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# The Impact Resistance and Deformation Performance of Novel Pre-Packed Aggregate Concrete Reinforced with Waste Polypropylene Fibres

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**Abstract:** Pre-packed aggregate fibre-reinforced concrete (PAFRC) is an innovative type of concrete composite using a mixture of coarse aggregates and fibres which are pre-mixed and pre-placed in the formwork. A flowable grout is then injected into the cavities between the aggregate mass. This study develops the concept of a new PAFRC, which is reinforced with polypropylene (PP) waste carpet fibres, investigating its mechanical properties and impact resistance under drop weight impact load. Palm oil fuel ash (POFA) is used as a partial cement replacement, with a replacement level of 20%. The compressive strength, impact resistance, energy absorption, long-term drying shrinkage, and microstructural analysis of PAFRC are explored. Two methods of grout injection are used—namely, gravity and pumping methods. For each method, six PAFRC batches containing 0–1.25% fibres (with a length of 30 mm) were cast. The findings of the study reveal that, by adding waste PP fibre, the compressive strength of PAFRC specimens decreased. However, with longer curing periods, the compressive strength enhanced due to the pozzolanic activity of POFA. The combination of fibres and POFA in PAFRC mixtures leads to the higher impact strength energy absorption and improved ductility of the concrete. Furthermore, drying shrinkage was reduced by about 28.6% for the pumping method PAFRC mix containing 0.75% fibres. Due to the unique production method of PAFRC and high impact resistance and energy absorption, it can be used in many pioneering applications.

**Keywords:** impact resistance; pre-packed aggregate fibre-reinforced concrete; strength; long-term shrinkage; microstructure; waste polypropylene fibres

## 1. Introduction

In general, conventional concrete is prepared by pre-mixing all the components after which the mixture of fresh concrete is poured into designed formwork. Concrete components may also be manufactured by first packing the coarse aggregate into the designed formwork, followed by injecting a special type of mortar (in the form of grout) in between the aggregates. Pre-packed aggregate concrete (PAC), 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 coarse aggregates of various sizes and shapes, depending on the application, in pre-planned fitments after which a specially prepared mortar (in the form of grout) is poured into the gaps amongst the aggregate particles [3]. This specific technique of concrete construction can be used in components with complex reinforcement. It can also be used in specific arrangements where the conventional type of concrete may interrupt

the pre-planned formworks, such as conduits, pipes, and openings [4]. Another application of the PAC method is mass concreting, such as in the cases of piers and bridge abutments. Moreover, the PAC technique is one of the most preferred methods for concreting underwater in which aggregate particles with different sizes are pre-placed in water, and then, a mixture of grout is injected into the gaps between the aggregate, thus replacing the water [5].

According to the literature [1–3], for pre-packed aggregate concrete (PAC), the grouting process can be attained by gravity or pumping methods. In the PAC technique of concreting, the grouting method may vary depending on the minimum size of aggregate used, as well as the depth of formworks. Generally, PAC grouting is done by either gravity or pumping methods [6]. In the gravity method, the grout mixture is poured onto the aggregates packed into the formwork and allowed to penetrate slowly downwards, under its own weight. The gravity method is usually used for thin concrete components with a depth of up to 300 mm and larger size of aggregates; for instance, road pavement slabs and floor slabs. However, with an increase in the depth of sections, the grout cannot completely cross through the entire thickness of the formwork. Therefore, in components with smaller-sized aggregates and deeper sections, the pumping method of grout injection is preferred. In this method, a pump with a pressure measuring device is used. The grout is pumped in between the pre-placed aggregates from the bottom of the formworks. Pipes with perforations, which are 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 [7]. PAC can be used in massive concrete where placement by conventional practices is very difficult [8,9]. As the coarse aggregates are pre-packed, the manufacturing process makes PAC one of the most desirable methods in the construction of nuclear power plants, where heavy minerals can be used together with coarse aggregates in the production of concrete without any segregation [10,11].

Concrete, in many different forms, is the most extensively used construction material worldwide. Plain concrete, however, is considered a brittle material due to its low tensile strength. Therefore, higher impact strength and energy absorption capacity are vital in different usages for PAC and conventional concrete. Other components are needed to develop these properties of concrete, where these features are vital [12,13]. Consequently, new materials which can develop the performance of concrete with higher energy absorption capability and superior ductility are in high demand. A related promising solution to achieve these properties in concrete is the addition of fibres at various dosages into the concrete mixture [14]. Pre-packed aggregate fibre-reinforced concrete (PAFRC) is a novel material made of pre-placed coarse aggregates of different sizes, which are mixed with short fibres and cementing materials mixed with sand in the form of grout, which is injected into the mixture of pre-packed aggregates and fibres. The utilisation of various types of fibres, such as polymeric and metallic fibres, in conventional concrete at volume fractions of 0.1% to 2.0%, has been recognised by many researchers [15,16]. Numerous kinds of research works have been conducted to investigate the ductility performance of fibre-reinforced concrete (FRC) with short fibres through impact resistance tests. In this regard, Mohammadhosseini et al. [17], as well as Awal and Mohammadhosseini [18], reported that the inclusion of waste polypropylene carpet fibres remarkably developed the impact strength and energy absorption of conventional concrete. However, PAFRC is a new sort of concrete reinforced with short fibres. The utilisation of recycled CFRP fibres at different lengths and dosages has been studied by Mastali et al. [19], who reported that these waste fibres significantly improved the impact resistance of conventional fibre-reinforced concrete. Furthermore, Alyousef et al. [15] reported that the inclusion of plastic fibres at different dosages could significantly enhance the performance of concrete. Ong et al. [20] found that the use of polymeric base fibres in combination with steel fibres remarkably enhanced the impact strength and energy absorption capacity of concrete slabs.

The production of polymeric fibres, as employed in the carpet and textiles industries, has been steadily rising, presently about 70 million tons annually [21,22]. However, a massive amount of these fibres is sent to landfill as waste during the manufacturing process. Like other countries, Malaysia produces carpets, and about 50 tons of polymeric fibres are sent to landfill as waste every

year [23]. Indeed, this option of waste disposal is gradually becoming unviable, owing to the increasing cost of landfilling in addition to the limited accessibility of discarding sites [24]. Consequently, the demand to reutilise waste materials is growing, due to a lack of landfill places globally and the preservation of natural resources [25]. In Malaysia, approximately 5 million tons of waste palm oil ashes (POFA) are produced per year as a waste material [26,27]. However, according to past studies, with proper treatment, POFA can be utilised as partial cement replacement in concrete, with adequate performance [28,29].

So far, there has been no study on the strength and impact resistant of PAC comprising waste carpet fibres and POFA. Given that POFA is categorised as a pozzolanic material and considering the local availability of industrial waste carpet fibre, these materials were used in the manufacturing of PAC. Therefore, the purpose of this research work was to study the combined influences of waste polypropylene carpet fibres and POFA on the mechanical properties and impact resistance of novel pre-packed aggregate concrete, in addition to understanding the way that waste carpet fibres contribute to the improvement in energy absorption, in comparison to plain PAC without any fibres.

## 2. Materials and Methods

### 2.1. Materials

In this study, a type I cement complying with the specifications of ASTM C 150-07 [30] was used. Ordinary Portland cement (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 a temperature of  $100 \pm 5$  °C and then sieved to remove the larger particles (i.e., over 150  $\mu\text{m}$ ). Subsequently, the small-sized ash particles were kept in a crushing machine and the grinding process was continued for about two hours per each 4 kg of ash. The ground POFA particles were then tested following the specifications of ASTM C618-15 [31] and BS 3892: Part 1–97 [32], in order to achieve the desired properties. The ashes which passed the standard requirements with the desired chemical compositions and physical properties (as given in Table 1) were then used as cementing materials. Moreover, sets of trial mixes were carried out using different percentages of POFA content. The results revealed that inclusion of POFA at more than 20% led to a reduction in the compressive strength of concrete, particularly at the early ages. However, according to the trial mix results and to reduce the consumption of OPC, 20% POFA content was selected as an optimum level to be used in the main experimental work.

**Table 1.** Characteristics of used palm oil fuel ash (POFA) and OPC.

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

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 grout mixture. The fineness modulus, specific gravity, and water absorption of sand particles were found as 2.3,

2.6 g/cm<sup>3</sup>, 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-05 [10]. Crushed granite coarse aggregates of 20–38 mm in size, 2.7 g/cm<sup>3</sup> specific gravity, and 0.5% water absorption were employed. The aggregates were cleaned and washed before placing in formworks, in order to eliminate any impurities. Additionally, multi-filament polypropylene waste fibres collected from the local carpet industry were used in this study to reinforce the PAC specimens. Initially, the fibres were collected in the form of waste yarn. Then, in order to use this yarn as a fibrous material in the concrete, several tests were carried out. After they satisfied the standard requirements (as given in Table 2), the yarns were cut and fabricated to the desired length of 30 mm with an aspect ratio (l/d) of 67, as illustrated in Figure 1.

