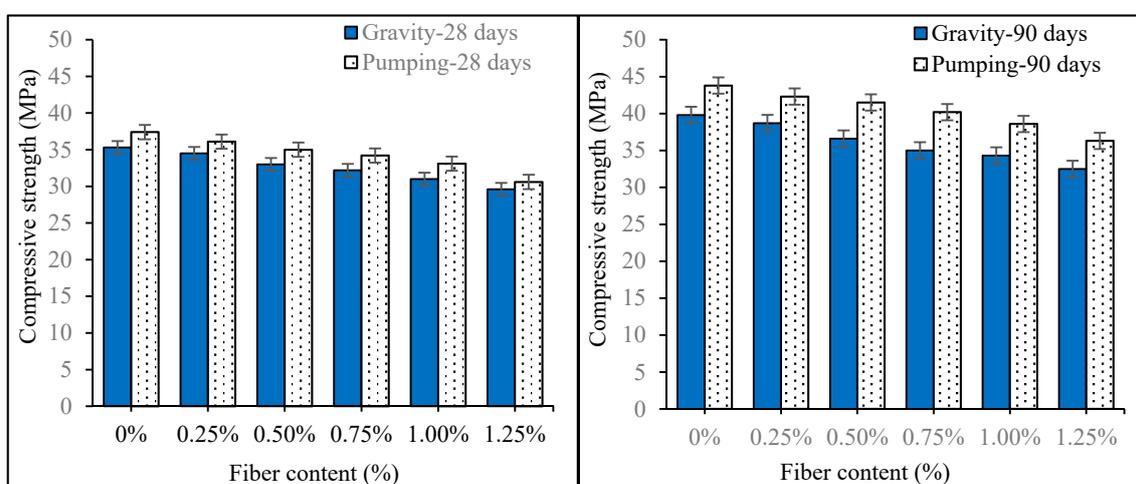


Figure 4. The variation in the compressive strength of PAFRC specimens.

According to the results obtained for PAFRC mixtures at the age of 90 days, a rise in strength of specimens was observed in gravity and pumping methods. With the replacement of 20% POFA, the compressive strength of concrete specimens tended to develop with the curing time, which might owe to the good pozzolanic reactivity of POFA along time, and smaller size of POFA particles, which caused in the enhancement of compressive strength of PAFRC [29]. It could be seen that the obtained outcomes of PAFRC specimens for the pumping technique shown higher strength values, in association with the specimens of the gravity method for the same fiber dosages.

3.2. Impact Resistance

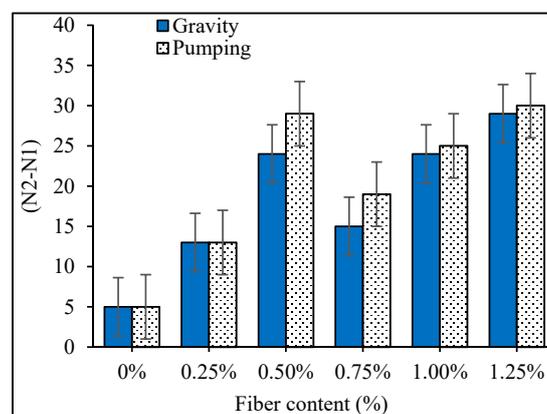
The drop weight impact resistance test was carried out on the PAFRC disk specimens. The number of blows for the first crack (N1) and cracks at failure (N2) to arise and the equivalent impact energy is presented in Table 4. Besides, the proportion of the increase in the number of post-first-crack blows to the ultimate failure blows ($N2-N1/N1$) are present in Table 4. From the results given in Table 4, for the gravity method mixes, the number of drops for the first crack to arise was noted as 16, 28, 45, 63, 84, and 102 for G0, G1, G2, G3, G4, and G5 mixes, respectively. Concerning the plain PAC mix without fibers, the number of blows for the first crack improved by the addition of PP fibers. Similarly, the number of blows at the failure was recorded as 41, 74, 82, 108, and 131 for G0, G1, G2, G3, G4, and G5 mixes, respectively.

Table 4. Experimental test results of impact resistance test.

