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Properties of Concrete Produced using Surface Modified Polyethylene Terephthalate Fibres

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Abstract

Conventional techniques of improving the bond properties of virgin Polyethylene Terephthalate Fibres reduce the mechanical strength of the fibres, are labour intensive, and present environmental hazards in the case of chemical treatment. This study introduces a new way of improving the bond properties of fibres obtained from waste Polyethylene Terephthalate bottles by coating the surface of the fibres with a thin layer of sand to counteract the above-mentioned shortcomings. Their performance was compared to that of embossed, serrated, and straight fibres and a control mix without fibres. Workability, compressive strength, tensile and flexural strength were used to assess this performance. Constant fibre length, width, and content were maintained for this exercise. Compared to the other fibres, sand-coated fibres gave the highest increment in tensile and flexural strength of 9.49% and 11.61% compared to the control mix, even though concrete's workability and compressive strength were decreased. Furthermore, the optimization of the fibre length and content for the sand-coated fibres was carried out. The 75 mm long fibres showed the highest improvement in tensile strength of 13.76% and flexural strength of 12.49% compared to other fibre lengths. The optimum percentage of fibres was 1.25% with a 15.49% and 17.26% increment in tensile and flexural strengths, respectively.

Keywords: Concrete; Polyethylene Terephthalate (PET); Workability; Compressive Strength; Split Tensile Strength; Flexural Strength; Surface Modification.

1. Introduction

Due to its versatility, concrete is one of the most commonly used building materials. It makes use of locally available materials, has the ability to be cast into different shapes, performs well under high temperatures, and can consume and recycle waste. Regardless of these desirable properties, concrete has several limitations. It has been classified as a quasi-brittle material with low tensile strength and low toughness (ductility), and therefore fails suddenly without giving enough warning signs.

Fibre reinforced concrete is one of the most innovative solutions to the problems highlighted above. When distributed uniformly through the concrete mix, fibres enhance the tensile, flexural, and impact strength, ductility, and toughness of the concrete through their crack-bridging effect [1]. Several types of fibres have been used, ranging from steel fibres, synthetic fibres, glass fibres, and natural fibres to pre or post-consumer waste fibres. Steel fibres have a high risk of corrosion that can lead to the rapid deterioration of concrete structures, while glass fibres show poor alkali resistance. While natural fibres are cheap and easily available, they have poor durability and can lead to the degradation of concrete

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structures [2, 3]. In the recent past, many studies have been conducted to reuse waste plastics as fibres in concrete and mortar composites to overcome the challenges experienced with other types of fibres as well as reduce the environmental degradation caused by plastic waste.

During the period 2015-2019, worldwide PET packaging usage increased at an annual average rate of 4.0% to 21.8 million tonnes. This is expected to expand at a 3.7% annual rate to 27.1% (Platt, 2020). In particular, the consumption of bottled water is increasing each year by 7% on average throughout the world, with a million plastic bottles being sold every minute throughout the world, Aslani et al. (2021) raising concerns over environmental pollution globally [3]. Kaza et al. (2018) noted that only 19% of the generated waste undergoes recycling, with 37% of waste ending up in landfills and 33% openly dumped. In Kenya, the sector produces around 20,000 tonnes of plastic waste per year, but only 5% of this is collected and recycled [4]. The bulky nature and slow degradation rate of plastics [5], not to mention their restriction of underground water movement and plant root growth, has necessitated their reuse in concrete as fibres to relieve many countries from environmental degradation caused by PET waste bottles [6, 7].

PET wastes can be recycled into fibres by a process that begins with crystallization, drying, dosing, extrusion, filtering, spinning, stretching, stabilization, winding and poly wrapping, and then the fibres are cut in the required diameter and surface geometry, guaranteeing higher fibre tensile strengths ranging from 263 to 550 MPa [6, 8, 9]. However, this process can be uneconomical and labour intensive and lots of difficulties are experienced in the automation of the sorting process [7]. Any contamination in this process can end up reducing the strength of fibres obtained through this method [10]. To overcome the rigorous recycling process required, researchers have recycled virgin PET bottles simply by slitting/cutting them into discrete fibres by hand [11-13] or with the help of locally manufactured cutters, guillotines, or paper shredders. The fibres that result from this process, although known to have relatively lower tensile strength, and elastic modulus have been utilized to lower plastic shrinkage and improve the flexure, compressive strength and toughness in mortars [14, 15]. Their use in concrete majorly improves both the tensile and flexural capacity of concrete as well as ductility in concrete beams [10, 16]

Several fibre/matrix interactions occur in Fibre Reinforced Concrete (FRC) composites to produce the toughening effect of fibres. Fibre bridging, debonding, pull out (sliding) and fibre rupture processes occur as the crack propagates through a fibre via the matrix. Fibre bridging causes the crack to close, reducing the stress intensity at the crack tip while fibre debonding and pull-out reduce the overall energy absorption. The capacity of the fibres to stabilize the crack propagation in the matrix is therefore strongly influenced by the fibre/matrix bond. Polymeric fibres have poor adhesion and wettability because of their chemical inertness and low surface energy, which results in a weak bond with the cement matrix [17]. Incorporating smooth fibres has shown a reduction in tensile strength of concrete from 9% to 16% according to a study by Meza et al. (2021) [18]. Similarly, Taherkhani (2014) [19] noted that smooth fibres reduce the tensile and flexural strengths of concrete due to a reduction in the bond between the fibres and the cement paste. Meza and Siddique (2019) [20] noted that the modulus of rupture reduces when fibres with high aspect ratios are used in concrete owing to their poor bond with cement mortar, causing micro cracks and voids. This calls for the development of various techniques to improve the interfacial bond of smooth plastic fibres to utilize their maximum strength.

Several interface-strengthening mechanisms that have been proposed and utilized to enhance the interfacial bond of polymeric fibres include fibre deformation techniques and fibre surface modification either through geometry modification or through plasma treatment, as shown by Trejbal et al. (2016) [21]. Figure 1 summarizes the approaches that can be adopted to improve the bond strength of PET Fibres.