**Table 2.** Typical properties of fabricated polypropylene (PP) waste fibres.

Waste PP Fibre	Length (mm)	Diameter (mm)	Density (kg/m <sup>3</sup> )	Melting Point (°C)	Tensile Strength (MPa)	Reaction with Water
Multi-filament polypropylene	30	0.45	910	170	400	Hydrophobic



**Figure 1.** Waste PP fibres with 30 mm length.

## 2.2. Mix Proportions

In this study, two groups of pre-packed aggregate concrete mixes, based on the method of grouting, were made: gravity (G) and pumping (P) mixes. For each group, five mixes were cast, where one was a control mix without any fibres (G0, P0) and another four mixes were reinforced with polypropylene (PP) fibre volume fractions of 0.25%, 0.50%, 0.75%, and 1.0%. In all mixes, OPC was replaced by 20% POFA, and the water/binder (w/b) ratio of 0.5 and cement/sand (c/s) ratio of 1/1.15 was kept constant. As the effect of fibres at different volume fractions was the main parameter to be investigated, the w/b and c/s ratios were kept constant to attain similar conditions for all PAFRC mixes. Table 3 lists the quantities of the various components used in the manufacture of PAFRC mixes.

**Table 3.** Proportions of various components used in the pre-packed aggregate fibre-reinforced concrete (PAFRC) mixes.

	Mix	Water (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	POFA (kg/m <sup>3</sup> )	Fine Aggregate (kg/m <sup>3</sup> )	Coarse Aggregate (kg/m <sup>3</sup> )	V <sub>f</sub> (%)
Gravity	G0	186	304	76	545	1320	0.0
	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

Table 3. Cont.

	Mix	Water (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	POFA (kg/m <sup>3</sup> )	Fine Aggregate (kg/m <sup>3</sup> )	Coarse Aggregate (kg/m <sup>3</sup> )	V <sub>f</sub> (%)
Pump	P0	186	304	76	545	1320	0.0
	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

### 2.3. Sample Preparation

The manufacture of PAFRC specimens was carried out in two phases. First, the dry mixture of coarse aggregate particles and PP fibres was placed and packed into the design formworks and moulds; then, the pre-mixed mortar made of blended cement and river sands, with adequate flowability and in the form of the grout, was injected in between the gaps amongst aggregates and fibres, either by the gravity or pumping methods. In the grouting process by the gravity method, a polyvinyl chloride (PVC) pipe with a diameter of 5 mm was placed at the centre of the cylindrical moulds of size 100 × 200 mm and 150 × 300 mm, and then, grout was injected under the force of gravity, as illustrated in Figure 2b. The grouting process in the pumping method was more complicated. In this method, as illustrated in Figure 2a, unplasticized polyvinyl chloride (UPVC) pipes of 100 and 150 mm diameter were used as moulds. The lengths of the pipes varied between 1 and 2 m, based on the number of required samples. The pipes were then arranged in a formwork made of plywood to prevent movement during the grouting process. A pump with a pressure control device was used, which was attached to the hopper for grout injection purposes. To avoid the overflow of grout, as well as to avoid the uplifting of the aggregate particles, a cap made of plywood was fixed to the top surface of the UPVC pipes. The entire process of grouting was monitored, in order to avoid any leakage of grout from the moulds as well as to prevent overflowing. After the casting process was carried out, the PAFRC specimens were cured for 24 h at an ambient temperature. The samples were then removed from the moulds and kept in a water tank at room temperature until further testing.



Figure 2. Methods of pre-packed aggregate concrete (PAC) grouting: (a) pumping; (b) gravity.



#### 2.4. Testing Methods

In order to explore the influence of POFA as a partial cement replacement on the consistency of the grout mixture, the flow property of the grout was assessed following the ASTM C939-16 [33]. The compressive strength test of PAFRC specimens was carried out following the specifications of ASTM C39M-18 [34], using cylindrical moulds of size 100 mm × 200 mm and 150 mm × 300 mm for gravity and pumping techniques. Further, scanning electron microscopy (SEM) was used to examine the microstructure of the grout paste. In addition, following the specifications of ASTM C512-10 [35], the long-term drying shrinkage test was also carried out on cylindrical specimens of size 100 mm × 200 mm, as shown in Figure 3.

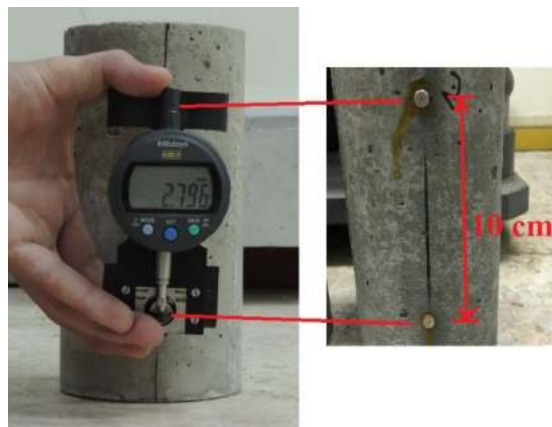


Figure 3. Drying shrinkage test setup.

Impact resistance and energy absorption tests were carried out on the PAFRC specimens in accordance with ACI 544.2R-99 [36]. For each batch of concrete, three disk samples with 64 mm thickness and 150 mm diameter were cut from the cylinders of size 150 × 300 mm and subjected to an impact load induced by a steel hammer with mass 4.45 kg, frequently released from a height of 457 mm on a stainless steel ball 63.5 mm in diameter positioned on the top surface of the centre of the concrete specimens. Figure 4 illustrates the drop weight impact resistance test device and the concrete disk samples. The number of drops for the first crack and failure were recorded as the first crack impact resistance (N1) and ultimate impact resistance (N2), correspondingly. Moreover, the impact energy induced by the hammer for blows at first crack and failure was evaluated according to Equations (1)–(4) [18]:

$$U = \frac{mV^2}{2} \quad (1)$$

$$m = \frac{W}{g} \quad (2)$$

$$V = gt \quad (3)$$

$$H = \frac{gt^2}{2} \quad (4)$$

where  $U$  is the impact energy of each drop (kJ mm);  $W$  is the weight of the hammer (4.45 kg);  $m$  is the mass of the hammer;  $g$  is the acceleration of gravity ( $9.81 \text{ m/s}^2$ );  $V$  is the velocity of the hammer;  $t$  is the required time for the hammer to drop (0.3053 s), and  $H$  is the falling height of the hammer (457 mm).

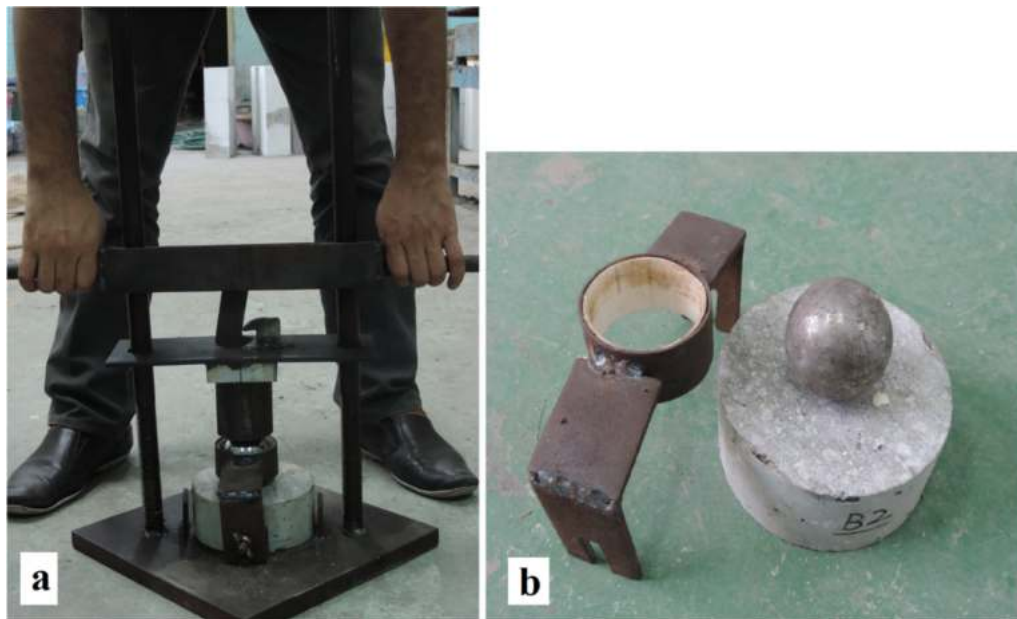


Figure 4. (a) Impact resistance test device and (b) steel ball and disk sample.

