

Article

Sustainable Use of Waste Polypropylene Fibres to Enhance the Abrasion and Skid Resistance of Two-Stage Concrete

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Abstract: Two-stage concrete (TSC), also known as prepacked aggregate concrete (PAC), differs from traditional concrete in terms of site application and manufacturing process. Although this type of concrete is not a replacement for conventional concrete applications, it is an ideal option for unusual and difficult placing conditions, especially for repairing existing concrete structures. In other words, this type of concrete is a newly developed concrete and made by placing and packing coarse aggregates and fibres in a designed formwork, then injecting a cement grout mixture into the free spaces between the aggregate particles using gravity or a pump device. For the mentioned system and others, concrete components used as floors or pavements must have an adequate degree of roughness during service life when exposed to skid and abrasion. Thus, this research work introduced a new concrete method (prepacked aggregates fibre-reinforced concrete—PAFRC) with high abrasion and skid resistance reinforced with waste polypropylene (PP) fibres from the carpet industry. The effects of PP fibres at 0–1% dosages on the mechanical properties, abrasion resistance, and skid resistance of PAFRC mixes were studied. The results revealed that the addition of PP fibres reduces the compressive strength of concrete mixtures. Nonetheless, the presence of PP fibres results in PAFRC mixes having higher tensile strength, abrasion resistance, and skid resistance than plain concrete. It was detected that in both grouting methods (gravity and pump), with the addition of PP fibre up to a specific dosage, the resistance against abrasion and skid was increased by about 26% compared to plain PAC mix. Additionally, the outcomes indicated that PAFRC is a promising material for applications such as pavements with high abrasion and skid resistance.

Keywords: sustainability; abrasion; skid resistance; prepacked aggregates concrete; waste polypropylene fibres



Citation: Alyousef, R. Sustainable Use of Waste Polypropylene Fibres to Enhance the Abrasion and Skid Resistance of Two-Stage Concrete. *Sustainability* **2021**, *13*, 5200. <https://doi.org/10.3390/su13095200>

Academic Editor: Jorge de Brito

Received: 20 March 2021

Accepted: 4 May 2021

Published: 6 May 2021

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1. Introduction

Two-stage concrete (TSC) or prepacked aggregate concrete (PAC) is a type of concrete that is manufactured in two stages, by initial insertion of coarse aggregates with various sizes and shapes in the formworks, and then the inner free spaces and voids are filled with grout, which is a mixture of cement and with high fluidity [1,2]. The packing process allows more coarse aggregates to pack into formwork and interlock with each other, which is unique to conventional concrete [3]. This interlocking behaviour increases the contact among the aggregate particles and reduces the voids, leading to a better distribution of stresses during loading, and consequently, enhancing concrete performance [4].

In general, the application and size of aggregate used in PAC production are among the key parameters in choosing the appropriate method for grouting between the aggregate particles [5,6]. Therefore, two grouting methods have been used in PAC through injection or weight, pumping and gravity methods. In the applications where smaller sizes of aggregates are used, and the depth of formwork is higher than 30 cm, as the placement of aggregates is congested with the smaller size of voids, the injection method using a controlled-pressure pump is favoured [7]. In the applications with a maximum depth of 30 cm and a larger aggregates size, the grout injects into the gaps amongst the aggregate

particles under the gravity from the formworks' top surface [8]. Although PAC is not a replacement for conventional concrete, it is ideal for several demanding and special applications, particularly for repairing existing concrete components and several infrastructure applications such as pavement. This unique method of concrete production is also applicable in structures with compound steel reinforcement [9]. Moreover, PAC can be used in a particular arrangement with the unique shape of formworks, where the normal types of concrete may disturb the designed formwork, for example, pipes, piers, bridge abutments and tunnel openings [1].

Concrete in different forms is the major infrastructure and construction materials, which is relatively brittle with low energy absorption and tensile strength [10]. Bridge decks, roads and airport pavements made of conventional concrete and PAC are mostly subjected to wear and heavy impact loads [11]. Furthermore, the mechanical properties of concrete, environmental conditions, and the constituents used in PAC production and conventional concrete considerably affect the performance of concrete components used as the pavement under impact loads and exposed to abrasion [12]. Therefore, novel and modified materials with higher resistance against impact loads and wear are essential for this kind of application [13]. Based on PAC's unique method and its high performance, it has potential to be used as concrete pavements, particularly airport runways. However, it may be exposed to high impact loads and abrasion [14]. Consequently, to improve concrete pavements' properties and attain the required performance, a novel type of concrete with superior resistance against abrasion and skid is vital. The inclusion of short fibres with a length of up to 30 mm in the PAC mixture could be a potential material to achieve the preferred properties [15]. The current study planned a new kind of PAC with adequate skid and abrasion resistance and impact loads. Prepacked aggregates fibre-reinforced concrete (PAFRC) is a particular type of concrete formed by combining aggregates with various size and short polypropylene (PP) fibres and high-quality grout mixtures.

The abrasion and skid resistance of PAC or PAFRC have not been investigated previously. However, the reinforcement of conventional concrete with polymeric and metallic fibres at dosages of 0.1% to 2.0% has been recognised by many researchers to develop concrete resistance against skid and abrasion [16–18]. In this regard, Horszczaruk [19] and Febrillet et al. [20] reported that conventional concrete resistance against abrasion was remarkably improved by adding fibres combined with high-volume fly ash. Mastali et al. [21] also investigated the influence of steel fibres, PP fibres, and glass fibres on conventional concrete's abrasion resistance. They reported that, in concrete mixtures reinforced with 1, 5, 10, and 20 kg/m³ fibres, the abrasion resistance was considerably enhanced compared with plain conventional concrete. Moreover, the effect of fly ash as partial cement replacement (up to 50%) was studied by Yen et al. [22] to investigate the changes in the abrasion resistance of concrete. The results of their study revealed that the replacement level of 15% is sufficient to increase the resistance of concrete components against abrasion due to the pozzolanic nature of ash, which results in higher strength concrete.

In the previous studies, in order to investigate and measure the skid resistance of concrete specimens, the British Pendulum tester device was used, and British Pendulum Number (BPN) was used as the index to evaluate the skid resistance. Skid resistance is the resistance to slipping and rotation of car wheels in direct contact with the pavement's surface. It is typically associated with concrete or asphaltic textures [23]. Skid-related accidents may occur on concrete roadways without a suitable wearing texture [24]. The skid resistance of concrete pavements mostly depends on the composition of the surface and the mixture's components. Generally, low skid resistance numbers imply low friction between the vehicle's wheels and the pavement surface, which can compromise pavement safety. Consequently, on some pavements, a thin wearing layer course is spread on the top surface to improve skid resistance and minimise accidents. Using these additional materials, however, increases the total construction expense [25].