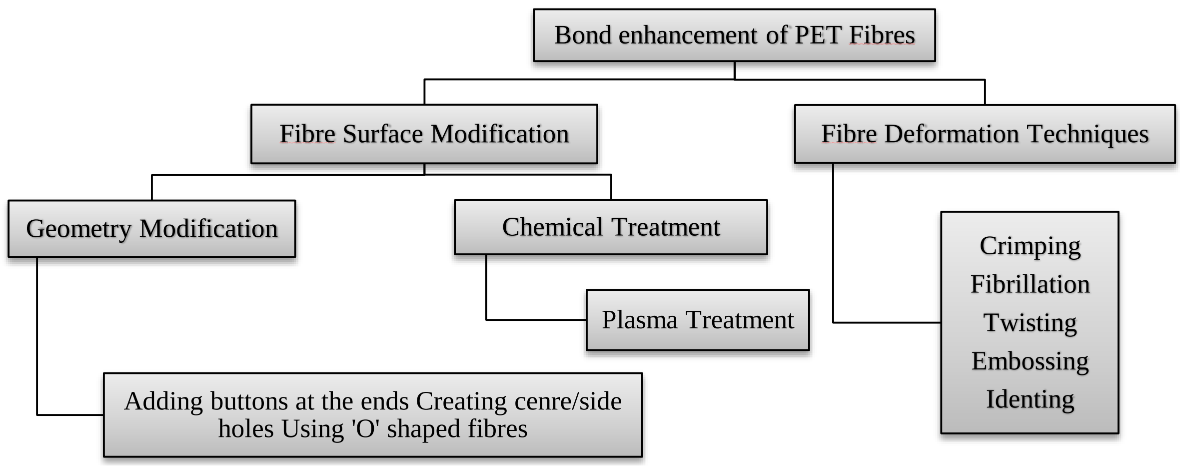


Figure 1. Bond enhancement techniques for PET fibres

Fibre deformation and surface modification techniques have been applied to virgin PET bottles with desirable results. Borg et al. (2016) [10] noted that deformed fibres showed high resistance to tensile strength compared to smooth fibres due to the provision of a sufficient mechanical bond. Similarly, Marthong & Sarma (2016) [12], and Kumar & Suman (2018) [22] noted that modifying the geometry of the fibres improved both the tensile and flexural strength response of the concrete composites. While it is easier to modify the geometry of extruded recycled fibres during the manufacturing process, modifying the surface of virgin PET fibres can be quite a difficult task and time-consuming given the shape of the bottles as noted by Marthong & Sarma (2016) [12]. Chemical treatment may reduce the mechanical strength and the disposal of the waste products from such processes can become an environmental problem. Fibre deformation techniques such as embossing and indentation reduce the cross-section of the fibre, which eventually reduces its tensile strength [17], and hence reduced tensile strength enhancement in concrete. Kim et al. (2008) [23] observed that crimping reduces the initial stiffness of the composite due to the initial stretching of the fibre, a factor that could contribute to early cracking in the composite.

Despite the significant progress that has been made in improving the bond properties of virgin PET fibres, several shortcomings have been experienced with the current methods calling for new solutions that provide optimal performance. This study, therefore, suggests a new way of modifying the surface of virgin PET fibres by coating the surface of the fibres with a thin layer of 0.3 mm-sized sand grains using clear waterproof epoxy. This approach does not reduce the cross-section of the fibres and provides a relatively rough surface, providing sufficient bond with concrete. The methodology adopted in producing these fibres is novel and less time-consuming compared to traditional surface modification methods. The performance of these surface modified fibres was compared to that of embossed fibres, serrated fibres (whose edge is modified by cutting the fibres using serrated scissors), and smooth fibres. The effectiveness was determined by examining their impact on the fresh and hardened properties of concrete at constant fibre length and content. The degree of performance of FRC depends on the quality and quantity of the fibres used, dimensions and shape, as well as their bond with the concrete mix. Increasing the bond performance can therefore aid lower the length (aspect ratios) and/or volume fraction while maintaining practically the same crack resistance [17]. For this reason, once the performance of sand-coated fibres was identified, the length and the dosage of these fibres were varied to obtain the optimum values, which can be recommended for the industry.

2. Materials and Methods

The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.

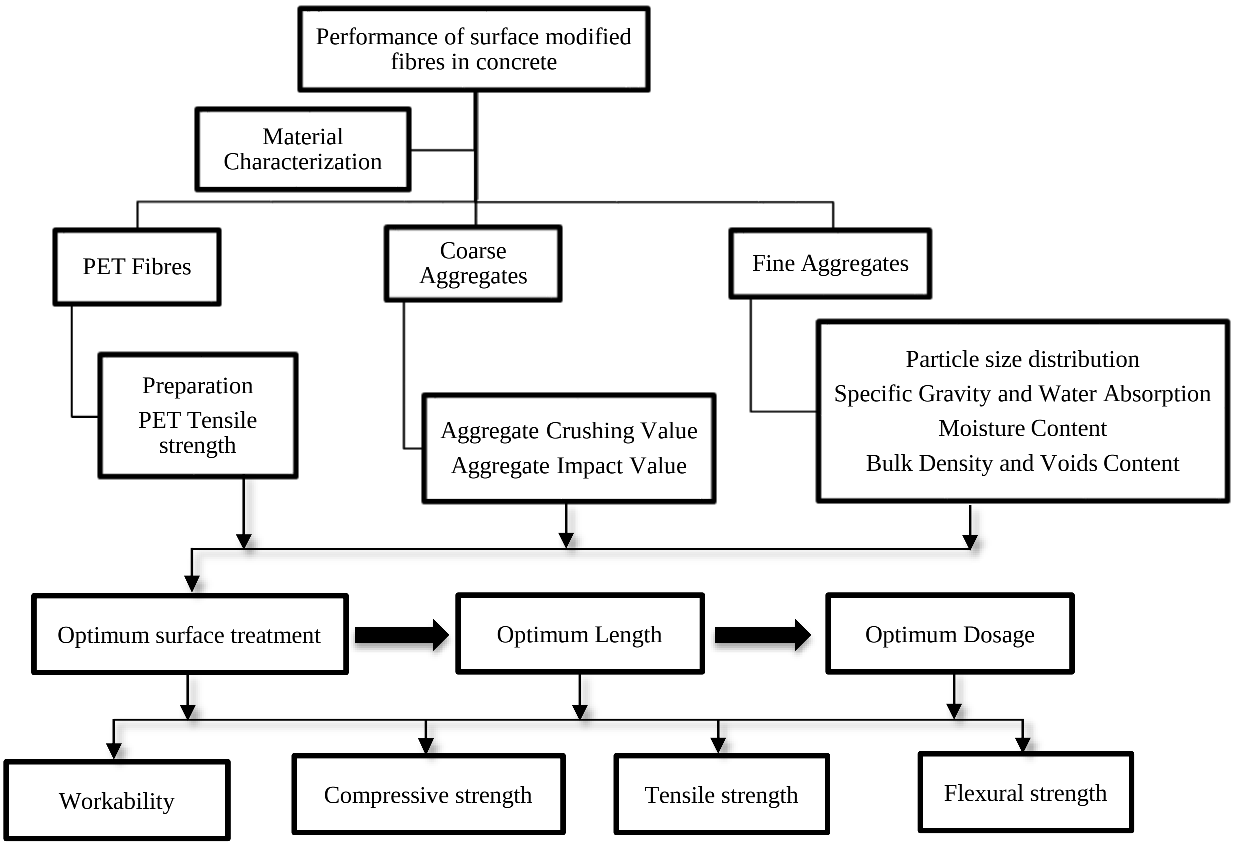
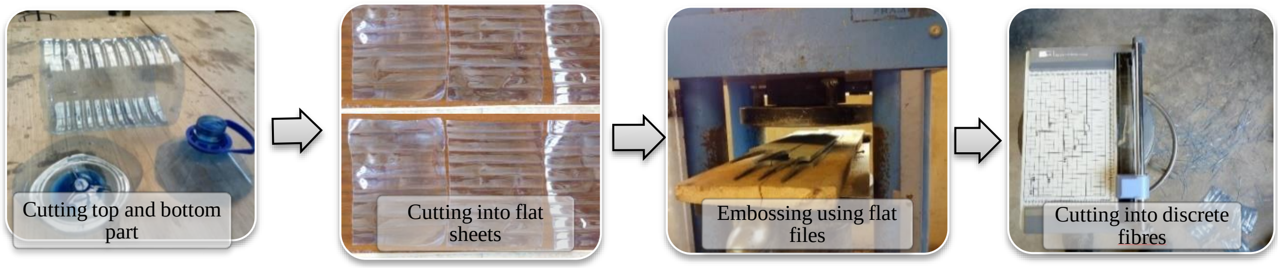