### 3. Results and Discussion

#### 3.1. Grout Fluidity

In PAC, flowability and uniformity of the grout are essential, as they have a significant influence on its pumpability and permeability. The fluidity of grout was assessed through the flow cone test. Figure 5 shows the outcomes of the fluidity test of the 100% OPC grout mixture and the mixture containing 20% POFA. It was observed that the fluidity of the grout mixture (with constant w/c and c/s) increased when the OPC was replaced by 20% POFA. For the POFA-based grout mixture, the fluidity was noted as 13.1 s, which was comparatively lower than that (15.2 s) found for the grout mixture with 100% OPC. The higher flowability of the POFA-based grout could be due to the finer size of POFA ashes, as compared to OPC particles. The smaller particle size of POFA could, therefore, ease in the movement of the grout mixture and result in higher fluidity [37,38].

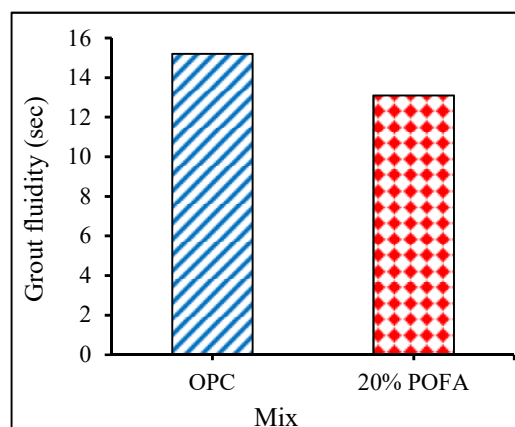
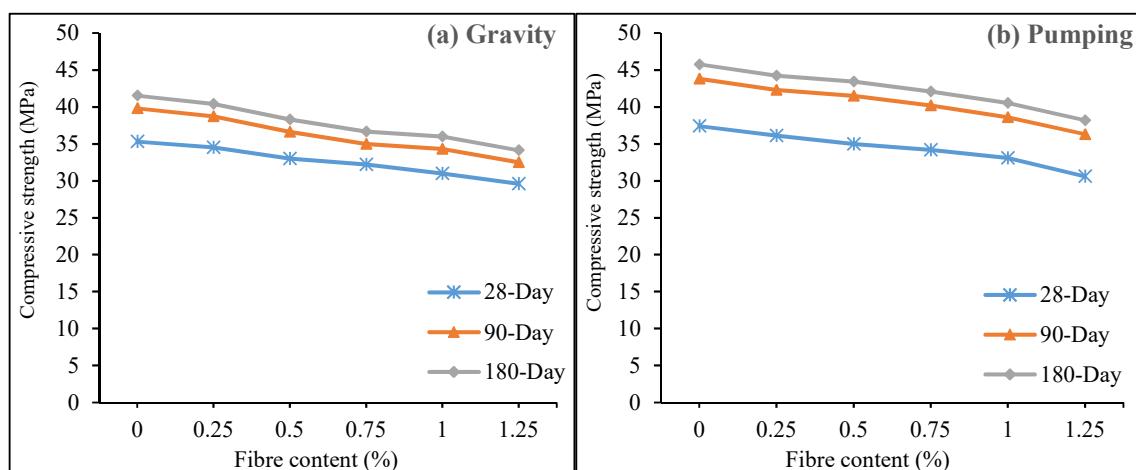


Figure 5. Grout fluidity of the OPC and POFA grout mixtures.

#### 3.2. Compressive Strength

The compressive strength values of PAFRC specimens at 28, 90, and 180 days were measured and are presented in Figure 6. The compressive strength of PAFRC specimens shows that reinforcement

of plain PAC with PP fibres resulted in a slight reduction in the strength values. The decrease in the compressive strength of PAFRC specimens might be due to the presence of cavities in the matrix, which would be increased with the inclusion of fibres at high dosage. Higher fibre content induces the balling effect, void formation, and clustering, consequently making the matrix weaker and more prone to cracking, therefore reducing the amount of grout injected between the mixture of coarse aggregates and fibres, leading to the reduction in compressive strength of the concrete [39,40]. It can be observed that the compressive strength of gravity method PAFRC specimens was reduced by 2.3%, 6.5%, 8.8%, 12.2%, and 16.1% when adding 0.25%, 0.5%, 0.75%, 1%, and 1.25% fibres, respectively, as compared to the plain PAC mix. Likewise, the pumping method specimens showed a minor reduction in compressive strength values, as compared to that of the plain PAC mix. The compressive strength reduced by about 3.4%, 6.4%, 8.5%, 11.4%, and 18%, respectively, for the same fibre dosages as above. However, a remarkable rise in compressive strength values was noted at the curing period of 90 days, as compared to those recorded at 28 days. This could be attributed to the pozzolanic nature of POFA for which the rate of hydration is slow during the early curing periods [41]. Additionally, the reduction in compressive strength values was considered for the delay in the hydration process and lower development of the C–S–H gel, which negated the increase in compressive strength. To improve the hydration process, Chandara et al. [29] suggested the use of finer ash particles in the cement composite. In a detailed study, they demonstrated that ground POFA is highly pozzolanic and can be used as supplementary cementing material, for up to 40% by weight of OPC.



**Figure 6.** Variation in the compressive strength of (a) gravity and (b) pumping method PAFRC specimens.

Moreover, beyond 28 days, the compressive strength of the PAFRC mixes tended to increase with the curing age for all fibre volume fractions and gave higher compressive strength than those at early ages. This can be explained by the fact that the higher-fineness POFA develops pozzolanic properties and particle packing density [42]. It was also detected that the pumping method samples obtained a higher strength value, in comparison with the specimens using the gravity technique. The higher strength values of the pumping method specimens were due to the uniform distribution of grout mixture under pressure across the formwork, which provided a dense matrix. As the volume and quality of cement paste directly influence the strength of concrete, consistent distribution of grout under the control pressure results in a denser microstructure and higher strength values [5].

### 3.3. Impact Resistance and Energy Absorption

In this study, the number of drops for the first crack and ultimate failure were recorded, and based on these numbers, the impact resistance and energy absorption were determined, the results of which are shown in Figures 7 and 8. The increase in the first crack and ultimate crack impact resistance and impact energy, which indicated how many times it increased in comparison to the reference mixes (G0



and P0), are also shown. As shown in Figure 7, in the gravity method specimens, the number of drops for the first crack was recorded as 16, 28, 45, 63, 84, and 102 for the G0, G1, G2, G3, G4, and G5 mixes, correspondingly. It can be seen that, by adding fibres and with an increase in the fibre dosages, the number of drops remarkably improved. Likewise, the number of drops to failure in the specimens were noted as 21, 41, 74, 82, 108, and 131 for G0, G1, G2, G3, G4, and G5 mixes, correspondingly. These outcomes indicate that the mixes with higher fibre volume fractions performed better under impact loads. A similar tendency was noted for the pumping method of PAFRC specimens. As revealed in Figure 7, the impact resistance of PAFRC samples at the first crack was enhanced by about 90%, 215%, 320%, 405%, and 555% with the addition of 0.25%, 0.5%, 0.75%, 1%, and 1.25% PP fibres, respectively, as compared to the plain mix (P0). Additionally, for the same fibre dosages, the impact resistance at failure was improved by 104%, 248%, 296%, 404%, and 544%, respectively. As the test was carried out after 90 days of curing, owing to the pozzolanic nature of POFA and the creation of additional hydration products, such as C–S–H gels, the strength of specimens increased, therefore resulting in the higher impact resistance of PAFRC specimens [43]. Khankhaje et al. [42] reported that hydration products (e.g., C–S–H gels) are developed at longer curing periods, resulting in a denser matrix and, therefore, higher strength values.