A novel technique or material to increase pavements' roughness is essential to increase the skid resistance of pavements and reduce skid-related accidents. The use of high-grade

crush aggregate particles in concrete pavements has been investigated in order to improve the roughness of pavement and, therefore, higher resistance against skid in dry and wet conditions [26]. In addition, Adamu et al. [27] investigated the use of crumb rubber as aggregates with different replacement levels of 10–30% in roller-compacted concrete. They reported that crumb rubber utilisation as fine aggregates significantly increased the skid resistance of concrete pavements by providing a rougher surface due to crumb rubber particles' projection. Yoshitake et al. [28] also stated that using fly ash as cement replacement up to 40% with limestone aggregates enhances concrete specimens' skid resistance.

Since PAC is a unique concrete method and has been used as pavement material previously, it can be modified with the addition of short fibres to attain the desired abrasion and skid resistance. Assessing the resistance of concrete components against abrasion and skid is vital as well as PAC's mechanical properties while using concrete as a pavement material. To the best of the authors' knowledge, there is no literature on the skid resistance and abrasion of PAC reinforced with PP fibres. The aim of this study was, therefore, to investigate the performance of novel PAFRC components containing PP fibres at different dosages for abrasion and skid resistance. Accordingly, experimental studies were piloted to investigate PAFRC specimens' possibility as a pavement material.

2. Experimental Setup

2.1. Materials and Mix Proportions

In this study, ordinary Portland cement (OPC) of type I with a Blaine-specific surface area of 3990 cm²/g and a specific gravity of 3.15 was used to produce a grout mixture. In addition, palm oil fuel ash (POFA) was used as a 20% replacement of OPC in all mixes. Based on the obtained compositions given in Table 1, the ash was graded as between classes C and F by ASTM C618-05. As a fine aggregate, clean and dry natural river sand with a maximum size of 4.75 mm, a specific gravity of 2.6, and water absorption of 0.70% was used. The coarse aggregates, as the major skeleton of PAC, were prepared according to the specification of ACI 304.1R-1997 [29]. In this study, the coarse aggregates with size varying from 20 to 38 mm, which are crushed granite and have 2.7 g/cm³ specific gravity and 0.5% water absorption, were used. In this study, the waste carpet fibres were collected from Carpet Industries as waste fibres in various lengths. The fibres are multi-filament polypropylene type carpet fibres and were cut manually to a length of 30 ± 2 mm to be used in this study, as shown in Figure 1. Table 2 presents the common properties of waste PP fibres used in the production of PAFRC mixtures.

Table 1. Properties of OPC and POFA.

Physical Properties	OPC	POFA	Chemical Composition (%)	OPC	POFA
Specific gravity	3150	2420	SiO ₂	20.41	62.60
Blaine fineness (cm ² /g)	3990	4930	Al ₂ O ₃	5.22	4.65
Passing sieve 10 µm (%)	19	33	Fe ₂ O ₃	4.18	8.12
Soundness (mm)	1	2	CaO	62.41	5.70
			MgO	1.53	3.52
			K ₂ O	0.005	9.05
			SO ₃	2.09	1.16
			LOI	2.34	6.25

A total of 12 mixtures were produced, divided into two groups based on the grouting method, as pumping (P) and gravity (G). The PP fibre dosages of 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1.0% were used by volume with a fibre length of 30 mm in both methods. Additionally, POFA was used as partial cement at the replacement level of 20% in all mixes. The constant cement/sand (c/s) ratio of 1/1.15 and water/binder (w/b) ratio of 0.5 were used. The proportion of materials used for the production of PAFRC are listed in Table 3.



Figure 1. Waste polypropylene fibres from the carpet industry.

Table 2. Engineering properties of waste PP carpet fibres.

Type of Fibre	Length (mm)	Aspect Ratio (l/d)	Diameter (mm)	Density (kg/m ³)	Melting Point (°C)	Tensile Strength (MPa)	Reaction with Water
Multi-filament polypropylene	30 ± 2	67	0.45	910	170	400	Hydrophobic

Table 3. The constituents used in the production of PAFRC mixtures and their proportions.

	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 (%)
Pump	P0	186	304	76	545	1320	0.0
	P1	186	304	76	545	1320	0.2
	P2	186	304	76	545	1320	0.4
	P3	186	304	76	545	1320	0.6
	P4	186	304	76	545	1320	0.8
	P5	186	304	76	545	1320	1.0
Gravity	G0	186	304	76	545	1320	0.0
	G1	186	304	76	545	1320	0.2
	G2	186	304	76	545	1320	0.4
	G3	186	304	76	545	1320	0.6
	G4	186	304	76	545	1320	0.8
	G5	186	304	76	545	1320	1.0

2.2. Sample Preparation and Test Methods

Unlike conventional concrete, PAFRC samples were made in two steps. Initially, the desired amount of coarse aggregates were prepared and premixed with the short PP fibres, i.e., dry mix. In this study, an electric concrete mixer, shown in Figure 2a, was used for drying mix purposes. The required volume of fibres was added to the mixture of aggregates in the mixer, and the mixing process was continued for about two minutes to ensure that the fibres were evenly dispersed in the dry mix. It is interesting to note that, as no water was added to the mixture, no negative effects such as balling effects were detected for all fibre volume fractions. However, the effect of a higher volume of fibres was noted mostly in the reduction in compressive strength of mixtures, which will be discussed in the next sections. The mixture of aggregates and fibres were then transferred and placed in the designed formworks. After proper placing and packing, the mix of sand and cement in the form of high fluidity grout was injected into the formwork in the next stage. As shown in Figure 2c, a polyvinyl chloride (PVC) pipe with a diameter of 5 mm was inserted into the cylindrical moulds for the grouting process under the gravity force in the gravity method of grouting. The pumping method was more complex, as shown in Figure 2b. In the pumping method, 100- and 150-mm unplasticised Polyvinyl Chloride (UPVC) pipes with a length of up to 120 cm were used as moulds. To keep the pipes and prevent any movement while grouting, a proper formwork made of plywood was designed and installed. A mechanical pump with a pressure control mechanism was applied to inject grout into the formwork in order to achieve a homogeneous and uniform distribution. Additionally, a plywood

cap was attached to the pipes' top surface to prevent the grout's overflow. The grouting process was carefully controlled to avoid any leakage or failure in the formworks. The moulds were wrapped and cured at room temperature for 24 h after the grouting process was done. The PAFRC specimens were removed from the moulds the next day and placed in the water tank until the testing date.