Mix	Impact Resistance		N2-N1	(N2-N1/N1)(100)
	First Crack (N1)	Failure (N2)		
G0	16	21	5	31.3
G1	28	41	13	46.4
G2	45	74	29	64.4
G3	63	82	19	30.2
G4	84	108	24	28.6
G5	102	131	29	28.4
P0	20	25	5	25.0
P1	38	51	13	34.2
P2	63	87	24	38.1
P3	84	99	15	17.9
P4	101	126	25	24.8
P5	131	161	30	22.9

Furthermore, the addition of PP carpet fibers improved the first and ultimate impact strength of the PAFRC specimens by the pumping method. It could be seen that the reinforcement of plain PAC with PP fiber at the dosages of 0.25%, 0.5%, 0.75%, 1%, and 1.25% significantly enhanced the impact resistance of the PAFRC specimens at initial crack by 90%, 215%, 320%, 405%, and 555%, respectively. Additionally, the ultimate crack impact resistance of the PAFRC specimens increased by 104%, 248%, 296%, 404%, and 544% for the same fibers contents, correspondingly, as associated with that of the plain PAC mix (P0). It was observable that the initial and ultimate cracks impact strength for the PAFRC mixtures of the pumping method was significantly higher than that of the gravity technique PAFRC samples. Besides, the existence of POFA resulted in higher impact resistance for all specimens. As was stated previously, owing to the pozzolanic nature of POFA and better hydration process at extended curing periods, the microstructure of the matrix improved through the formation of additional C-S-H gel and developed both strength and higher energy absorption [30].

Moving on, Figure 5 illustrates the post-peak resistance (N2-N1) of the PAFRC specimens. The bridging effects of PP carpet fibers revealed the post-peak resistance with higher ductility performance in the PAFRC specimens. This result specified that the PP fibers considerably minimized the brittleness of the concrete samples. Additionally, it was noticeable that the maximum post-peak resistance was recorded for the PAFRC mix with 1.25% (pumping method group). It implied that the PAFRC specimens using the pumping method performed higher post-peak impact resistance than those of the gravity method specimens, and are highly potential to be used as impact-resistant components. Moreover, the existence of fibers in the PAFRC specimens played an essential role in bridging and arresting the cracks caused by higher energy absorption capacity.

**Figure 5.** Variation of impact resistance values of PAFRC specimens vs. fiber content.

According to the modes of failure detected after the drop-weight impact test, as shown in Figure 6, the plain control PAC for both gravity and pumping method (G0, P0) specimens had a lower energy absorption capacity, brittle failure, and was lacking in the capacity to restrict crack development, in which the sample broke into two pieces after just a few blows. In contrast, the PAFRC mixtures reinforced with carpet fibers of 0.25%, 0.5%, 0.75%, 1.0%, and 1.25%, attained a satisfactory ductile mode of failure and high capability to restrain the development of cracks, owing to the bridging action of the fibers in the PAFRC specimens. The modes of failure for the plain PAC specimen without any fibers and PAFRC specimens with fibers at various dosages after the drop weight impact loading are shown in Figure 6. It was detected that the modes of failure for the PAFRC specimens demonstrated the propagation of cracks on the top surface of the disk samples while resisting a high number of drops and had sturdier bonding anchorage and higher resistance capacity to deformation, which contributed to the arresting of cracks by the fibers, and thus, improved both the energy absorption capacity and impact resistance [31].



Figure 6. Failure modes of pumping method PAFRC specimens after impact load.

3.3. Drying Shrinkage Development

Figure 7 demonstrates the obtained results of the drying shrinkage test for PAFRC mixes up to 180 days. The outcomes exposed that the inclusion of fibers into the PAFRC specimens the drying shrinkage reduced for all fiber dosages in which the highest shrinkage values were observed for the gravity method plain PAC mix without any fiber (G0). It was observed that the rate of shrinkage at the early testing periods up to 28 days was faster than that of the testing periods afar 28-day. At 180-day shrinkage test, for the pumping method PAFRC specimens, the drying shrinkage values reduced by 11.43%, 23.3%, 29.5%, 16.8%, and 4.5% for the fiber volume fractions of 0.25%, 0.5%, 0.75%, 1%, and 1.25%, respectively, as related to that of plain PAC mix (P0).