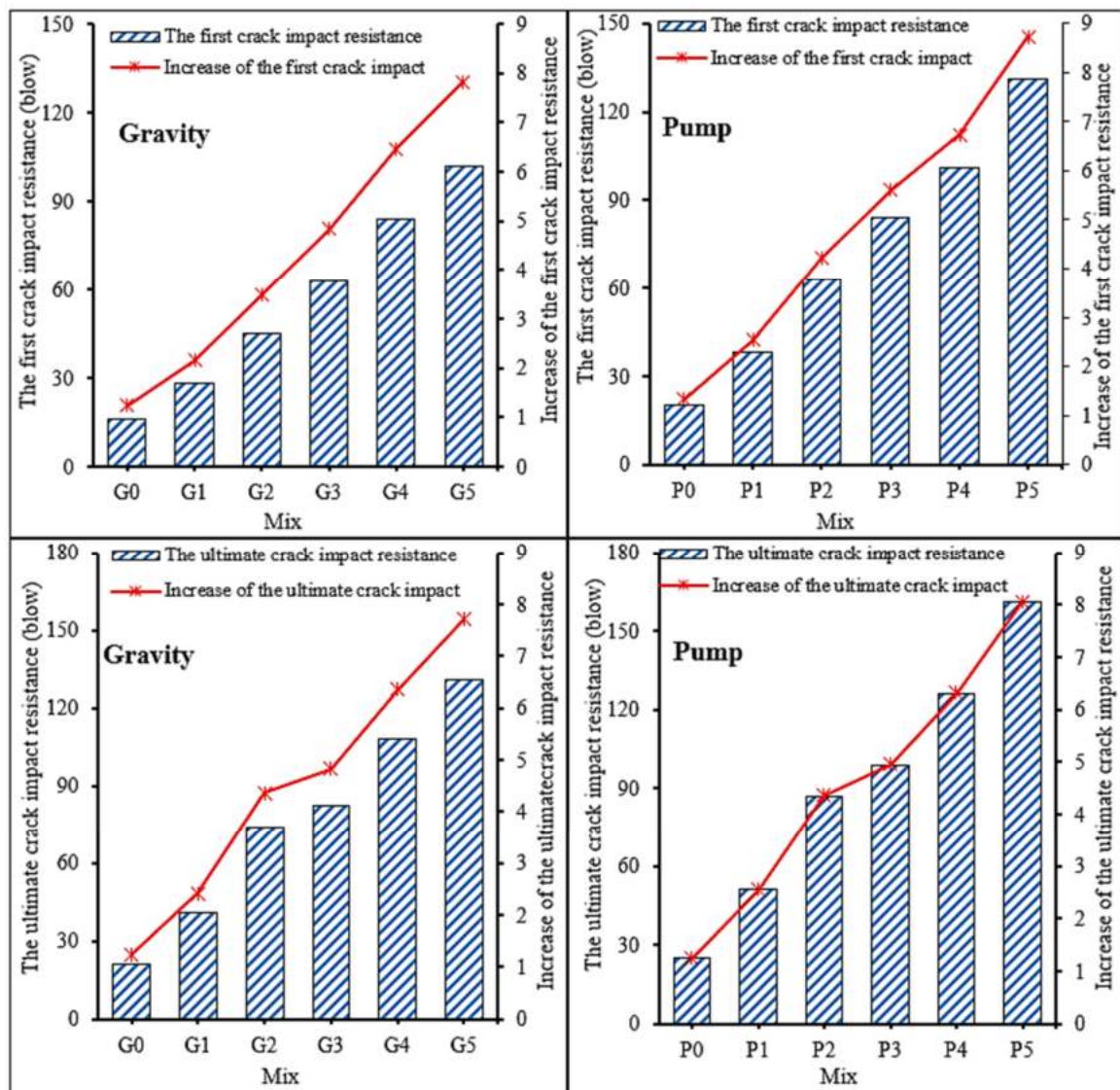


Figure 7. Impact resistance of PAFRC specimens for gravity and pumping techniques.

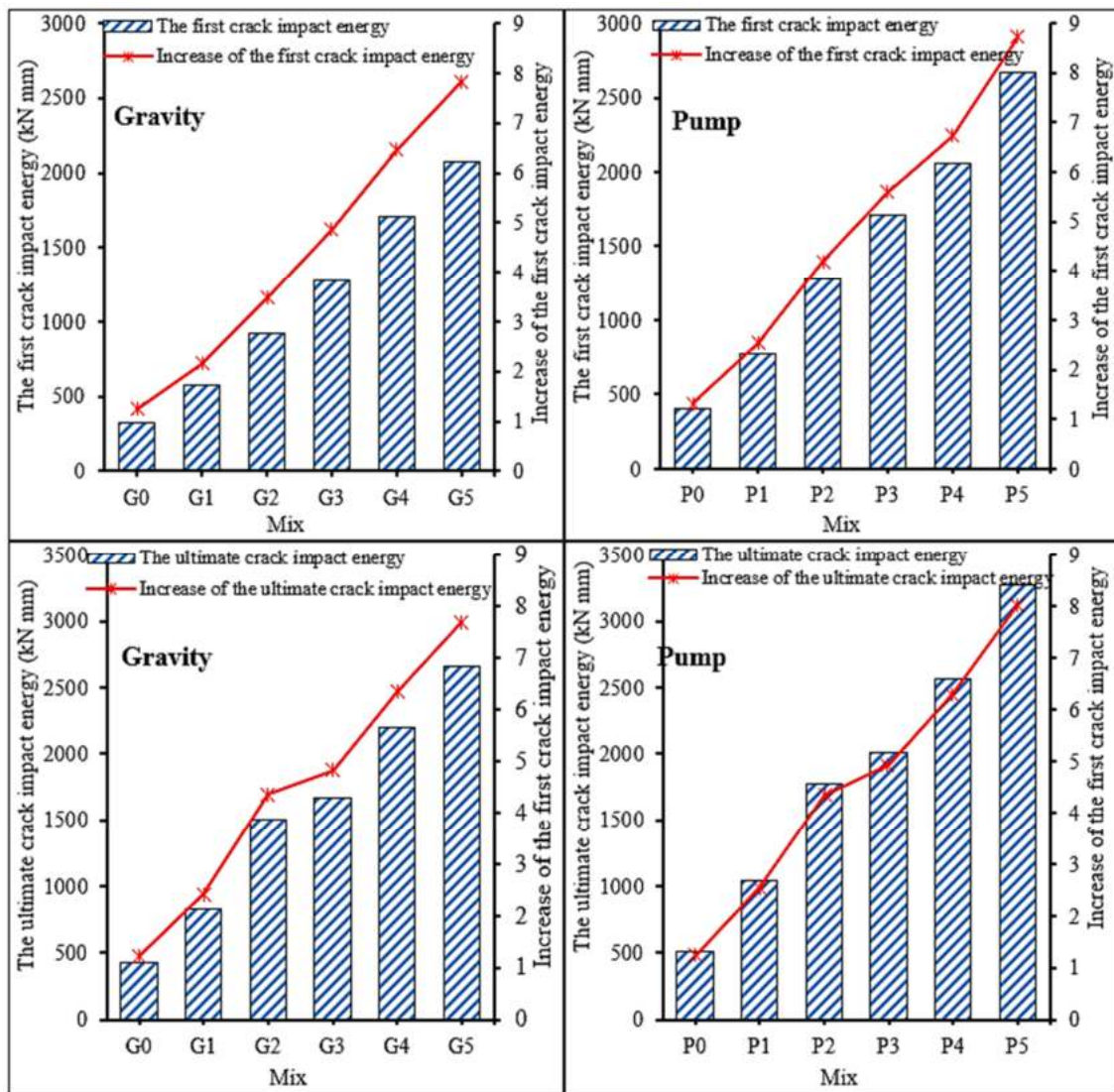


Figure 8. Impact energy of PAFRC specimens for gravity and pumping methods.

Furthermore, the impact energy levels of the PAFRC samples at first crack and failure were calculated following Equation (1). It is clear that the inclusion of fibre into the PAFRC specimens noticeably increased the number of repeated drops to the first crack and failure, with reference to the plain PAC specimens. The obtained impact energy values of the PAFRC specimens are demonstrated in Figure 8. In the gravity method group, the highest impact energies were 2076 and 2667 kN mm, recorded for the PAFRC mix reinforced with 1.25% PP carpet fibres (G5) at initial crack and failure, respectively.

A similar tendency to that of the gravity method was noticed for the impact energy of the pumping method group. Higher fibre content resulted in more considerable impact energy in the PAFRC specimens. From Figure 8, it can be seen that the highest impact energies of 2666 and 3277 kN mm were noted for the PAFRC specimens reinforced with 1.25% fibres at first crack and ultimate failure, respectively, in comparison with that of the plain PAC (P0) mix. By comparing the obtained results of the impact energy, it was revealed that the initial crack and failure impact energies of the PAFRC specimens (for all fibre volume fractions), which were grouted by the pumping technique, were considerably higher than those of the gravity samples. The results obtained in this study confirmed the findings of Abirami et al. [14] for layered concrete slabs reinforced with steel fibres and Mastali et al. [44] with the inclusion of recycled CFRP fibres into the concrete. They both reported that the addition of short fibres resulted in higher impact resistance and energy absorption under impact loads.