Figure 2. Methodology framework

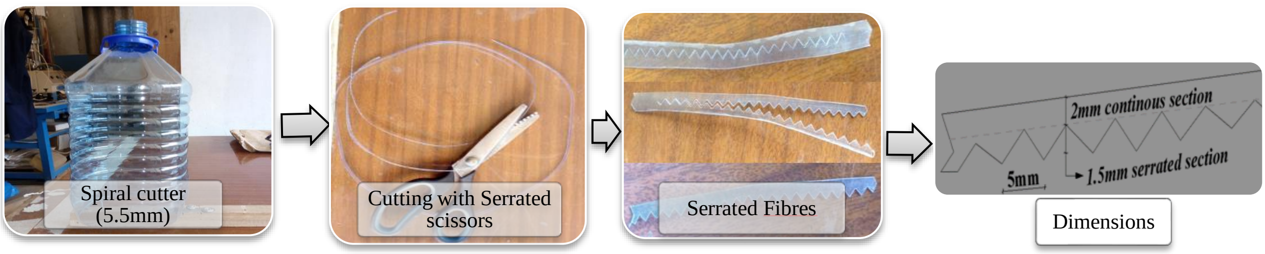
The main objective of this research work was to analyze the effect of surface modified virgin PET fibres (sand-coated) in comparison with geometrically modified (serrated), deformed (embossed), and smooth fibres, and their optimal values of dosage and dimensions. This was carried out through the characterization of the fibres and the concrete constituent materials, and the determination of the workability, compressive strength, tensile strength, and flexural strength of fibre concrete.

2.1. Materials

Materials used in this study include Ordinary Portland Cement (OPC) class 42.5N conforming to standard [24], fine aggregates (ordinary river sand) obtained locally, coarse aggregates which were mixed thoroughly on arrival, and clean portable water. PET fibres were obtained from waste 5-litre PET bottles obtained from a local plastic handling company in Nairobi, Kenya. The PET bottles were cut into discrete fibres using a paper cutter, a pair of scissors, and a locally made spiral plastic cutter. Three fibre treatments were carried out. Serrated scissors were used to produce serrated fibres while embossing of flat plastic sheets was done using flat files compressed with a mechanical press at 25 kN, which were then cut into discrete embossed fibres. The sand-coated fibres were produced by applying a thin layer of sand of 0.3 mm (based on a study by Al-Mahmoud et al. (2007) [25]) on the surface of the fibres using clear epoxy. Figures 3 and 4 show the respective preparation stages and the different fibres used.



(a) Embossing process



(b) Serrating process

(c) Sand-coating process

Figure 3. Preparation of fibres: (a) Embossing, (b) Serrating, (c) Sand-coating

Smooth Fibres | Embossed Fibres | Serrated Fibres | Sand-coated Fibres

Figure 4. PET Fibres

2.2. Methods

2.3.1. Characterization of Constituent Materials Methods

Fine and coarse aggregates occupy 60 to 75% of the concrete volume and have a significant impact on concrete's fresh and hardened properties and its cost. Aggregates must therefore meet certain standards for optimum engineering use and hence they must be tested before being used in concrete. For instance, the grading of aggregates affects their proportions in the mix, cement and water requirements, workability, porosity, uniformity, and durability of concrete. The specific gravity and the density of the aggregates are used in mixture proportioning computations during the mix design phase. Table 1 shows the characterization tests performed on aggregates, and the PET fibres and the corresponding test standards.

Table 1. Characterization tests of constituent materials

Material	Tests	Standards
Fine aggregates (River sand)	Particle size distribution	British Standard Institution (1985) [26]
	Specific gravity & water absorption	British Standard Institution (1995) [27]
	Moisture content	British Standard Institution (1990) [28]
	Bulk density & voids content	British Standard Institution (1995) [27]
Coarse aggregates	Particle size distribution	British Standard Institution (1985) [26]
	Specific gravity & water absorption	British Standard Institution (1995) [27]
	Moisture content	British Standard Institution (1990) [28]
	Bulk density & voids content	British Standard Institution (1995) [27]
	Aggregate crushing value	British Standard Institution (1990) [29]
	Aggregate impact value	British Standard Institution (1990) [30]
PET Fibres	Tensile strength test	British Standard Institution (2006) [31]

Tensile strength tests were carried out to characterize the PET fibres used in this study. This test was carried out using a tensometer where single fibres were clamped and tensioned until breakpoint, as shown in Figure 5. The force and elongation at break were recorded and the tensile strength was calculated from the dimensions of the fibre.

Figure 5. PET Fibre tensile strength test

2.3.2. Mix Proportions

A mix design of 30 MPa characteristic strength was carried out according to the Building Research Enterprise (BRE) method [32]. Workability tests were carried out as referenced in BS 1881-102 (1983) [33] while the compressive strength tests were carried out according to BS 1881-116 (1983) [34] for 100 mm by 100 mm by 100 mm cubes. Table 2 shows the trial mix proportions.

Table 2. Mix Proportions for class 30 concrete

W/C Ratio	Water (kg/m^3)	Cement (kg/m^3)	Coarse agg. (kg/m^3)	Fine Agg. (kg/m^3)	Ratio
0.55	190	347.5	1200.7	649.5	1:1.9:3.5

These mix design proportions were maintained throughout the study to assess the effects of surface-modified PET fibres on the properties of concrete. The study was conducted in three stages. The first stage was to determine the performance of sand-coated fibres compared to the other fibres. A constant length of 100 mm, a width of 2 mm, and a fibre content of 1% (by weight of cement) were maintained for all the different surface treatments based on Meza et al. (2021) [18] and Taherkhani (2014) [19]. The surface-treated fibres that gave better results in terms of split tensile and flexural strength were then selected for optimization. This was carried out in the second and third stages. The second stage was to determine the optimum length of the selected fibres. In this stage, the fibre percentage was maintained at 1% while the fibre length varied from 50 mm to 100 mm at 25 mm increments. Last, the optimum fibre length obtained was used to determine the optimum content by varying the fibre percentage from 0.75% to 1.5% at intervals of 0.5%.