Moreover, the reduction in the drying shrinkage values of the gravity method PAFRC specimens was noted, but lower than those of pumping method specimens. For example, at 180 days, for the gravity method PAFRC samples comprising 0.25%, 0.5%, 0.75%, 1%, and 1.25% PP fiber, the shrinkage values dropped by 8.8%, 20.62%, 25.9%, 12.64%, and 4.25%, respectively, as related to that of plain PAC mix (G0). Besides, for both pumping and gravity methods, the PAFRC mix comprising 0.75% fibers shown the minimum shrinkage values. According to Havlásek and Jirásek [32], the bridging action of fibers, which acts as a crack arrester, resulted in the reduction in drying shrinkage values. Karahan and Atis [33] also stated that in concrete mixtures, the existence of fibers results in a significant reduction in shrinkage values, in which fibers arrest the cracks and prevent the development of the microcracks in the specimens and results in lower shrinkage.

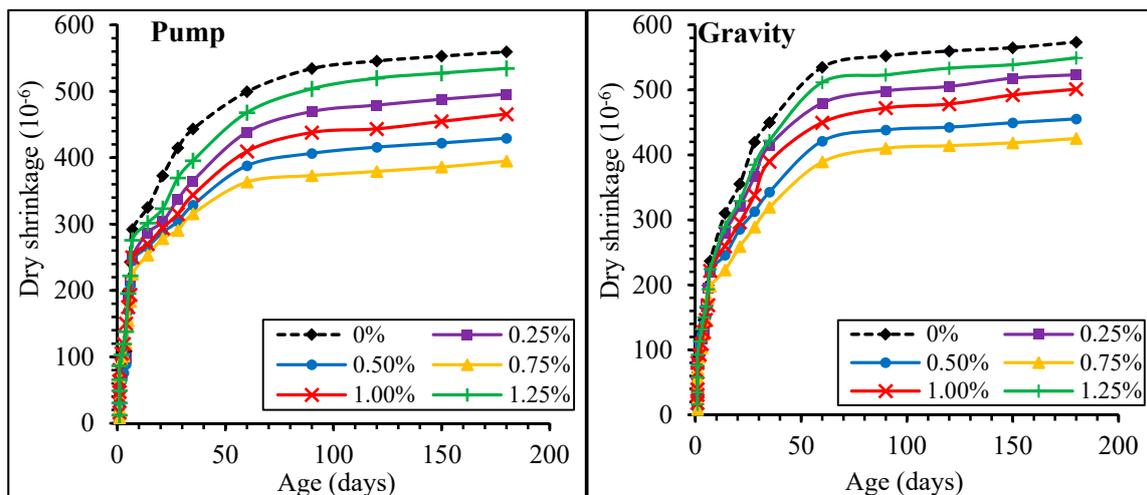


Figure 7. Drying shrinkage of PAFRC specimens.

3.4. Microstructural Analysis

Scanning electron microscopy (SEM) test was carried out to assess the microstructure of grout pastes of mixtures used in PAFRC specimens with POFA at the replacement level of 20%. The microstructural analysis was piloted to investigate the consequence of POFA on the formation of hydration products and the strength gain of the specimens. Figure 8a,b shows the distribution of C-S-H gels in the pastes at the curing periods of 28- and 90-day. It could be seen that the C-S-H gel was uniformly distributed in the paste of 90-day as compared to the 28-day paste. It seemed that the 28-day paste contained many crystallines that interweaved together with the C-S-H gels, and numerous pores were visible amongst these crystallines. In contrast, the 90-day paste contained many gel components and had fewer cavities. The fine distribution of C-S-H gels and the growth of additional C-S-H crystals owing to the use of portlandite in the pozzolanic reaction of POFA at the ultimate ages, caused in strength development [29].