PAFRC samples were prepared for compressive and tensile strength tests using cylindrical moulds of sizes 100 mm × 200 mm and 150 mm × 300 mm, according to ASTM C39M-18 and ASTM C496-17 specifications, respectively. The ultrasonic pulse velocity (UPV) test was also conducted in accordance with ASTM C597-09. Furthermore, cubic samples with a size of 71 mm were made for abrasion resistance testing using the Bohme abrasion test device, in accordance with BS EN 14157-17. The specimens were correctly positioned, and the concrete cubes were subjected to a load of 294 N. After that, abrasion dust, which was Aluminum Oxide (Al_2O_3), was scattered on a disk with a diameter of 750 mm and a rotation speed of 30 cycles per minute. Per time, the disk was rotated for 22 cycles. On each side of the specimen, four periods were performed. Afterwards, the specimen was turned 90 degrees, and the process was constant on all sides of the cubes. The abrasion resistance of the specimens was calculated in terms of volume reductions in $cm^3/50\text{ cm}^2$ at the end of the test. Next, as illustrated in Figure 3, the British Pendulum Tester device was used to evaluate the skid resistance of the PAFRC samples in wet and dry conditions, according to ASTM E303-13 guidelines. Prism specimens measuring 90 mm in length, 50 mm in width, and 15 mm in height were made for this test.

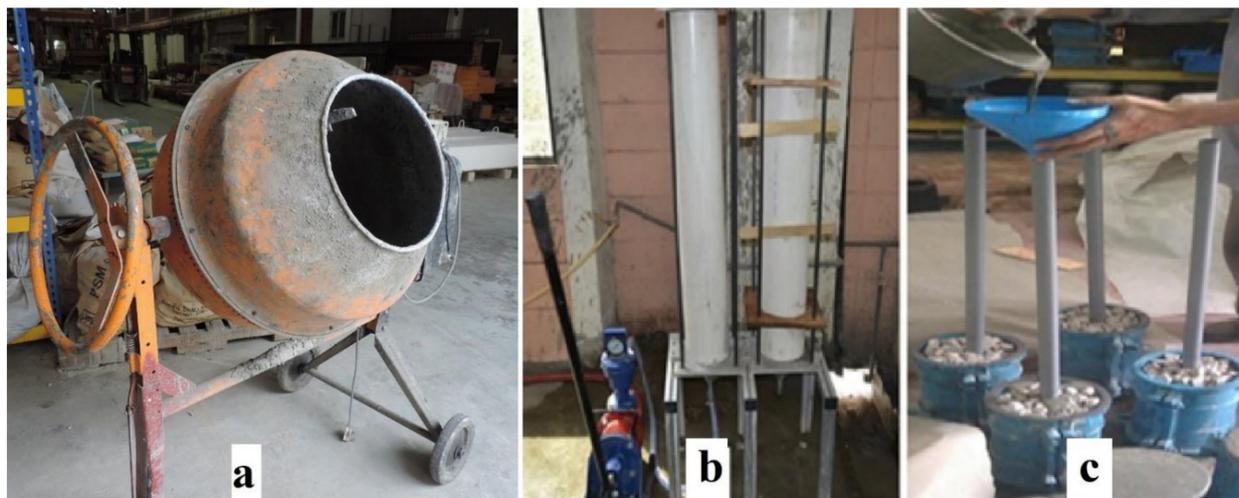


Figure 2. (a) Concrete mixer used for dry mix of fibres and aggregates, (b) pumping and (c) gravity methods of grouting for PAFRC.



Figure 3. British Pendulum Tester device used for skid resistance test.

3. Results and Discussion

3.1. Fresh Properties of Grout

The mixture of sand and OPC/POFA was prepared in the form of grout, and fresh properties such as fluidity and bleeding were investigated. Two grout mixtures with 100% OPC and 20% POFA replacement were made and tested. Figure 4 shows that the grout mixture of 20% POFA was found to be more flowable than that of 100% OPC. The fluidity of the 20% POFA grout mixture was 13.4 sec, which was less than the 15.3 sec obtained for the 100% OPC mix. It indicates that the mixture containing POFA as partial cement replacement is more flowable. This might be attributed to the fact that the POFA particles are smaller than OPC particles [30]. The higher fluidity of the POFA mixture could also be due to the spherical shape of POFA particles shown in Figure 5, which enhanced grout flow [31]. Figure 4 demonstrates the effects of the bleeding test for the OPC and POFA grout mixtures. The bleeding capacity of the grout mixture is defined as the ratio of the bleed water to the mixing water. It can be seen that a higher amount of water was absorbed by the POFA particles owing to the finer size. As shown in Table 1, the Blaine fineness of OPC and POFA are 4930 and 3990 cm^2/g , respectively, which indicates the finer size of POFA particles and, therefore, reduction in the bleeding of the POFA mixture in comparison with that of OPC mixture. The bleeding rate in the POFA mixture was 8.5%, which is significantly lower than the 10.6% rate in the OPC mixture. The POFA mixture's lower bleeding reflects that the finer POFA particles will absorb extra water in the mixture, lowering the bleeding percentage [30].

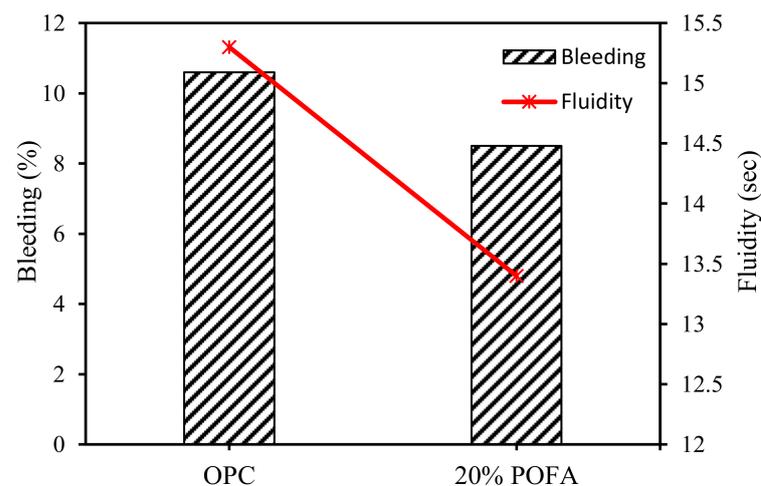


Figure 4. Fluidity and bleeding of OPC and POFA grout mixtures.

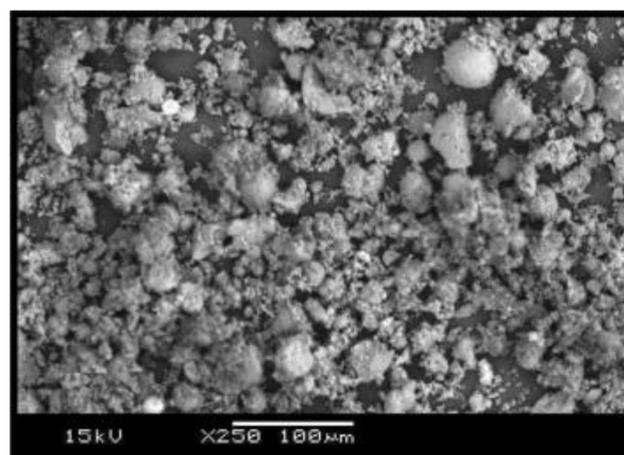


Figure 5. Scanning electron microscopy of POFA particles.