2.3.3. Methods for Testing Fresh and Hardened Properties of Concrete

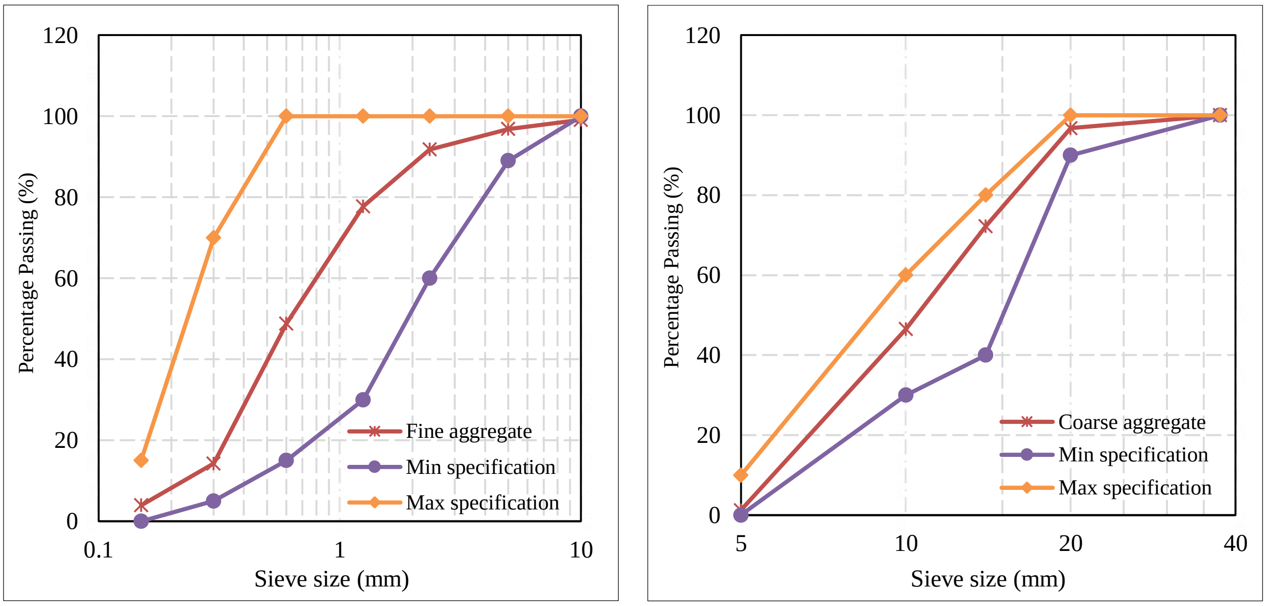
The workability of fresh concrete was determined using the slump test according to [33] with a slump cone of dimensions 30 cm height, 10 cm top diameter, and 20 cm bottom diameter. The sampling of fresh concrete was done under BS 1881-101 (1983) [35]. Tests on hardened concrete properties carried out include the compressive strength, split tensile strength, and flexural strength tests following BS 1881-116 (1983) [34], BS 1881-117 (1983) [36], and BS 1881-118 (1983) [37], respectively. Cubes with dimensions of 100 mm and cylinders with dimensions of 100 mm diameter and 200 mm height were used to cast the specimens. Prismatic specimens of dimensions 150 × 150 × 530 mm were cast for flexural strength determination. Three specimens for each mix were cast as specified in BS 1881-108 (1983) [38], BS 1881-110 (1983) [39], and BS 1881-109 (1983) [40], and cured for 7, 14, and 28 days for cubes and cylinders while flexure beams were tested at 28 days. The specimens were loaded using a universal testing machine conforming to BS 1881-116 (1983) [34], BS 1881-117 (1983) [36], and BS 1881-118 (1983) [37] to determine the compressive, split tensile and flexural strength, respectively.

3. Results and Discussion

3.1. Material Characterization

Grading of Aggregates

Figure 6 shows a plot of the particle size distribution of the fine and coarse aggregates with the maximum and minimum curves as defined in BS 882 (1992) [41]. It can be observed that the results fall within the defined limits and thus the fine and coarse aggregates were well graded, guaranteeing a workable and uniform mix.



(a) (b)

Figure 6. Grading curves (a) Fine aggregates, (b) Coarse aggregates

Physical and Mechanical Properties

Table 3 summarizes the physical and mechanical properties of the fine and coarse aggregates.

Table 3. Physical and Mechanical Properties of Coarse and Fine aggregates

Test	Fine aggregates	Coarse aggregates
Specific Gravity	2.5	2.68
Water Absorption	1.01%	3.65%
Moisture Content	4.63	–
Bulk Density	1609.58 kg/m^3	1498.27 kg/m^3
Percentage of voids	34.97%	39.88%
Aggregate Crushing Value (ACV)	–	18.35%
Aggregate Impact Value (AIV)	–	6.71%

The specific gravity and the bulk density for both the fine and coarse aggregates were within the recommended limits, guaranteeing a stronger mix. The aggregate crushing value and the impact value met the specifications outlined in BS 882 (1992) [41] and BS EN 12620 (2013) [42], respectively. The water absorption and moisture content values were considered in the mix design to produce a workable mix with the desired strength.

PET Fibres

Figure 7 shows a plot of the tensile strength test results and the corresponding elongation for the PET fibres. There was a subsequent reduction in strength for the various surface treatments compared to the smooth fibres (control), which had a tensile strength of 87.7 N/mm^2. Embossed fibres had a tensile strength of 45.0 N/mm^2 corresponding to the highest strength reduction (48.8%), followed by serrated fibres which had a strength of 57.83 N/mm^2 (34.1% reduction). Sand-coated fibres showed the highest tensile strength increment of 298% and an elongation of 9.34 mm corresponding to a 42.3% increase compared to straight fibres, which have an average elongation of 6.56 mm. This is because of the additional elasticity provided by the epoxy coating.