The PAFRC samples used for impact strength test and the failure modes after the impact test are illustrated in Figure 9. It was detected that the plain specimens without any fibres absorbed less energy and were broken into a few pieces with a small number of drops. This could be due to the brittle nature and lower energy absorption capacity of plain concrete under impact loads. However, by adding PP fibres and with an increase in the fibre dosages, the ductility and energy absorption capacity of PAFRC specimens were significantly enhanced. As shown in Figure 9, the failure modes of the reinforced specimens changed, the specimens became more ductile without sudden failure, and cracks only occurred on the surface of specimens. The enhancement in the ductility and energy absorption of the PAFRC specimens may have been due to the bridging action of PP fibres, which arrests cracks and prevents sudden failure in the specimens. In addition, the uniform distribution of fibres resulted in the propagation of cracks on the top surface of disks and, therefore, absorbed a higher amount of energy before failure [8].

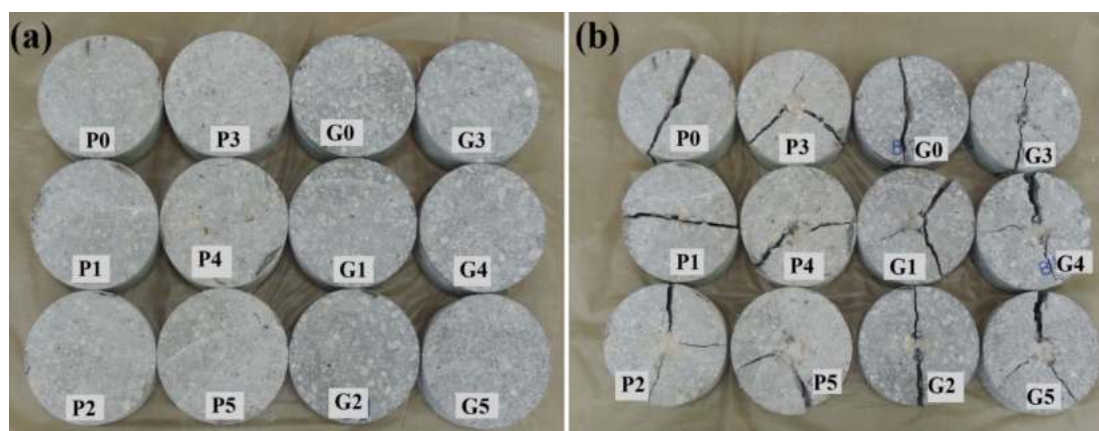
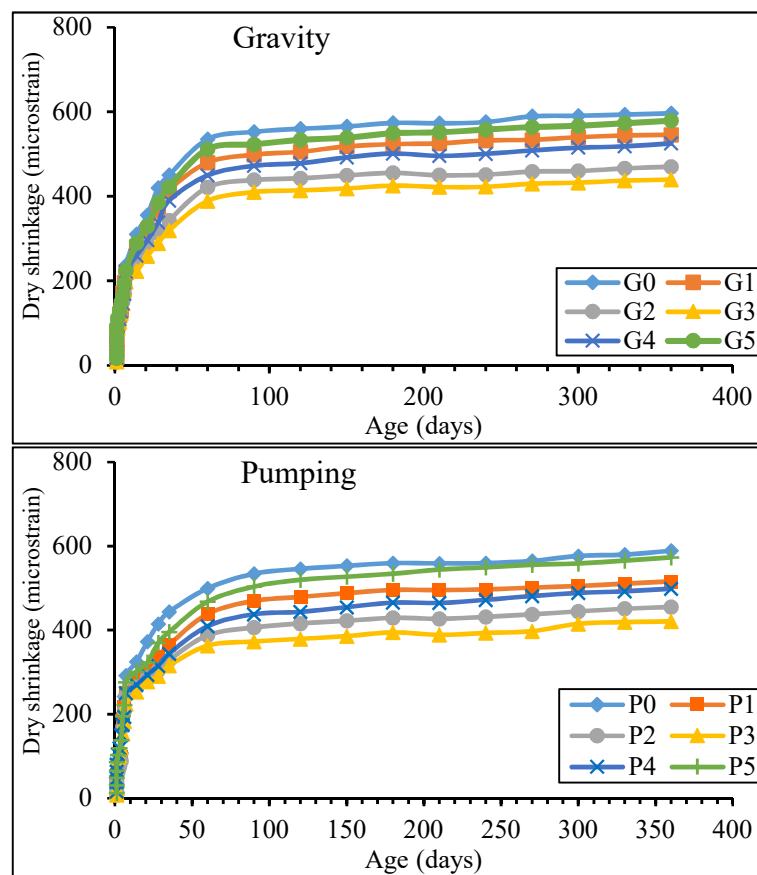


Figure 9. PAFRC specimens (a) before and (b) after impact load.

#### 3.4. Long-Term Drying Shrinkage

Drying shrinkage is one of the most common causes of the cracking in concrete structures, which directly affects the durability and strength properties of concrete. Drying shrinkage of concrete cannot be recovered by rewetting. Therefore, the addition of PP provides an alternative solution to reduce drying shrinkage, which is bound to occur over time [21]. As PAC is a preferred type of concrete in massive concreting, thermal cracks are one of the critical problems, which affect the long-term performance of the structure. Consequently, the addition of short PP fibres may also provide an alternative solution to minimise such cracks [1]. Therefore, in this study, the long-term drying shrinkage of PAFRC specimens containing PP fibres and POFA was measured. The main purpose of this experimental work was to investigate the influence of fibres and POFA on the shrinkage behaviour of pre-packed aggregate concrete over a one-year testing period. The experiments performed indicated that the inclusion of PP fibres (up to a specific fibre volume fraction) and POFA has a dominating effect on the drying shrinkage of PAFRC. As shown in Figure 10, the presence of fibres in the PAFRC mixes reduced the drying shrinkage values in which the maximum shrinkage value was detected for the plain mix of gravity method (G0). It can be seen that, up to 28 days of testing, the rate of shrinkage was high for all mixes. However, over time, the rate of variation in the shrinkage of the specimens reduced. It was also detected that the pumping method PAFRC samples attained smaller drying shrinkage values than gravity technique samples. This could have been due to the better distribution of the grout mixture amongst the mixture of aggregates and fibres.





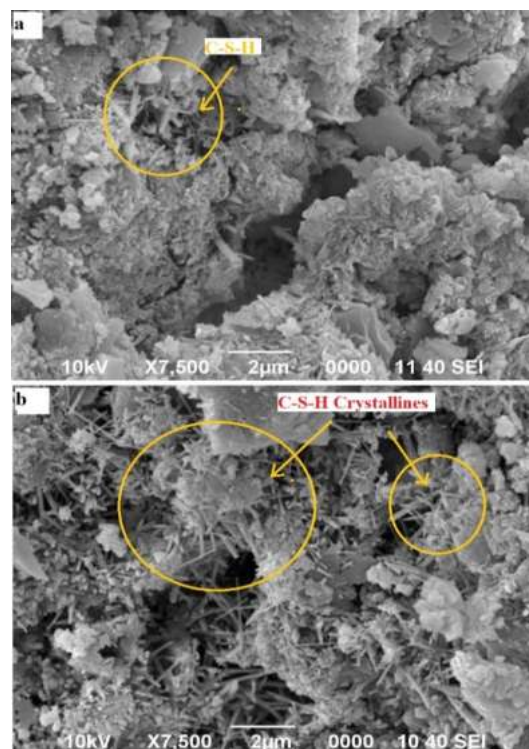
**Figure 10.** Long-term drying shrinkage of PAFRC specimens reinforced with PP fibres.

It is well-known that the shrinkage of concrete depends on the quality of the cement paste, the volume of voids, and (to some extent) on the strength level of the concrete [38]. Therefore, the proper injection of grout leads to a denser matrix, which causes lower drying shrinkage values. Moreover, at the end of the testing period of 365 days, the addition of 0.25%, 0.5%, 0.75%, 1%, and 1.25% PP fibres into the gravity method PAFRC specimens resulted in the reduction in drying shrinkage of 8.5%, 21.2%, 26.3%, 11.9%, and 2.3%, correspondingly, as compared to that of the plain mix (G0) without any fibre. Likewise, in the pumping method PAFRC samples with the same fibre dosages, the shrinkage values were reduced by 12.4%, 22.5%, 28.6%, 15.3%, and 2.9%, correspondingly, as compared to that of the plain mix (P0). The results show that the pumping method specimens obtained lower drying shrinkage values than the gravity method specimens, which may be due to the dense microstructure of the pumping method specimens, a consequence of the uniform distribution of grout into the formworks filling up the voids and the consequent lower volume of pores [3,6].