3.2. Compressive Strength

In this study, PAFRC compressive strength at the age of 180 days ranges from 34 MPa to 45.7 MPa for gravity and pumping methods specimens reinforced with fibres, as shown in Figure 6. Based on the attained outcomes, the inclusion and increase in fibre content affect the compressive strength of PAFRC mixtures. In gravity method specimens, the addition of PP fibres at the doses of 0.2%, 0.4%, 0.6%, 0.8% and 1% reduced the compressive strength values by 2.75%, 7.8%, 11.7%, 13.55% and 17.8%, respectively, in association with the control mix. While in pumping method specimens, the reduction rate was comparatively lower; for example, the strength values reduced by 3.3%, 5.1%, 7.95%, 12.4% and 16.5%, respectively, as associated with that of the plain PAC. The compressive strength of PAFRC mixes was decreased as the fibre volume fraction in mixtures rose. This reduction in strength could be due to the excess fibres in high dosage, which causes disturbance in the proper flow of grout, particularly in the gravity method specimens and, therefore, leaves voids in the interface and between the coarse aggregates causing a slight reduction in strength.

Moreover, the good distribution of grout under the high pressure provides by the pump causes higher strength values than those specimens filled under the gravity force. Consequently, it affords a reduction in the volume of voids and provides a dense microstructure matrix [1]. In addition, the presence of POFA with high pozzolanic activity at ultimate age results in improved PAFRC samples' performance due to the formation of additional hydration products such as C-S-H gels. These additional C-S-H gels can improve the bonds between the aggregates and fibres and fill up the matrix's voids [32].

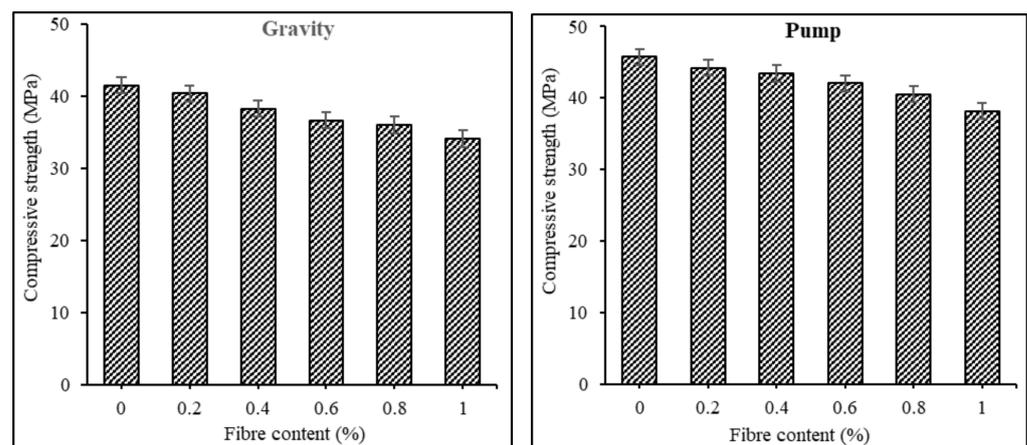


Figure 6. Compressive strength of PAFRC mixes with various fibre dosages.

3.3. Tensile Strength

Figure 7 summarises the obtained splitting tensile strength values of PAFRC specimens at the age of 180 days. As expected, the PP fibres had a major impact on the tensile strength of the PAFRC specimens. PAFRC mixes reinforced with PP fibres at different fibre volume fractions exhibited higher tensile strength values than those of plain PAC specimens for both grouting techniques. The tensile strength of PAFRC depends on the fibre dosage content. In the gravity methods PAFRC mixes, the inclusion of 0.2%, 0.4%, 0.6%, 0.8% and 1% PP fibres enhanced the tensile strength values by 20.6%, 28.4%, 31.6%, 22% and 18.8%, respectively, in association with plain PAC mix. Compared to the gravity method, pumping method PAFRC mixes have a higher tensile strength, which signifies that good distribution of grout maximises the enhancement in the tensile strength. It was found that, for the same fibre content, the tensile strength of pumping method specimens increased by 23.7%, 30.3%, 36.8%, 25.5% and 19.7%, respectively, as compared with that of plain PAC. Amongst all mixes, PAFRC mixes reinforced with 0.6% PP fibres have the highest tensile strength values of 4.54 MPa and 5.2 MPa, respectively. However, further increasing PP fibres could lead to a slight decrease in the tensile strength of mixes. The higher tensile strength in specimens reinforced with PP fibres may be attributed to fibres' interaction with aggregates

and cement paste and the bridging action of PP fibres, preventing microcrack formation and propagation [30]. Consequently, the inclusion and increase in PP fibre dosages could lead to better deformation capacity of PAFRC specimens. Similarly, Liu et al. [33] stated that combining hybrid steel–Polyvinyl Alcohol (PVA) fibres and pozzolanic materials such as fly ash and slag powder could improve the tensile strength of concrete by about 37%.

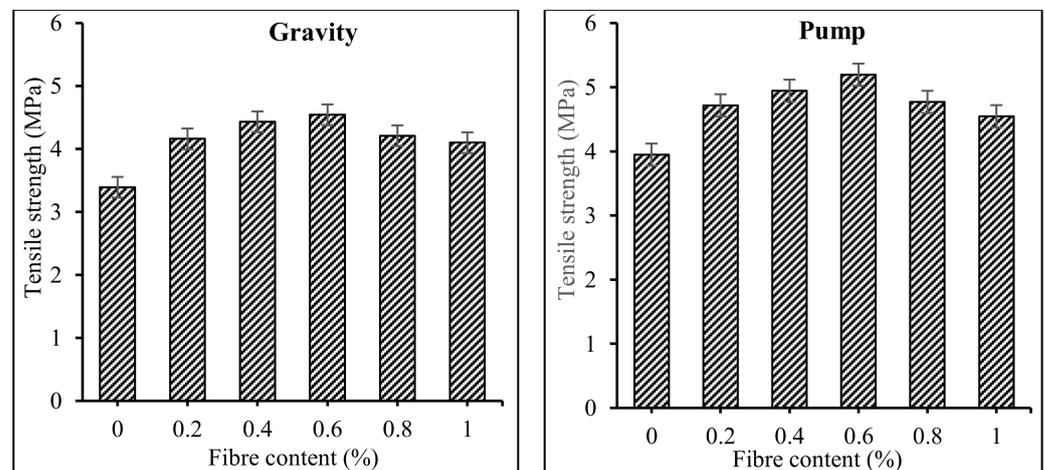


Figure 7. Tensile strength of PAFRC specimens with various fibre dosages.