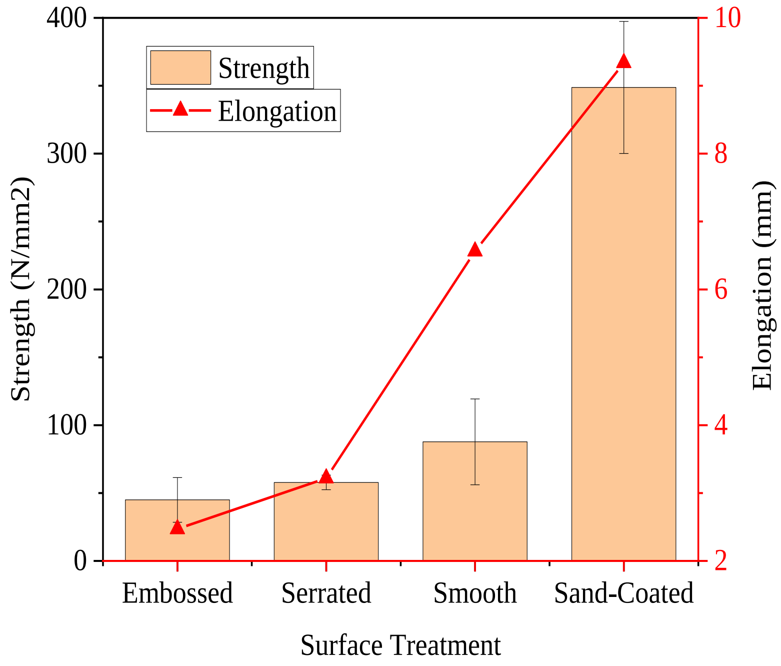


Figure 7. Tensile strength and elongation for PET Fibres

Serrated and embossed fibres had an elongation of 3.22 mm and 2.47 mm, which corresponds to a reduction of 51% and 62.4% respectively compared with the smooth fibres. Serrating the fibres creates a zone of stress concentration at the surface transitions, hence reducing the strength of the fibre and the elongation. Given the small thickness of the PET bottles (0.25 mm), embossing weakens the plastic material and thus reduces its tensile strength and elasticity, an observation made by Singh et al. (2004) [17]. Table 4 summarizes the tensile strength values for both virgin and recycled PET fibres from previous studies. Sand coated fibres give a considerably higher tensile strength within the range of recycled PET fibres making them superior to all other virgin PET fibres reviewed except the study by Awoyera et al. (2021) [43] which records a tensile of virgin PET fibre of around 450 MPa.

Table 4. Tensile Strength Values for Virgin and Recycled PET fibres

Author(s)	Tensile Strength (MPa)	
	Virgin PET	Recycled PET
Marthong (2015) [44]	155	
Fraternali et al. (2011) [45]		550, 264, 274, 250
Kim et al. (2010) [8]		420.7
Bui et al. (2018) [46]	122	
Foti (2013) [47]	160	
Won et al. (2010) [48]		420.7
Hidaya et al. (2017) [49]	254	
Ochi et al. (2007) [9]		450
Kassa et al. (2019) [50]	84	
Fraternali et al. (2013) [51]		550, 274
Awoyera et al. (2021) [43]	450	
Anandan & Alsubih (2021) [52]	31.5	

3.2. Effects of PET Fibres on Concrete Properties

3.2.1. Properties of Concrete Produced with Surface Modified Fibres

This section presents the results of the performance of sand-coated fibres compared to the other fibres in concrete. The content of the fibres was maintained at 1% by weight of cement and the length was 100 mm for all fibres.

Workability

The mechanical, physical, and durability aspects of concrete composites are all affected by workability. Figure 8 shows the effect of the surface modified PET fibres on the workability of the concrete mix.

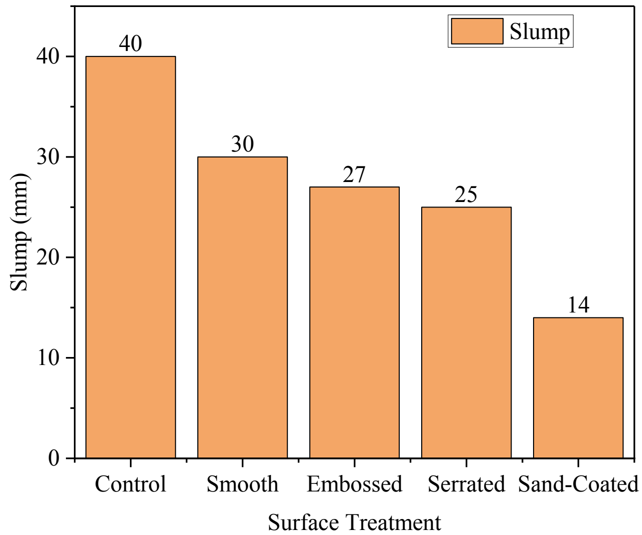


Figure 8. Slump test results for different surface-modified fibres

In general, it can be observed that the fibres reduced the workability of fresh concrete compared to the control mix. This reduction in workability could be attributed to the adherence of the fibres to the concrete ingredients restraining their movement within the mix. The geometry and the surface texture of the fibres further affect the workability of the fresh concrete. There was a subsequent reduction in the workability of fresh concrete mix from straight fibres to sand-coated fibres. Embossed fibres reduced the workability due to their rough indented surface, which adhered to the concrete ingredients. The sharp edges of the serrated fibres further restrained the movement of the materials within the mixture [13]. The surface of the sand-coated fibres was extremely rough and adhered most to the concrete ingredients compared to all other surface geometries and hence the high reduction in slump. These findings concur with Kumar et al. [22] who observed that increasing the anchorage of PET fibres through geometry modification led to a 25 – 30% reduction in the workability of concrete. Figure 9 shows the slump of the control mix compared to that of the mix with sand-coated fibres.


(a)


(b)

Figure 9. Slump for (a) Control mix; (b) Mix with sand coated fibres

Compressive Strength

Figure 10 shows the compressive strength results for the different surface-modified fibres compared to the control mix and the mix with smooth fibres. Smooth and embossed fibres met the lower limit for Grade M30 concrete but reduced the 28-day strength by 4% and 13%, respectively, compared to the control mix. Serrated and sand-coated fibres showed an 18% and 21% reduction respectively, compared to the control. The reduction in strength compared to the 28 days' lower limit for M30 concrete was minimal, corresponding to 5% and 8% for serrated and sand-coated fibres, respectively. Sand coated fibres reduced the strength by 17.8%, 9.4%, and 3.2% compared to smooth, embossed, and serrated fibres, respectively. The failure of PET fibre specimens was less brittle with a prolonged re-loading phase compared to the control specimens.

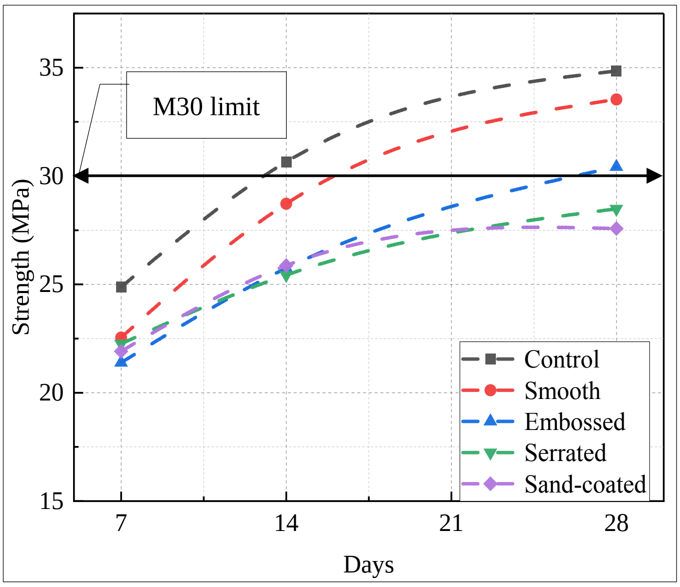


Figure 10. Compressive strength results for the different surface modified PET fibres