It can be observed that all mixtures reinforced with PP fibres obtained lower drying shrinkage values after the one-year testing period. However, a further rise in fibre dosages beyond 0.75% caused higher shrinkage values, particularly in the gravity method specimens. This could be due to the existence of the larger amount of fibres in the mixture preventing the uniform distribution of grout amongst the aggregates and, therefore, increasing the volume of voids and causing higher shrinkage values. These outcomes are in agreement with the results reported by Karahan and Atis [45]. They reported that the application of PP fibres in concrete composites was able to considerably reduce drying shrinkage by improving the tensile performance and bridging action along the forming cracks. Medina et al. [46] also demonstrated that the inclusion of PP fibres into concrete composite reduced its drying shrinkage, while also observing a decrease in drying shrinkage related to the increment of fibre content after a certain amount. They stated that the utilisation of PP fibres controlled the movements of the fine cracks in cement paste through a bridging action.

### 3.5. Microstructural Analysis

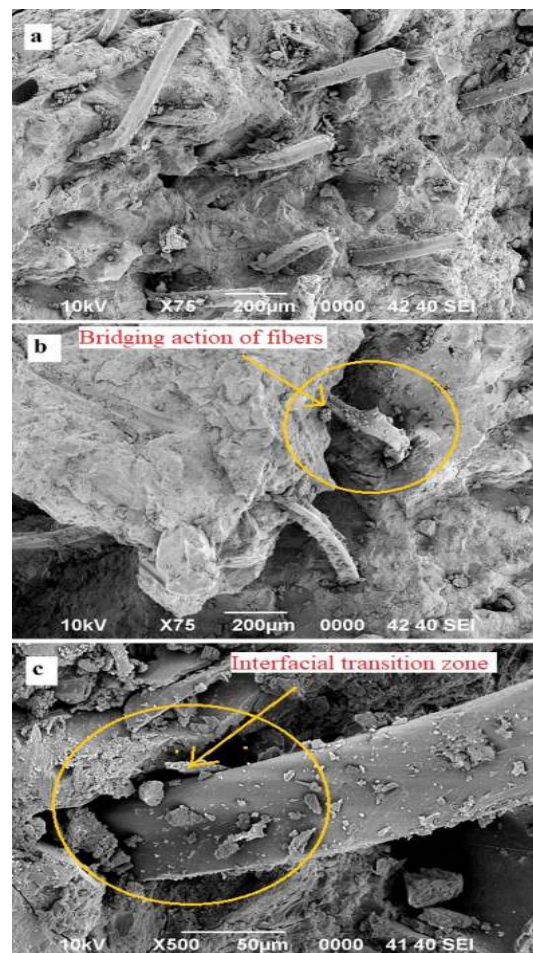
Microstructural analysis of the grout paste was carried out in terms of SEM analysis, in order to explore the effects of POFA replacement on the hydration product. In addition, the role of PP fibres in enhancing the interfacial transition zone in the matrix was assessed. It was observed that the substitution of OPC with 20% POFA in PAFRC mixes resulted in higher strength values at the ultimate ages. This can be attributed to the pozzolanic nature of POFA, which contains a large volume of reactive SiO<sub>2</sub>. With the existence of moisture, over time, this reactive SiO<sub>2</sub> chemically reacts with the released CH—which is the hydration product of OPC—and forms extra C–S–H gels in the matrix. Consequently, these supplementary hydration products, which are due to the pozzolanic action of POFA, fill up the cavities and decrease the porosity in the matrix, leading to a dense microstructure. This denser microstructure then results in the enhanced strength and durability of concrete [43,47]. Figure 11 displays the SEM image of POFA-based paste in PAFRC samples at the ages of 28 and 90 days. The uniform spreading of C–S–H gels at the age of 90 days is revealed, indicating the denser matrix at the ultimate ages, as compared with the 28-day paste. Besides, the homogeneous distribution of hydration products, such as C–S–H gels is shown in the 90 days SEM image, which filled up the cavities in the matrix and provided a solid microstructure.



**Figure 11.** SEM images indicating the hydration products at the ages of (a) 28 and (b) 90 days.

Figure 12 illustrates the uniform distribution of PP fibres in the matrix and the linking action of fibres, in addition to the interfacial transition zone among fibres and cement paste in the concrete matrix afterwards. The SEM image reveals a robust bond among fibres and the blended cement paste. This strong bonding between fibres and paste provides a reliable solid microstructure in the matrix, which results in a reduction in crack formation at the interface zone [48]. Consequently, the lower volume of cracks leads to strength development and high impact resistance, as well as the better ductility and energy absorption of PAFRC specimens. The utilisation of waste PP fibres in conventional fibre reinforced concrete has also been studied by Mohammadhosseini et al. [17], who revealed that waste PP fibres and cement paste provide a strong interfacial transition zone; therefore, the consequent concrete specimens could absorb higher energy, resulting in better ductility performance under impact loads.





**Figure 12.** (a) Distribution of PP fibres; (b) bridging action of fibres; (c) the interfacial transition zone between paste and fibre.

#### 4. Statistical and Analytical Analyses

In this section, the probability distribution of tensile ( $F_t$ ) and compressive ( $F_c$ ) strengths, first crack (FC), and ultimate crack (UC) impact resistance of PAFRC specimens containing PP carpet fibres are discussed. In this study, to better understand the performance of PAFRC specimens under impact loads, statistical analyses of the obtained data were deemed necessary. The effects of fibre dosage on distribution and statistical parameters of compressive and tensile strengths and impact resistance of PAC were also considered significant. Empirical relationships were developed for the compressive strength of PAFRC specimens by gravity and pumping methods. To carry out the statistical calculations, the Statistical Package for the Social Sciences (SPSS) software was used. Thus, the Kolmogorov–Smirnov (K–S test) technique, as proposed by Mastali and Dalvand [19], was applied to test the normality of the obtained experimental data. The K–S test method is based on the maximum deviation of the detected cumulative histogram from the hypothesised cumulative distribution function. The normal distribution can well-characterise the strength variability of most ductile materials, such as FRC. Furthermore, most recent studies on FRC have used a normal distribution [19,44], and as such, this study also used a normal distribution to analyse the strength properties of the PAFRC specimens using carpet fibres. From Figure 13, it can be seen that the histogram of the strength and impact resistance of PAFRC specimens reinforced with PP carpet fibres followed a normal distribution. According to the statistical analysis results, p-values of above 0.05 were obtained for all tests, which quantified the strength of evidence against the null hypothesis. The hypotheses for the normal distribution were as follows:

**H1.** The compressive strength of pumping and gravity method PAFRC specimens reinforced with PP fibres follows the normal distribution.

**H2.** The tensile strength of pumping and gravity method PAFRC specimens reinforced with PP fibres follows the normal distribution.

**H3.** The first crack impact resistance of pumping and gravity method PAFRC specimens reinforced with PP fibres follows the normal distribution.

**H4.** The ultimate crack impact resistance of pumping and gravity method PAFRC specimens reinforced with PP fibres follows the normal distribution.

The obtained p-values for all tests were found to be above 0.05. This finding corroborates the null hypothesis at the 0.05 significance level. Consequently, the compressive strength, tensile strength, and first and ultimate crack impact resistance of PAFRC reinforced with waste PP fibres followed normal distributions. The attained outcomes of the current study were similar to the results described by Song et al. [49] and Mohammadhosseini et al. [50], who reported that the mechanical properties of conventional concrete reinforced with PP fibres followed a normal distribution, while the first and the ultimate crack impact resistance hardly followed a normal distribution.