3.4. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity results (UPV), a non-destructive test for PAFRC specimens reinforced with PP fibres, are illustrated in Figure 8. The effects of PP fibre volume fractions on the UPV values of PAFRC mix at the age of 180 days were investigated. The fibre volume fractions considered are 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1% for both gravity and pumping methods. It was found that the addition of PP fibres into the PAFRC mixes produced no particular influence on the UPV values. The mixes containing 0.2% and 0.4% PP fibres obtained the UPV values higher than those of plain PAC mixes without any fibres in both methods. However, in the mixes containing 0.6% PP fibres and beyond, the UPV values reduced and were found to be lower than those of plain mixes. The UPV values of plain gravity and pumping PAC mixes without fibres were recorded as 4552 m/s and 4571 m/s, respectively. In addition, with the addition of 0.2% PP fibres into the PAFRC mixes, the UPV values increased and were recorded as 4575 m/s and 4584 m/s for gravity and pumping method mixes, respectively.

This increase in UPV values can be due in part to the PP fibres' bridging action, which decreases the development of micro-cracks in the matrix [34]. With a lower volume of cracks and voids, the matrix is denser with higher UPV values. However, it was observed that a further increase in the fibre dosages results in reduction in UPV values in PAFRC mixes. The drop in UPV values could be due to the development of voids and non-homogeneity in PAFRC specimens. The use of fibres at high dosages reduced the grout's flowability, particularly in the gravity method and, consequently, the volume of voids increased and caused lower UPV values [35]. Interestingly, the UPV values of the pumping method PAFRC samples were greater than those of the gravity method mixes. It is mainly due to the matrix's homogeneity and a lower volume of voids and cracks. Moreover, as the noted UPV values for all mixes were higher than 4400 m/s, PAFRC mixes are classified as good quality concrete [36]. The UPV test results for both PAFRC specimens' methods were correlated with the corresponding compressive strength values at the age of 180 days. A good correlation between the recorded compressive strength and UPV values is evident, as shown in Figure 9. A power regression method was used to understand the relations amongst compressive strength and UPV of all mixes. For this correlation, the coefficient of determination (R^2) was found as 0.84, which signifies high confidence for the correlation.

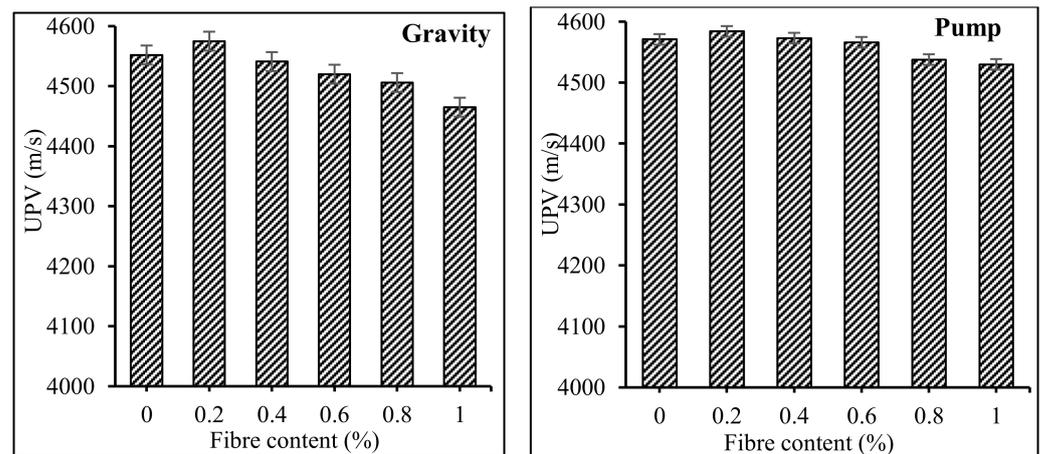


Figure 8. UPV values of PAFRC specimens with various fibre dosages.

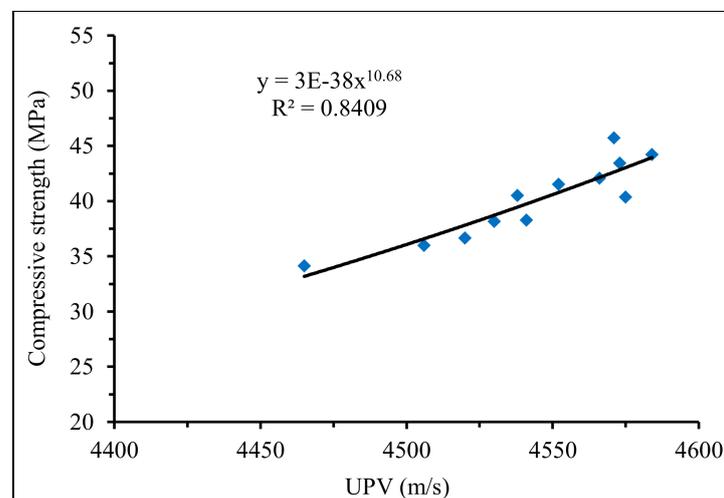


Figure 9. The correlation between compressive strength and UPV of PAFRC mixes.

3.5. Abrasion Resistance

The resistance of PAFRC specimens against abrasion was investigated using Bohme surface abrasion test machine. The experimental results of the abrasion resistance test for both methods PAFRC mixes are illustrated in Figure 10. The abrasion resistance of the cubic specimens was determined by measuring the reduction in volume. The results showed that adding PP fibres to the PAFRC mixture improved the abrasion resistance compared to plain PAC mixes without fibres. The abrasion resistance of gravity and pumping PAFRC mixes improves as the fibre volume fractions raise. The addition of PP fibres to concrete greatly increases abrasion resistance and decreases wear thickness. While the presence of PP fibres does not affect the compressive strengths of the PAFRC mixes, it significantly improves the resistance of concrete against abrasion and higher splitting tensile strength.

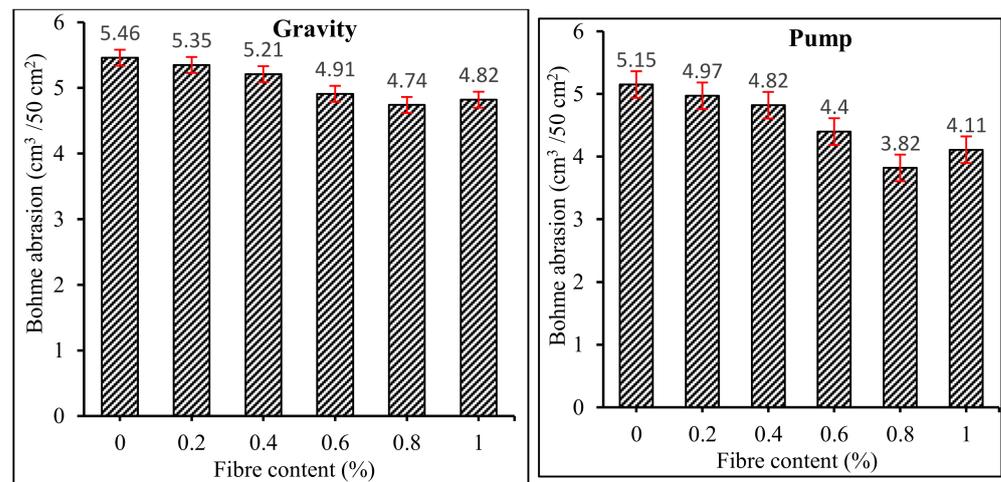


Figure 10. Abrasion resistance of PAFRC specimens with various fibre dosages.