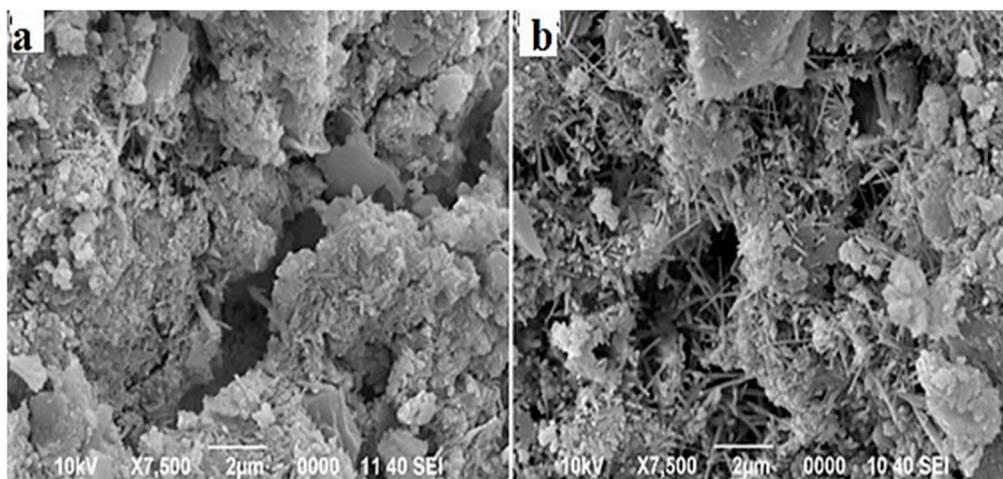
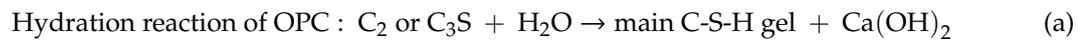


Figure 8. SEM images of (a) 28-day and (b) 90-day grout pastes used in PAC.

As it can be seen in the following chemical reactions, with the addition of water to the blended cement, calcium silicate hydrate (C-S-H) was formed due to the existence of C_2 or C_3S in OPC, and resulted in the liberation of calcium hydroxide (CH), as illustrated in Equation (a). This chemical reaction was comparatively quick. Instead, when POFA was included in the concrete mix, the reactive silica (SiO_2), which is in high amount in POFA, reacted with the released CH to form additional C-S-H

gel in the existence of water as revealed in Equation (b). Nevertheless, the reaction was relatively slow, therefore causing slow strength improvement in addition to lesser heat of hydration of mixture [34].



The results of the XRD test for grout paste used in PAFRC specimens at the ages of 28 and 90 days are shown in Figure 9a,b. The results indicate that at 28 days curing, the observed peaks are mostly Quartz (Q), Portlandite (P), and Gypsum (G), which are the results of the OPC hydration. As the hydration process of POFA is comparatively slow at an early age, the intensity of C-S-H (C) was found to be lower. However, at a longer period of 90 days following the Equations (a) and (b), the hydration products of OPC such as CH reacts with the active SiO_2 in POFA, and therefore, resulted in the formation of additional C-S-H gels and increased their intensities as compared to the 28-day intensity.

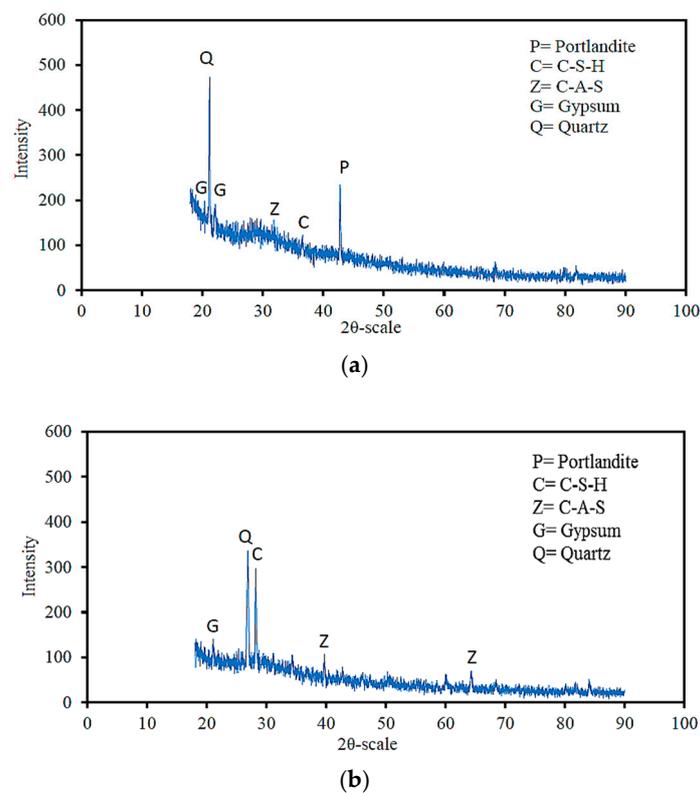


Figure 9. The X-Ray Diffraction (XRD) results of grout paste used in PAFRC specimens at (a) 28-day; (b) 90-day.