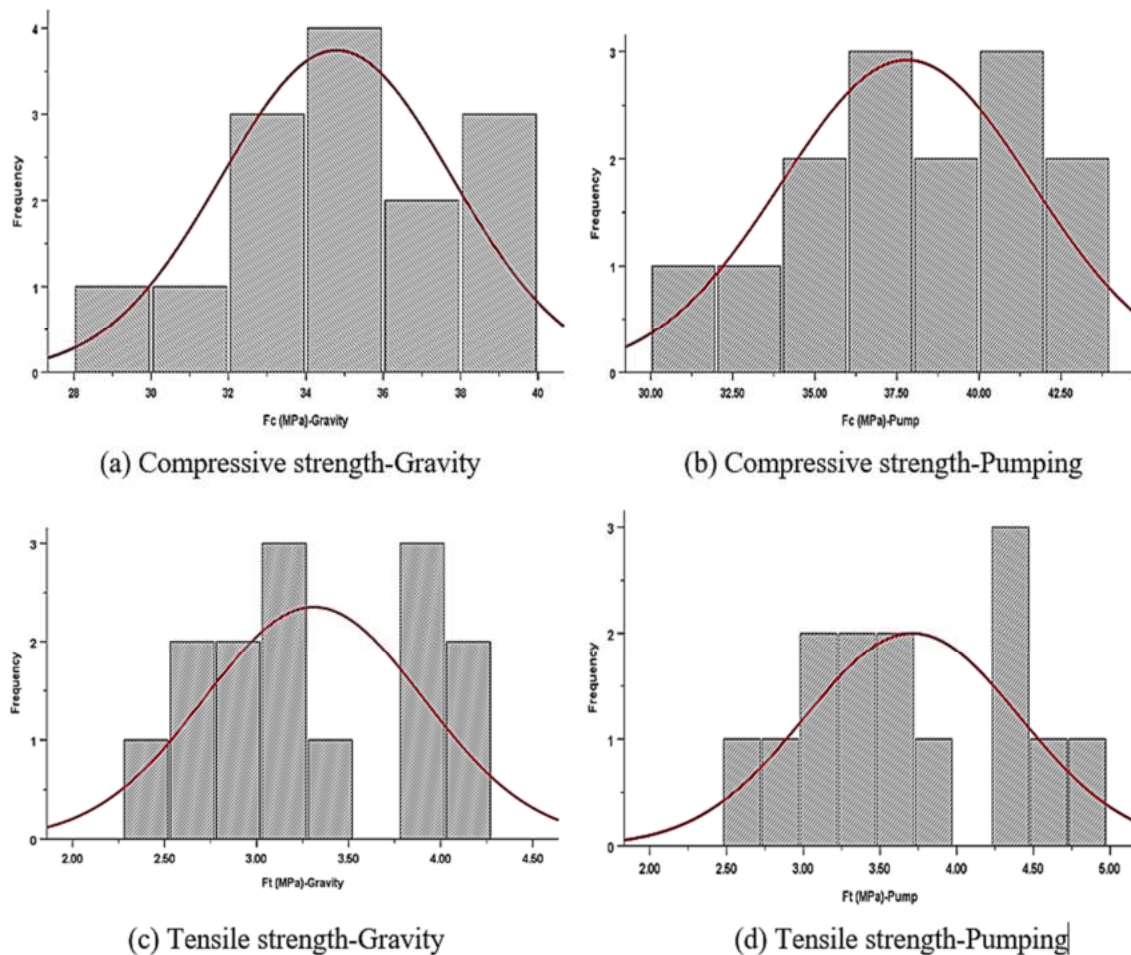


Figure 13. Cont.

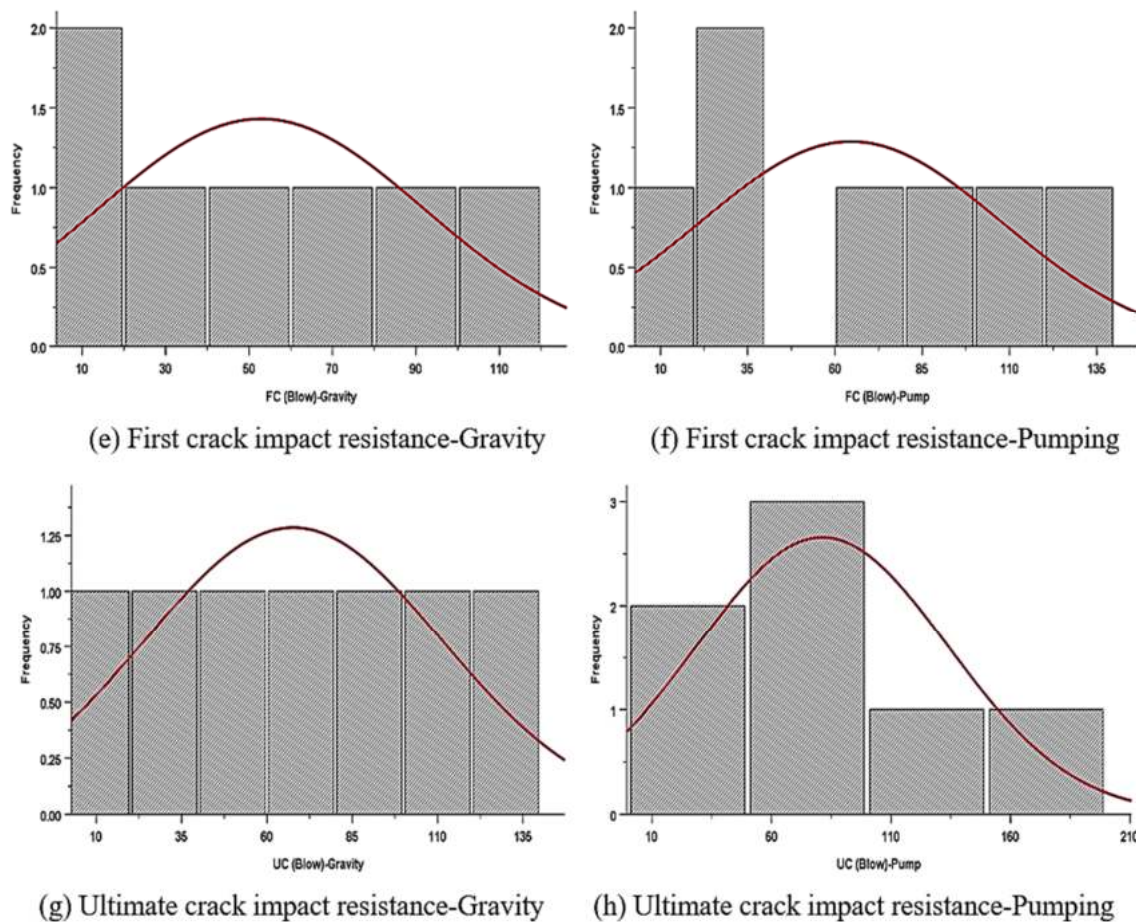


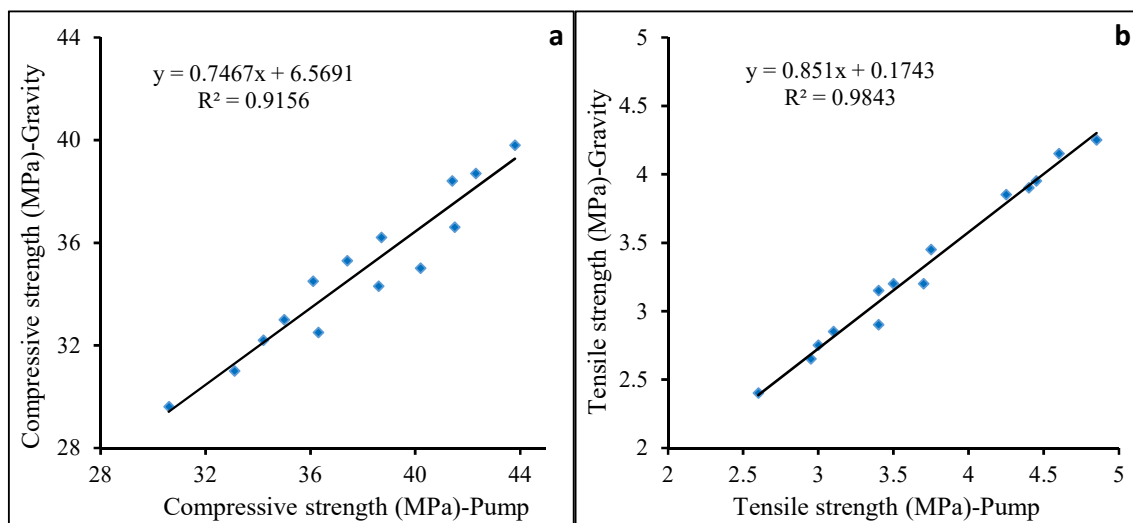
Figure 13. Histograms of strength properties of PAFRC specimens.

According to the collected experimental data, the mechanical properties and impact resistance of the PAFRC specimens could be correlated through empirical relationships with a high coefficient of determination ( $R^2$ ). The correlations were developed by a regression analysis of the given data. Linear regression analyses, as revealed in Figure 14a,b were used to correlate the compressive strength and tensile strength values of PAFRC for the pumping and gravity methods specimens in which a high  $R^2$  value was found, thus showing a good relationship between the variables. Concerning the developed Equations (5) and (6), the obtained  $R^2$  values were 0.9156 and 0.9843, respectively, which signified a great confidence level for the relationships:

$$f_{cG} = 0.7467f_{cP} + 6.5691, \quad R^2 = 0.9156 \quad (5)$$

$$f_{tG} = 0.851f_{tP} + 0.1743, \quad R^2 = 0.9843 \quad (6)$$

where  $f_{cG}$  and  $f_{cP}$  are the compressive strength (MPa) of the PAFRC specimens by gravity and pumping methods, respectively;  $f_{tG}$  and  $f_{tP}$  are the tensile strength (MPa) of the PAFRC specimens by pumping and gravity methods, respectively.