It can be seen that the abrasion values of 5.35, 5.21, 4.91, 4.75, and 4.82 cm³/50 cm² were obtained with the addition of 0.2, 0.4, 0.6, 0.8, and 1.0% PP fibres to the gravity PAFRC mixes, respectively, which are all lesser than the 5.46 cm³/50 cm² achieved with the plain PAC mixture. Furthermore, the pumping system PAFRC mixes showed higher resistance to abrasion. For the same fibre volume fraction, the values of 4.97, 4.82, 4.4, 3.82, and 4.11 cm³/50 cm² were reported, all less than the plain PAC's 5.15 cm³/50 cm². However, the abrasion resistance is decreased at a volume fraction of 1% due to weaker bonds amongst the high volume of fibres and cement paste [28]. The higher abrasion resistance of PAFRC mixes, particularly the pumping method specimens, might be owing to the fibres' bridging action and the existence of a strong bond between fibres and the cement paste in the matrix. This strong bond resulted in higher energy absorption, abrasion resistance and tensile strength of the reinforced PAFRC mixes [30]. In this regard, Atis et al. [37] stated that adding PP fibres to concrete improved its abrasion resistance by bridging the cracks and preventing the concrete's degradation. Additionally, it was found that the abrasion resistance of fibre reinforced concrete is highly correlated with the splitting tensile strength.

A linear regression analysis was used to find a direct connection between the fibre dosages and the abrasion resistance of PAFRC mixes. The fibre dosages were associated with the abrasion resistance of gravity and pumping method PAFRC mixes, as shown in Figure 11. For these correlations, the coefficient of determination (R^2) values of 0.90 and 0.86 was found for the gravity and pumping methods PAFRC mixes, respectively. Strong R^2 values indicate a high degree of confidence in the correlations. Furthermore, it has been found that adding PP fibres up to a certain level improves the resistance of PAFRC specimens to abrasion.

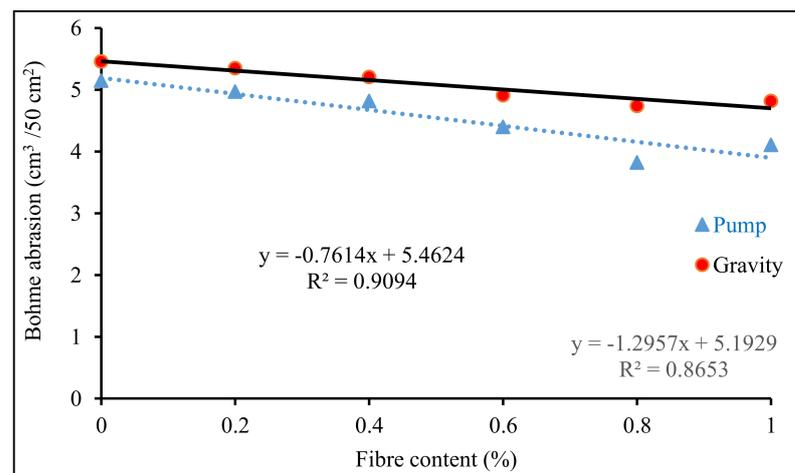


Figure 11. Correlation between abrasion resistance and fibre dosages of PAFRC mixes.

3.6. Skid Resistance

The British Pendulum Number (BPN) test was applied to assess the skid resistance of PAFRC samples under dry and wet environments. In general, the greater the BPN values are, the rougher the concrete specimens' surfaces are, and hence the more significant the skid resistance. The measured BPN values of the PAFRC mixtures using gravity and pumping methods are shown in Figure 12. The addition and increase in the dosage of PP fibres were found to increase BPN values. The maximum BPN value in the dry conditions for the gravity method PAFRC mixes containing 1% PP fibres was 67.1, which is around 20% greater than the BPN value for the plain PAC mix. Likewise, in the pumping method mix reinforced with 1% PP fibres the BPN value was recorded as 68.9, which is about 21% more than that recorded for the plain PAC in the dry condition. The higher BPN values of the pumping method PAFRC mix compared to the gravity method mixtures can be related to firmer bonds between concrete constituents and PP fibres and higher mix strength due to well-distributed grout and fewer voids in the matrix [37,38].

Furthermore, the results show that PP fibres can increase the skid resistance of PAFRC mixes in wet conditions but with lower BPN values than in dry conditions. The surface texture of the PAFRC specimens becomes more slippery, and the friction is decreased when water is sprayed onto the exposed surface, reducing the skid resistance. The BPN values for the gravity and pumping methods PAFRC mixes reinforced with 1% fibres are decreased by around 15.9% and 15.1%, correspondingly, under wet conditions associated with the values observed under dry conditions using same amount of fibres.

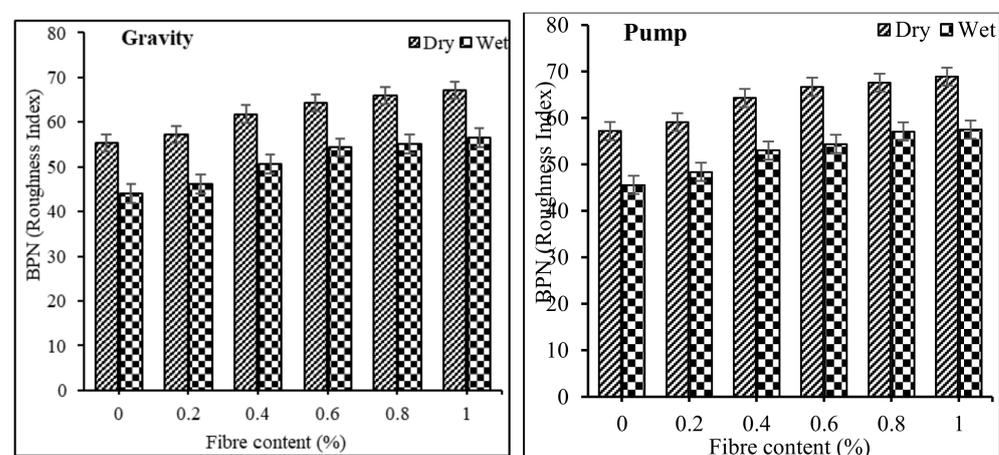


Figure 12. Skid resistance of PAFRC mixes with various fibre dosages.