As revealed in Figure 9b of the XRD analysis for grout paste at 90 days, the paste is conquered by high peaks of C-S-H at 2θ of 28.8° . The C-S-H crystals are liable for properties of blended cement paste as it forms a steady deposit that binds together the unique cement constituents into a coherent entire. Therefore, the formation of these additional C-S-H gels filled up the pores in the matrix and resulted in a dense concrete matrix with superior deformation and strength properties [35,36].

4. Conclusions

The current paper was written to evaluate the strength and deformation properties of a new prepacked aggregate fiber-reinforced concrete comprising waste polypropylene fibers and palm oil fuel ash. The succeeding conclusions can be drawn based on the observed results from the experimental investigations.

- (1) The inclusion of waste PP fibers into the mixture results in the reduction of the compressive strength of PAFRC specimens. Initially, in the early curing periods, owed to the slow pozzolanic reaction of POFA, the strength improvement of PAFRC mixtures was marginally lesser than that of the plain PAC mix with OPC. However, at the age of 90 days, the obtained strength values were greater than those of the OPC mixes. The rate of strength enhancement was more remarkable in the pumping technique PAFRC mixtures, as associated with those of gravity technique samples.
- (2) A remarkable rise in the number of blows under impact load for the first and ultimate cracks impact strength was detected for PAFRC samples reinforced with PP carpet fibers. Besides, the highest impact resistance values were recorded for PAFRC specimens reinforced with 1.25% fibers. In general, pumping method specimens obtained higher values than those of the gravity method.
- (3) The results of the impact resistance test revealed that the PAFRC specimens reinforced with waste PP fibers are highly potential to resist against impact loads through the bridging action of fibers, and consequently, reduced the brittleness and delayed the sudden failure of the PAFRC specimens.
- (4) The drying shrinkage values of all PAFRC specimens reinforced with waste polypropylene fibers were comparatively lower than those of plain PAC specimens. The highest reduction in drying shrinkage was noted for the PAFRC mix of pumping method containing 0.75% fibers, which were 29.5% lower than that of the plain mix.
- (5) The analysis of the microstructure of the grout paste indicated that the existence of POFA results in enhanced performance of PAFRC specimens by providing a dense microstructure and filled up the voids with additional hydration products, particularly at the ultimate ages.
- (6) The new method of reinforcing prepacked aggregates concrete has delivered a technique to move from conventional FRC to novel PAFRC, which also provides new considerations for the future sorts of FRC.

Author Contributions: Conceptualization: M.M.T., H.M. and F.A.; methodology: R.A. and H.A.; validation: Y.R.A. and A.A.; formal analysis: H.M. and F.A.; investigation: H.M. and R.A.; resources: F.A. and R.A.; data curation: H.A. and Y.R.A.; writing, original draft preparation: H.M.; writing, review, and editing: H.M., F.A., and R.A.; visualization: Y.R.A.; supervision: M.M.T.; project administration: A.A. All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through research group no. RG-1441-440.

Acknowledgments: The authors gratefully acknowledge the technical support received from the Universiti Teknologi Malaysia (UTM).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mastali, M.; Abdollahnejad, Z.; Pacheco-Torgal, F. Performance of waste based alkaline mortars submitted to accelerated carbon dioxide curing. *Resour. Conserv. Recycl.* **2018**, *129*, 12–19. [[CrossRef](#)]
2. Abdollahnejad, Z.; Mastali, M.; Dalvand, A. Comparative Study on the Effects of Recycled Glass–Fiber on Drying Shrinkage Rate and Mechanical Properties of the Self-Compacting Mortar and Fly Ash–Slag Geopolymer Mortar. *J. Mater. Civ. Eng.* **2017**, *29*, 04017076. [[CrossRef](#)]
3. Mastali, M.; Abdollahnejad, Z.; Pacheco-Torgal, F. Carbon dioxide sequestration of fly ash alkaline-based mortars containing recycled aggregates and reinforced by hemp fibres. *Constr. Build. Mater.* **2018**, *160*, 48–56. [[CrossRef](#)]
4. Abdelgader, H.S. How to design concrete produced by a two-stage concreting method. *Cem. Concr. Res.* **1999**, *29*, 331–337. [[CrossRef](#)]
5. Najjar, M.F.; Soliman, A.; Nehdi, M. Critical overview of two-stage concrete: Properties and applications. *Constr. Build. Mater.* **2014**, *62*, 47–58. [[CrossRef](#)]
6. Mohammadhosseini, H.; Tahir, M.M.; Alaskar, A.; Alabduljabbar, H.; Alyousef, R. Enhancement of strength and transport properties of a novel preplaced aggregate fiber reinforced concrete by adding waste polypropylene carpet fibers. *J. Build. Eng.* **2020**, *27*, 101003. [[CrossRef](#)]