As noted earlier, PET fibres lowered the workability of fresh concrete, which made it difficult to achieve complete compaction, particularly with sand-coated fibres. In addition, PET fibres make the concrete mix more porous, creating weak zones inside the concrete, resulting in the propagation of cracks and hence the reduction in strength. A reduction in the ultrasonic pulse velocity of samples with PET fibres has been noted by Sayi and Eren (2021) [53] confirming the possibility of porosity formation in PET concrete. Similar observations on strength reduction have been made by Meza et al. (2021) [18] who noted a 6% reduction in strength related to the effect of porosity and low adherence of fibres to the concrete matrix. In addition, Borg et al. (2016) [10] noted a 0.5% to 8.5% strength reduction that on the addition of PET fibres in concrete due to the low elastic modulus of plastic fibres resulting in poor composite action [54], findings which have been supported by other researchers [55]. However, some studies show a slight improvement of compressive strength at 0.5% [44, 50] and 1% [56] fibre dosage. It is worthwhile to note that in most of the studies that report an increase in compressive strength, short, smooth fibres were used, and hence fair compaction was achieved. Short fibres are evenly distributed in the matrix, reducing the micro-crack envelopes, and hence increased loading is required to propagate cracks until failure [57]. This explains why there is a subsequent reduction in the compressive strength of concrete when PET fibres are introduced into concrete at a high aspect ratio.

Split Tensile Strength

Split tensile strength tests for a standard cylinder (100×200 mm) were carried out at 7, 14, and 28 days. Figure 11 shows the effect of the different fibres on the split tensile strength of concrete. PET fibres showed an improvement in the tensile strength of concrete at a constant fibre percentage and length. Smooth, embossed, and sand-coated fibres showed an increase in the tensile strength corresponding to 5.53, 8.79, and 9.49% respectively, compared to the control mix while serrated fibres showed a 0.46% reduction in the tensile strength compared to the control mix. This corresponds to a 4, 1, and 9% increase in tensile strength of sand coated fibres in comparison with straight, embossed, and serrated fibres respectively. Sand-coated fibres show a 4% increment in tensile strength compared to smooth fibres. A single line crack appeared on the face of the control specimen cylinder and the failure was sudden while the cylinders with fibres failed smoothly, forming multiple cracks at the surface due to crack redistribution. The plastic fibres still held the concrete together after the failure load, as shown in Figure 12.

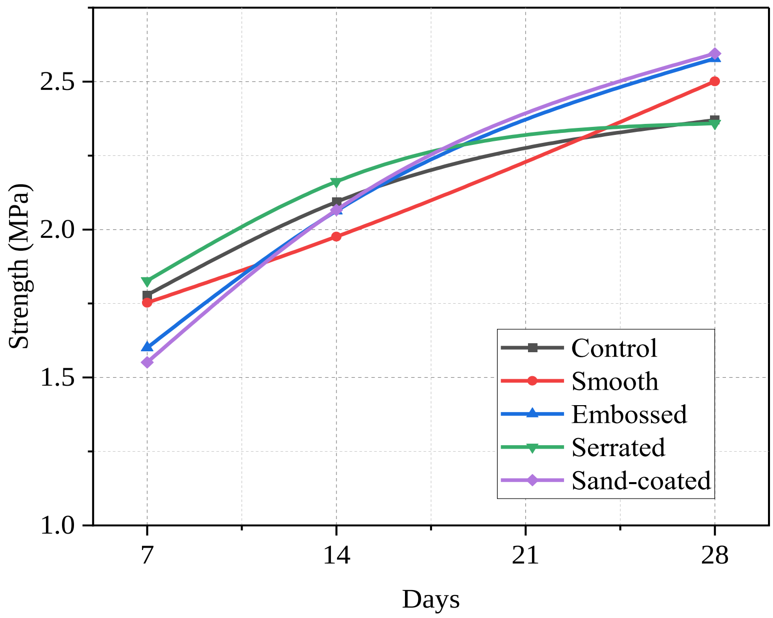
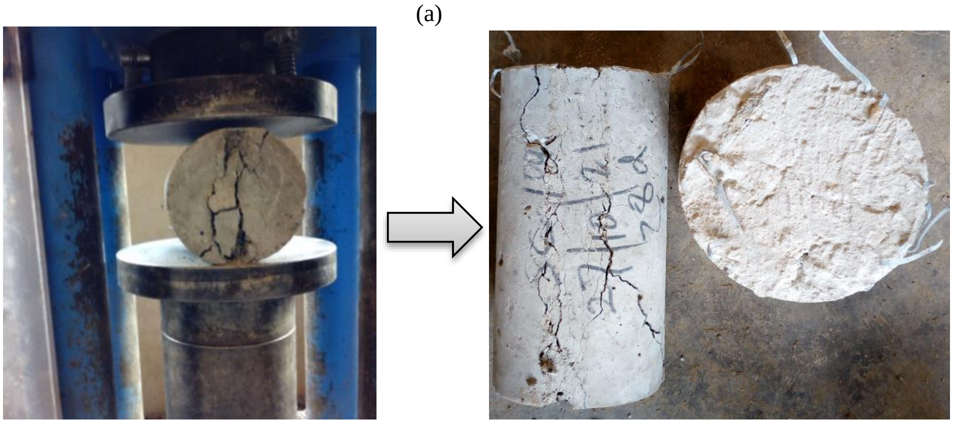


Figure 11. Split tensile strength results for the different surface modified PET fibres

(a)



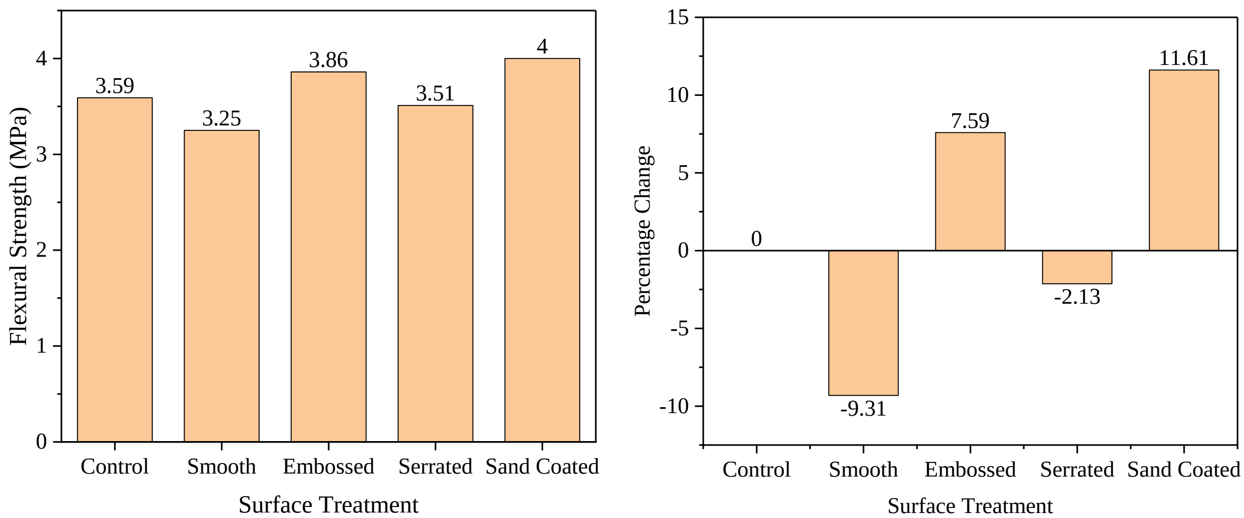
(b)