The improved skid resistance of the reinforced PAFRC mixes is mainly attributable to the fibre projections on the concrete specimens' exposed surface [39]. As exposed in Figure 13, fibres' existence provides a rough surface and increases the friction between the surface of concrete and testing machine and, therefore, higher resistance against skid. Moreover, the high fibre content, in conjunction with the POFA, which offers extra hydration products, implies that the concrete components are in more contact with one another. As a result, the concrete resists better and has a rougher texture, increasing its skid resistance [38]. By comparing the obtained BPN values in this study to the minimum values recommended by ASTM E303-97 (Table 4), it can be detected that the reinforced PAFRC specimens can be used for category B, which are class 1 roads, motorways, trunks, and heavy traffic roads in urban areas carrying more than 200 vehicles per day. Nonetheless, all of the concrete mixes investigated in this study have the capacity to be used in the various applications under category C, which are freeways and rural roads.

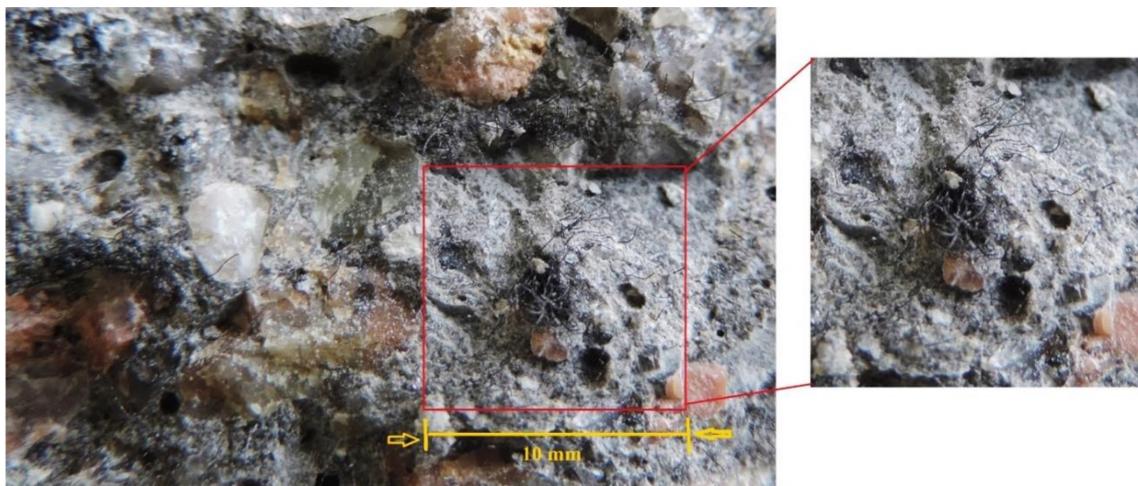


Figure 13. Distribution and projection of PP fibres in PAFRC matrix containing 0.8% PP fibres.

Table 4. The limits specified by ASTM E303-97 for skid resistance under wet condition.

Grouping	Minimum BPN Values of Wet Surface	Sort of Site
A	65	Difficult sites such as: (i) Roundabouts (ii) Bends with radius less than 150 m on unrestricted roads
B	55	Motorways, trunk and class 1 roads and heavily trafficked roads in urban areas (carrying more than 200 vehicles per day)
C	45	Other sites

As mentioned earlier, the presence of PP fibres in PAFRC specimens considerably improved concrete performance in terms of abrasion and skid resistance. Scanning electron microscopy (SEM) images were used to analyse fibres' influence in microstructural points of view, and the findings are shown in Figure 14. SEM images display the fibres' consistent spreading and bridging action. The fibres cross the cracks, prevent the concrete constituents from moving, and avoid crack growth under load. Furthermore, the embedded fibres demonstrate that the matrix and fibres are adequately bonded. The presence of fibres provides wear resistance, resulting in lower volume loss rates in the concrete samples [40]. The SEM images of PAFRC gravity specimens containing 0.8% PP fibres display the projection and distribution of fibres on the exposed surface of concrete, which

results in higher roughness of concrete components. Additionally, the projection of fibres and the strong bond between fibres and other particles lead to higher contact among the exposed surface of concrete and the vehicle's wheels, consequently enhancing the skid resistance and reducing the risk skid-related accidents [27,41,42].

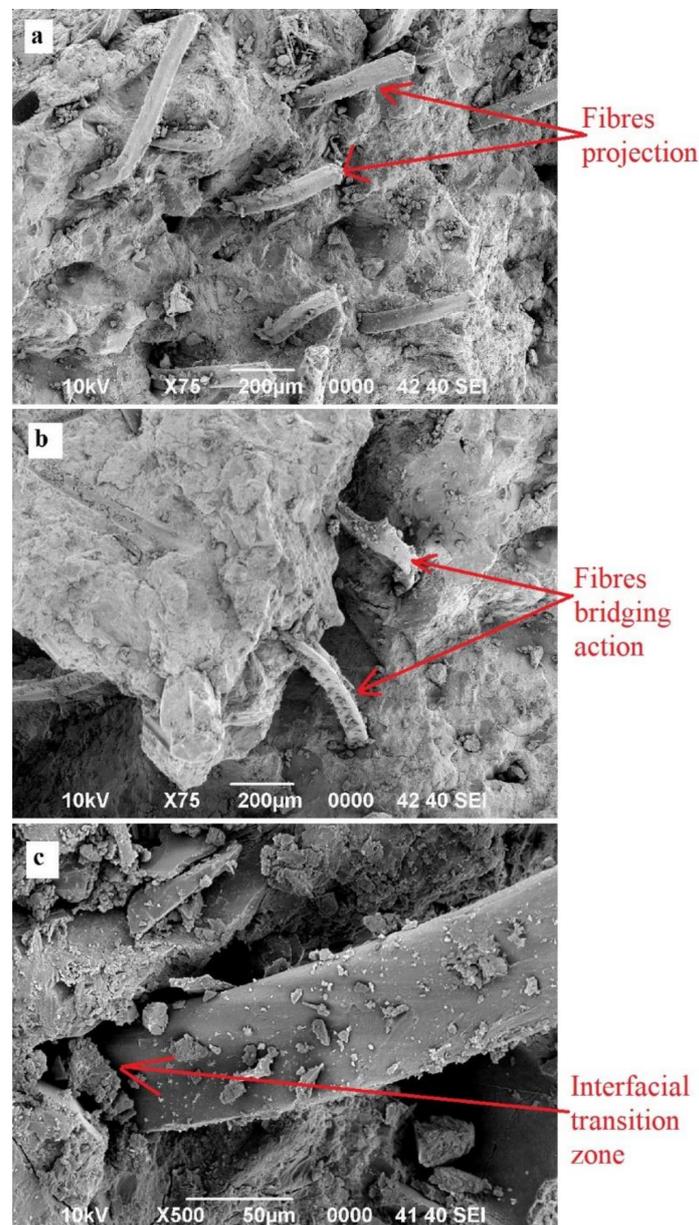


Figure 14. SEM images of (a) the uniform distribution, (b) bridging action and (c) interfacial transition zone PP fibres in PAFRC pumping specimens containing 0.8% PP fibres.