7. Swaddiwudhipong, S.; Zhang, J.; Lee, S.L. Prepacked Grouting Process in Concrete Construction. *J. Mater. Civ. Eng.* **2003**, *15*, 567–576. [[CrossRef](#)]
8. Mohammadhosseini, H.; Alyousef, R.; Lim, N.H.A.S.; Tahir, M.M.; Alabduljabbar, H.; Mohamed, A.M. Creep and drying shrinkage performance of concrete composite comprising waste polypropylene carpet fibres and palm oil fuel ash. *J. Build. Eng.* **2020**, *30*, 101250. [[CrossRef](#)]
9. Najjar, M.F.; Nehdi, M.; Soliman, A.; Azabi, T. Damage mechanisms of two-stage concrete exposed to chemical and physical sulfate attack. *Constr. Build. Mater.* **2017**, *137*, 141–152. [[CrossRef](#)]
10. Mastali, M.; Naghibdehi, M.G.; Naghipour, M.; Rabiee, S. Experimental assessment of functionally graded reinforced concrete (FGRC) slabs under drop weight and projectile impacts. *Constr. Build. Mater.* **2015**, *95*, 296–311. [[CrossRef](#)]
11. Murali, G.; Ramprasad, K. A feasibility of enhancing the impact strength of novel layered two stage fibrous concrete slabs. *Eng. Struct.* **2018**, *175*, 41–49. [[CrossRef](#)]
12. Ong, K.; Basheer Khan, M.; Paramasivam, P. Resistance of fibre concrete slabs to low velocity projectile impact. *Cem. Concr. Compos.* **1999**, *21*, 391–401. [[CrossRef](#)]
13. Abdelgader, H. Concrete repair using two-stage concrete method. *MATERIALY BUDOWLANE* **2015**, *1*, 68–70. [[CrossRef](#)]
14. Afroughsabet, V.; Ozbakkaloglu, T. Mechanical and durability properties of high strength concrete containing steel and polypropylene fibres. *Constr. Build. Mater.* **2015**, *94*, 73–82. [[CrossRef](#)]
15. Mastali, M.; Dalvand, A.; Sattarifard, A. The impact resistance and mechanical properties of the reinforced self-compacting concrete incorporating recycled CFRP fibre with different lengths and dosages. *Compos. Part B Eng.* **2017**, *112*, 74–92. [[CrossRef](#)]
16. Domski, J.; Zakrzewski, M. Deflection of Steel Fiber Reinforced Concrete Beams Based on Waste Sand. *Materials* **2020**, *13*, 392. [[CrossRef](#)] [[PubMed](#)]
17. Zhou, H.; Jia, B.; Huang, H.; Mou, Y. Experimental Study on Basic Mechanical Properties of Basalt Fiber Reinforced Concrete. *Materials* **2020**, *13*, 1362. [[CrossRef](#)]
18. Malek, M.; Jackowski, M.; Łasica, W.; Kadela, M. Characteristics of Recycled Polypropylene Fibers as an Addition to Concrete Fabrication Based on Portland Cement. *Mater.* **2020**, *13*, 1827. [[CrossRef](#)]
19. Mohammadhosseini, H.; Yatim, J.M.; Sam, A.R.M.; Awal, A.A. Durability performance of green concrete composites containing waste carpet fibers and palm oil fuel ash. *J. Clean. Prod.* **2017**, *144*, 448–458. [[CrossRef](#)]
20. Sotayo, A.; Green, S.; Turvey, G. Carpet recycling: A review of recycled carpets for structural composites. *Environ. Technol. Innov.* **2015**, *3*, 97–107. [[CrossRef](#)]
21. Mohammadhosseini, H.; Tahir, M.M.; Sam, A.R.M.; Lim, N.H.A.S.; Samadi, M. Enhanced performance for aggressive environments of green concrete composites reinforced with waste carpet fibres and palm oil fuel ash. *J. Clean. Prod.* **2018**, *185*, 252–265. [[CrossRef](#)]
22. Le Tang, W.; Lee, H.-S.; Vimonsatit, V.; Htut, T.; Singh, J.K.; Hassan, W.N.F.W.; Ismail, M.A.; Seikh, A.H.; Alharthi, N. Optimization of Micro and Nano Palm Oil Fuel Ash to Determine the Carbonation Resistance of the Concrete in Accelerated Condition. *Mater.* **2019**, *12*, 130. [[CrossRef](#)] [[PubMed](#)]
23. Mohammadhosseini, H.; Tahir, M.; Sayyed, M. Strength and transport properties of concrete composites incorporating waste carpet fibres and palm oil fuel ash. *J. Build. Eng.* **2018**, *20*, 156–165. [[CrossRef](#)]
24. Awal, A.A.; Mohammadhosseini, H. Green concrete production incorporating waste carpet fiber and palm oil fuel ash. *J. Clean. Prod.* **2016**, *137*, 157–166. [[CrossRef](#)]
25. Chandara, C.; Azizli, K.A.M.; Ahmad, Z.; Hashim, S.F.S.; Sakai, E. Heat of hydration of blended cement containing treated ground palm oil fuel ash. *Constr. Build. Mater.* **2012**, *27*, 78–81. [[CrossRef](#)]
26. Lim, N.H.A.S.; Mohammadhosseini, H.; Tahir, M.; Samadi, M.; Sam, A.R.M. Microstructure and Strength Properties of Mortar Containing Waste Ceramic Nanoparticles. *Arab. J. Sci. Eng.* **2018**, *43*, 5305–5313. [[CrossRef](#)]
27. Alsubari, B.; Shafiqh, P.; Jumaat, M.Z. Utilization of high-volume treated palm oil fuel ash to produce sustainable self-compacting concrete. *J. Clean. Prod.* **2016**, *137*, 982–996. [[CrossRef](#)]
28. Abdelgader, H.S.; Elgallud, A.A. Effect of grout proportions on strength of two-stage concrete. *Struct. Concr.* **2008**, *9*, 163–170. [[CrossRef](#)]
29. Khankhaje, E.; Hussin, M.W.; Mirza, J.; Raieizonooz, M.; Salim, M.R.; Siong, H.C.; Warid, M.N.M. On blended cement and geopolymer concretes containing palm oil fuel ash. *Mater. Des.* **2016**, *89*, 385–398. [[CrossRef](#)]