**Figure 14.** The correlations amongst (a) compressive strength and (b) tensile strength values of PAFRC specimens by gravity and pumping techniques.

Furthermore, the relationship between the first crack impact resistance versus the ultimate crack impact resistance of gravity and pumping methods PAFRC specimens is illustrated in Figure 15a,b. Relating to the obtained Equations (7)–(10), a linear regression analysis was carried out amongst the impact resistance values for the first and ultimate cracks and fibre contents of the gravity and pumping groups PAFRC specimens with  $R^2$  values of more than 0.98. It can be seen that the first and ultimate crack impact resistance values of the P5 mix had the highest slope. This indicated that the reinforcement of PAFRC specimens with 1.25% PP carpet fibres had the maximum rate of first crack and failure impact strength improvement.

$$P: FC = 88.625V_f + 17.094, \quad R^2 = 0.9956 \quad (7)$$

$$G: FC = 70.15V_f + 12.563, \quad R^2 = 0.9954 \quad (8)$$

$$P: UC = 107.05V_f + 23.938, \quad R^2 = 0.9897 \quad (9)$$

$$G: UC = 88.6V_f + 20.25, \quad R^2 = 0.989 \quad (10)$$

Here, FC and UC are the first crack and ultimate crack impact strength of PAFRC specimens, respectively, and  $V_f$  is the fibre dosage.

Finally, to explore the impact energy reliability, the relationships between the impact energies at first and ultimate cracks and fibre content of the gravity and pumping groups PAFRC mixtures were correlated; the results are demonstrated in Figure 16a,b. The results demonstrate that there exists a linear relationship between the first and ultimate crack impact energies of PAFRC specimens. Following the developed Equations (11)–(14), the  $R^2$  values were found to be higher than 0.9. According to the obtained results, the best performance in increasing the impact energy was detected in the pumping method for PAFRC specimens. The results of this study confirmed the findings by Song et al. [49], with regards to the existence of linear relationships among the first and ultimate crack impact energy of concrete reinforced with PP fibres.

$$P: E_{FC} = 1803.9V_f + 347.92, \quad R^2 = 0.9956 \quad (11)$$

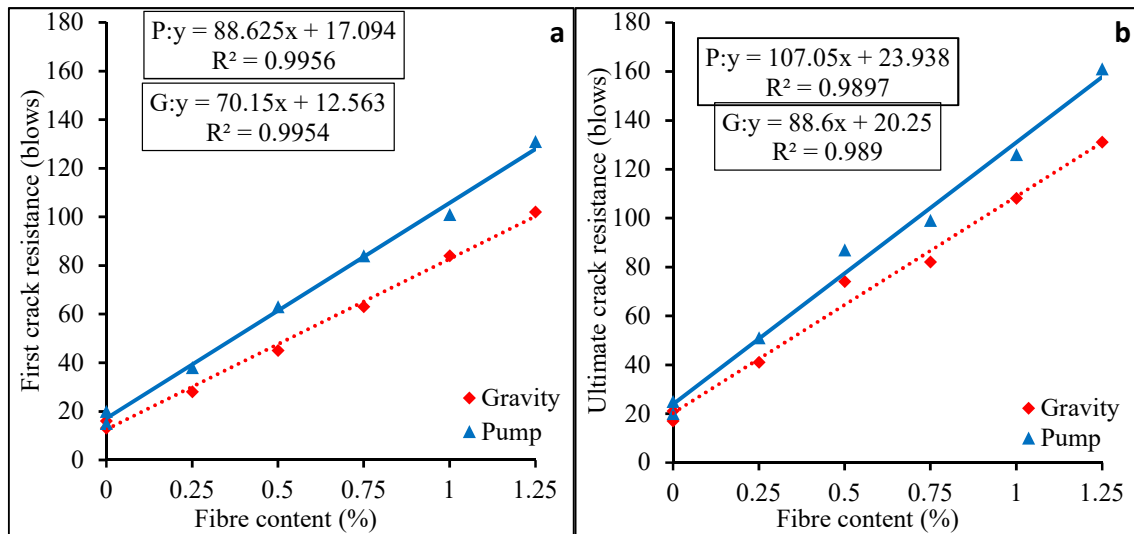
$$G: E_{FC} = 1427.8V_f + 255.7, \quad R^2 = 0.9954 \quad (12)$$

$$P: E_{UC} = 2178.9V_f + 487.22, \quad R^2 = 0.9897 \quad (13)$$

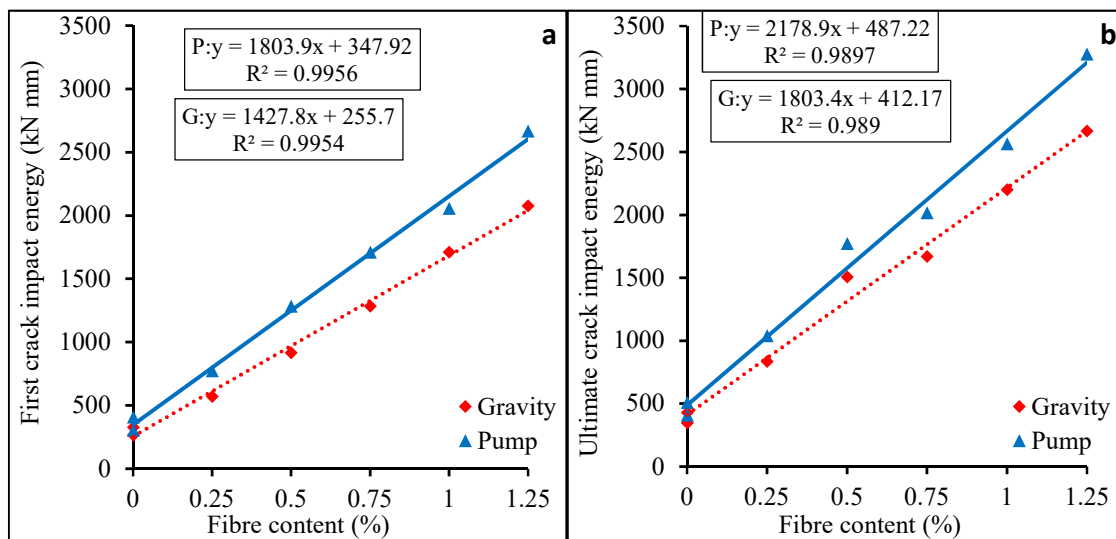
$$G: E_{UC} = 1803.4V_f + 412.17, \quad R^2 = 0.989 \quad (14)$$



Here,  $E_{FC}$  and  $E_{UC}$  are the first crack and ultimate crack impact energies of PAFRC specimens.



**Figure 15.** Impact resistance at (a) first and (b) ultimate crack vs. fibre content of PAFRC specimens.



**Figure 16.** (a) The first and (b) ultimate crack impact energy vs. fibre content of PAFRC specimens.

## 5. Conclusions

In this paper, the strength and impact resistance of a new pre-packed aggregate concrete reinforced with waste polypropylene fibres were investigated, both experimentally and statistically. The following conclusions could be drawn:

With the replacement of OPC by POFA, the fluidity of the fresh grout mixture was increased.

With the addition of fibres into the PAC mixtures, a minor reduction in the compressive strength was detected. At the early age of 28 days, owing to the slow rate of pozzolanic activity in POFA particles, the improvement in strength was marginally low. However, at the ultimate age of 180 days, the obtained strength values were improved, and the strength values were in the acceptable range for structural applications using gravity and pumping techniques.

In spite of lesser developments in compressive strength, noteworthy improvements were detected in the impact strength and energy absorption of PAFRC specimens. Furthermore, the maximum impact strength and energy absorption values were noted for the PAFRC mix containing 1.25% fibres. Overall, the specimens using the pumping technique performed better than those of the gravity method.



Waste PP fibres had a great influence on the long-term drying shrinkage of both gravity and pumping method PAFRC specimens. The lowest shrinkage values were recorded for the pumping method PAFRC mix comprising 0.75% fibres.

The existence of POFA resulted in providing a dense and amorphous microstructure in PAFRC specimens with less porosity and microcracks, as a result of the superior pozzolanic activity of POFA at the ultimate age.

Statistical analyses showed that the strength properties of all PAFRC mixes were normally distributed. Furthermore, the strength properties of PAFRC mixtures were correlated linearly, together with a high coefficient of determination ( $R^2$ ) values.

**Author Contributions:** Conceptualisation, M.M.T. and H.M.; methodology, F.A., R.A., and H.A.; validation, A.M.M. and H.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 A.M.M.; writing, original draft preparation, H.M.; writing, review, and editing, H.M., F.A., and R.A.; visualisation, A.M.M.; supervision, M.M.T.; project administration, H.A. All authors have read and agreed to the published version of the manuscript.

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