Figure 12. Failure modes for (a) Control mix without fibres, (b) mix with sand coated fibres

The high improvement in the tensile strength of the sand-coated fibre specimens could be attributed to the increased bond and elasticity of the fibres, allowing the concrete composite to carry more loads before fibre rupture. The relative reduction in tensile strength by the smooth fibres compared to the embossed and sand-coated fibres can be attributed to their weak bond and poor adhesion with the concrete ingredient materials, as noted by Kim et al. (2010) [8]. Serrated fibre specimens show a higher strength improvement at 7 days, which reduces at 28 days, compared with the control mix. The initial strength gain is due to the bridging effect of the fibres and their resistance to slip, given the surface geometry. However, as the concrete strength increases, on loading, stress concentrations build up at the surface transitions of these fibres, which eventually break. Previous studies on bond enhancement of PET fibres show a relative improvement in tensile strength compared to smooth fibres. Kumar and Suman (2018) [22] noted an increment of 7.41, 9.88, and 16.05% in tensile strength on using centre holed, two-side circular-cut, and one-side circular cut fibres respectively, compared to smooth fibres. A similar improvement of 20 to 43% has been reported by Marthong and Sarma (2016) [12] for flattened end and deformed fibres compared to smooth fibres. In the current study, sand-coated fibres only show an improvement of 3.96% compared to smooth fibres.

Flexural Strength

Flexural strength was determined using a prismatic specimen with dimensions 150×150×530 mm. The test specimen was loaded using a two-point-loading arrangement using a universal testing machine at 28 days. On incorporating sand-coated fibres, the flexural strength of concrete increased by 11.61%, which is 23.1% higher compared to smooth fibres. Embossed fibres showed an increase of 7.59% while serrated and smooth fibres recorded a decline of 2.13% and 9.31% respectively. This corresponds to an increase of 3.74% and 14.04% of sand-coated fibres compared to embossed and serrated fibres, respectively. No specimens with fibres experienced a sudden brittle failure, as was observed with the control mix without fibres. Figures 13 and 14 show the flexural strength results and the failure mode of the specimens with and without fibres, respectively.



(a) (b)

Figure 13. (a) Flexural strength results for different surface-modified fibres (b) Percentage change

(a) (b)

Figure 14. (a) Failure of a fibre concrete specimen (b) Failure of Control specimen (without fibres)

As mentioned earlier, coating the fibres with sand increased the bond capacity of the fibres and its elongation capacity before failure and hence the improvement in flexural strength. Similar reasons apply for the embossed fibres whose rough surface improved their bond capacity, even though not as much as the sand-coated since the width of the fibres restricts the depth of the deformations and hence, its roughness. Stress concentrations at surface transitions of the serrated fibres led to earlier fibre rupture, hence reducing the flexural strength of the matrix. It is recommended that the semi-circular serrations should be adopted to avoid stress concentrations as in the study by Kumar et al. (2018) [22] who noted a 39.24% increase in flexural strength when 1-sided circular-cut fibres were used. This translated to a 19.19% increase in flexural strength compared to the smooth fibres. The 23.1% increment in flexural strength of sand-coated fibres compared to smooth fibres is also in close agreement with the study by Marthong et al. (2016) [12] who noted an average increase of 27% in flexural strength when flattened end, deformed, and crimped end fibres were used compared to smooth fibres.

The low flexural strength obtained with smooth fibres shows the necessity of fibre surface modification. Studies by [31, 53, 59] show that smooth fibres do not have a significant improvement in flexural strength which is attributed to their poor bond strength. In another study, Marthong (2015) [44] noted that flattened end fibres gave higher flexural strength compared to smooth fibres by 2.98% while Borg et al. (2016) observed that deformed fibres had a slightly better performance than smooth fibres. Visual observations of the failed specimens showed that for the sand-coated and serrated fibre specimens, fibres failed by rupture while smooth fibres were observed one side of the specimen indicating possible pull out. A combination of both failures was experienced with embossed fibres. Sand-coated fibres, therefore, have an increased bond with the matrix and hence the failure by rupture. It was further noted that coating the surface of the fibres with sand improved their stiffness and therefore the fibres remained straight during mixing, providing a better stress transfer from concrete to the fibres, unlike the other fibres which deformed during mixing given their length and low stiffness. It is worthwhile noting that sometimes, at failure, the sand coating peeled off from the surface of the fibres. This indicates that the bond between the sand coating and the cement paste was stronger than the bond between the fibre and the sand coating layer and therefore effective roughening of the fibres (by use of a sand-paper) before sand coating the fibres is highly recommended.

The results from this section show that sand-coated fibres have a better performance in terms of split tensile and flexural strengths compared to the conventional surface modified fibres. This provides the industry with a new technique of modifying the surface of virgin PET fibres, which does not compromise the intrinsic properties of the fibre, like the reduction in tensile strength experienced with embossed fibres. Since the aspect ratio and dosage of fibres affect the performance of concrete, these were further studied to obtain optimal values of the sand-coated fibres in the next section.

3.2.2. Effect of Fibre Length on Concrete Properties

In the first section, to study the performance of sand-coated fibres in comparison with other types of fibres, the content and length were kept constant. However, increasing the bond of the fibres might reduce the length of fibres required to achieve the same tensile strength enhancement. In addition, the length of fibres affects concrete workability, fibre distribution, and crack prevention, which ultimately affects the compressive and tensile strengths of concrete. In this section, the length of the sand-coated fibres varied from 50 mm to 100 mm at 25 mm length increments. The content of the fibres was again maintained at 1% by the weight of cement.

Workability

Figure 15 shows the effect of fibre length on the workability of fresh concrete.