30. Mohammadhosseini, H.; Alyousef, R.; Lim, N.H.A.S.; Tahir, M.M.; Alabduljabbar, H.; Mohamed, A.M.; Samadi, M. Waste metalized film food packaging as low cost and ecofriendly fibrous materials in the production of sustainable and green concrete composites. *J. Clean. Prod.* **2020**, *258*, 120726. [[CrossRef](#)]
31. Mohammadhosseini, H.; Awal, A.S.M.A.; Yatim, J.B.M. The impact resistance and mechanical properties of concrete reinforced with waste polypropylene carpet fibres. *Constr. Build. Mater.* **2017**, *143*, 147–157. [[CrossRef](#)]
32. Havlásek, P.; Jirásek, M. Multiscale modeling of drying shrinkage and creep of concrete. *Cem. Concr. Res.* **2016**, *85*, 55–74. [[CrossRef](#)]
33. Karahan, O.; Atiş, C.D. The durability properties of polypropylene fibre reinforced fly ash concrete. *Mater. Des.* **2011**, *32*, 1044–1049. [[CrossRef](#)]
34. Mohammadhosseini, H.; Awal, A.S.M.A.; Sam, A.R.M. Mechanical and thermal properties of prepacked aggregate concrete incorporating palm oil fuel ash. *Sadhana* **2016**, *41*, 1235–1244. [[CrossRef](#)]
35. Huseien, G.F.; Tahir, M.; Mirza, J.; Ismail, M.; Shah, K.W.; Asaad, M.A. Effects of POFA replaced with FA on durability properties of GBFS included alkali activated mortars. *Constr. Build. Mater.* **2018**, *175*, 174–186. [[CrossRef](#)]
36. Mohammadhosseini, H.; Yatim, J.M. Microstructure and residual properties of green concrete composites incorporating waste carpet fibers and palm oil fuel ash at elevated temperatures. *J. Clean. Prod.* **2017**, *144*, 8–21. [[CrossRef](#)]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).