Empirical correlations were used to relate the BPN values obtained for the PAFRC mixtures under dry and wet conditions. The PP fibres' effect on the concrete specimens' skid resistance was measured using linear regression analysis. A superior relationship amongst the wet and dry BPN values in the PAFRC mixes was obtained with R^2 values of higher than 0.98, as revealed in Figure 15. The wet condition's BPN values are lower than the dry condition, despite the fact that the experimental results are well-correlated. Furthermore, the BPN and abrasion values of PAFRC mixes with PP fibres were correlated and found to have a good correlation. These values are greatly affected by the addition of PP fibres and an increase in fibre dosages. This may signify that higher PP fibre dosages

increase concrete's abrasion and skid resistance significantly [43,44]. The attained BPN and abrasion values were correlated using a linear regression method. As shown in Figure 16, these values correlate with the obtained R^2 values of higher than 0.81, suggesting a high degree of certainty in the relationship.

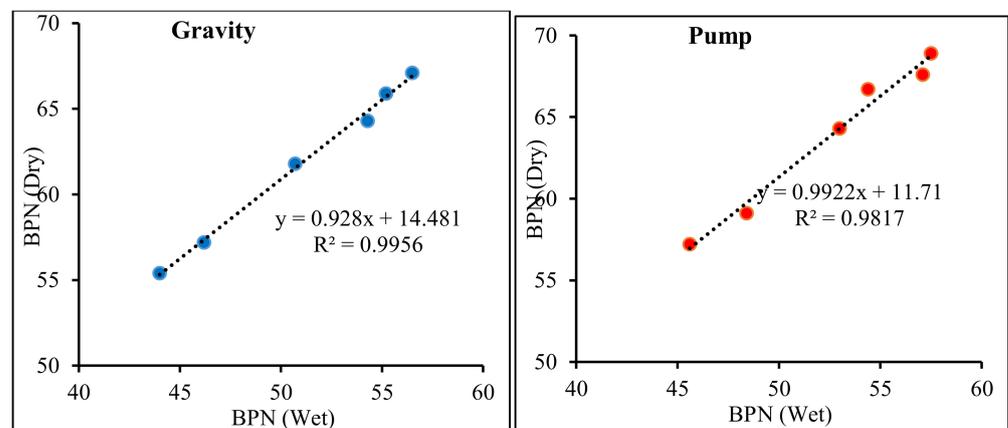


Figure 15. Correlations between BPN values of PAFRC mixes in dry and wet conditions.

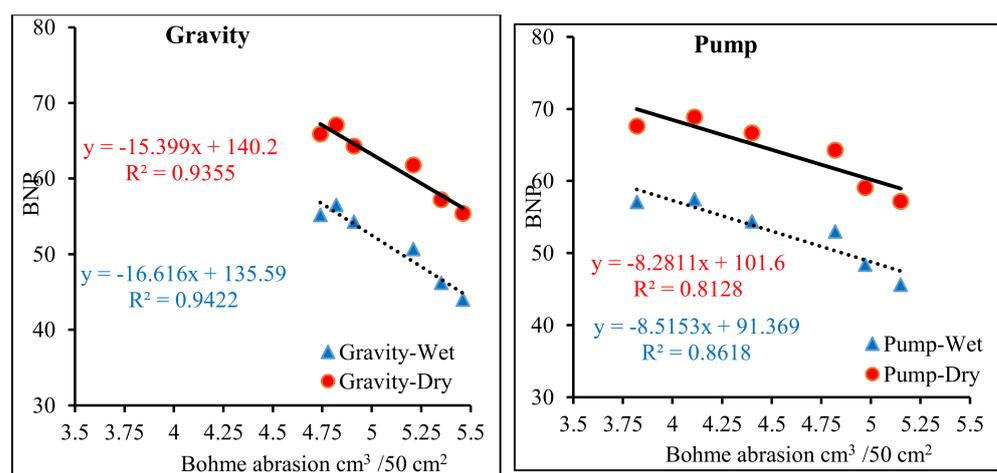


Figure 16. Correlations between BPN and Bohme abrasion values of PAFRC mixes.

4. Conclusions

A new prepacked aggregate fibre reinforced concrete method containing polypropylene fibres with adequate mechanical properties, high abrasion and skid resistance was proposed. PAFRC mixes of 0-1% fibre dosages were developed using two gravity and pumping methods. Abrasion and skid resistance are two critical aspects to consider when designing and choosing materials for building floors and pavements. Consequently, the abrasion resistance, dry and wet skid resistance, and mechanical strengths of PAFRC mixes were investigated in this study. The following are the study's conclusions:

The compressive strength of reinforced PAFRC mixtures containing PP fibres was lower than that of plain PAC mixes. Owing to the homogeneous spreading of grout in the matrix under pressure, the pumping technique PAFRC samples had higher strength values than the gravity method PAFRC specimens. Furthermore, the effect of POFA was beneficial owing to excessive pozzolanic properties and the development of hydration products.

Despite the lower compressive strength, PP fibres significantly increased the tensile strength of the PAFRC mixes. The tensile strength of a pumping type of PAFRC mix containing 0.6% PP fibres increased by approximately 33% compared to a PAC mix without any fibres.

The obtained UPV values of all of the PAFRC mixes ranged between 4400 and 4600 m/s, signifying good quality concrete.

Adding PP fibres to all PAFRC mixes improved their abrasion resistance substantially at all dosages. The abrasion resistance improved as the fibre volume fractions increased. The pumping PAFRC mix comprising 0.8% PP fibres achieved the highest abrasion resistance, which is 26% higher than the plain PAC mix.

Adding PP fibres to the PAFRC mixes significantly increased the specimens' skid resistance in both dry and wet environments. For the PAFRC mixes, the estimated BPN value varies from 55 to 69 and from 44 to 56 in dry and wet conditions, respectively. As a consequence, these PAFRC mixtures can be used in several applications requiring high skid resistance.

For all fibre dosages, there was a clear association amongst abrasion and skid resistance. The splitting tensile strength of the PAFRC mixes was found to be more significant than the compressive strength values in terms of correlations between abrasion and skid resistance.

Generally, in PAFRC mixtures, the addition of 0.8% PP fibres was the optimum dosage of fibres to achieve satisfactory mechanical properties and high resistance against abrasion and skid.

Author Contributions: All authors contributed to the paper evenly. Conceptualisation, R.A.; methodology, R.A.; software R.A.; validation, R.A.; formal analysis, R.A.; investigation, R.A.; resources, R.A.; data curation, R.A.; writing—original draft preparation, R.A.; writing—review and editing, R.A.; visualisation, R.A.; supervision, R.A.; project administration, R.A.; funding acquisition, R.A. All authors have read and agreed to the published version of the manuscript.

Funding: The project was supported by the Deanship of Scientific Research at Prince Sattam bin Abdulaziz University (Saudi Arabia) under research project No. 2020/01/16810.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the size of the research.

Acknowledgments: The project was supported by the Deanship of Scientific Research at Prince Sattam bin Abdulaziz University (Saudi Arabia).

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

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