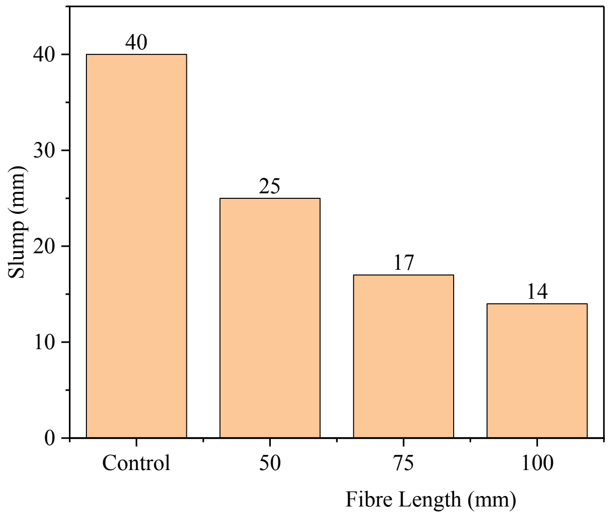


Figure 15. Slump values for varying fibre lengths

There was a subsequent reduction in concrete workability as the length of the fibre increased. As noted by Sayı & Eren [53] and Haque et al. (2021) [58], the longer the fibre, the greater the surface area adhering to the mix ingredients, and therefore the reduction in workability. Ninan et al. (2018) [59] also observed that workability was higher for shorter fibres (20 mm) compared to longer fibres (80 mm). Meza and Siddique (2019) [20] argued that longer fibres have a large surface area for the cement paste to cover, resulting in a reduction in workability. The findings of this study regarding the effect of fibre length agree with these and other studies reported in the literature. The effect of changing the length (aspect ratio) of sand-coated fibres on workability is similar to that of other virgin PET fibres.

Compressive Strength

Compressive strength tests were carried out to assess the effect of the different fibre lengths on the hardened properties of concrete. There was a strength reduction on introducing PET fibres by 20.9, 16.9, and 8.2% for 100 mm, 75 mm, and 50 mm long fibres respectively compared with the control as shown in Figure 12. 100 mm and 75 mm long fibres showed an 8.1% and 3.5% reduction in the compressive strength compared to the lower limit of M30 concrete at 28 days as shown in Figure 16.

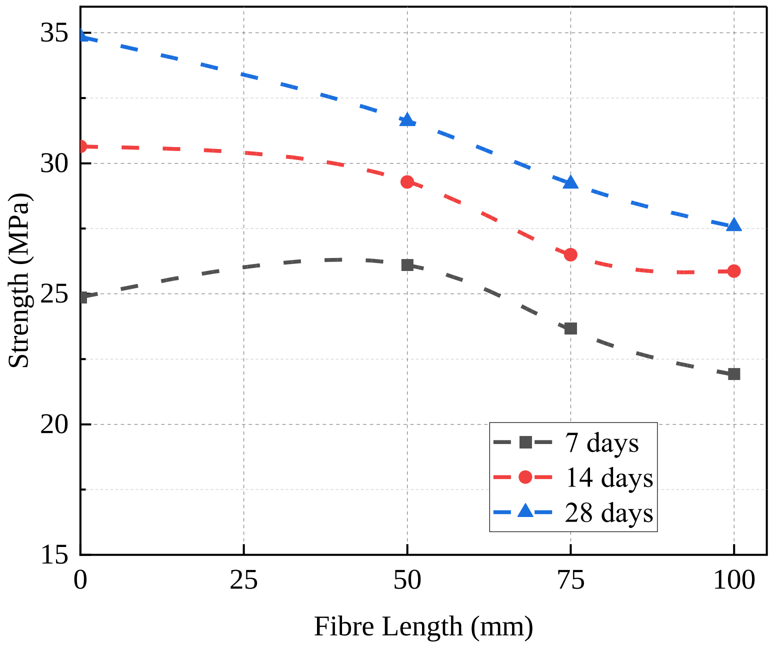


Figure 16. Compressive strength values for varying fibre lengths

Increasing the length of the fibres leads to a subsequent reduction in workability, making it difficult to achieve complete compaction, which in turn lowers the compressive strength. The initial strength improvement achieved by shorter fibres (50 mm) could be attributed to the bridging effects of the fibres before the cement paste fully hydrates. The mechanical optimization of concrete with PET fibres carried out by Meza et al. (2021) [18] also shows that the reduction in compressive strength in FRC composites is related to the aspect ratio of the fibres, where the samples with higher aspect ratios show lower performance than those with shorter dimensions. The findings of this agree with global data, especially regarding the study by Mohammed and Mohammed (2021) [54]. They carried out a regression analysis on a large data set and observed that for the same fibre cross-section, the compressive strength reduction increases with an increase in fibre length.

The lack of composite action between the fibres and concrete ingredients creates lines of weakness and introduces voids in the matrix, making the concrete porous and thus lowering its compressive strength. Uneven distribution of fibres is experienced with longer fibres, increasing the micro-crack envelopes and hence reducing the loading required to propagate cracks until failure [13, 56]. This, coupled with the incomplete compaction as the fibre length increases, leads to a subsequent reduction in the compressive strength.

Split Tensile Strength

Figure 17 shows the effect of fibre length on the split tensile strength of concrete at 7, 14, and 28 days. 50 mm long fibres show a 4.98% increase in tensile strength while 100 mm and 75 mm long fibres show 9.49% and 13.76% respective improvements in tensile strength at 28 days compared to the control.

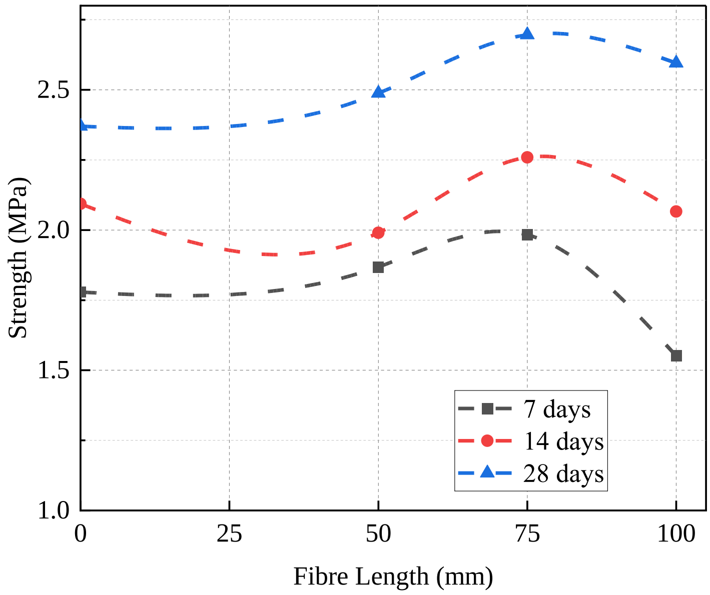


Figure 17. Split tensile strength results for varying fibre lengths

An increase in the length of the fibres improves the tensile strength up to a certain point and then the strength declines. This agrees with a study by Kausik and Sharma (2014) [60] who noted that split tensile strength increased up to 15.66% at a fibre aspect ratio of 45, beyond which there was no increase in strength. Ninan et al. (2018) [59] observed that 80 mm long fibres provided a 2.15% increase in split tensile strength compared to 20 mm long fibres at 1% fibre dosage. Contrary to these findings, the statistical analysis of large data carried out by Mohammed and Mohammed (2021) [54] concludes that the loss in tensile strength is high when fibres of large fibre index are used. In addition, Meza et al. (2021) [18] noted that for low fibre dosage, longer fibres give high tensile strength results.

In this study, however, at a constant fibre dosage of 1% by weight of cement, 75 mm long fibres seem to give optimal results. This means that increasing the bond strength of fibres lowers the surface area of the fibre required to achieve the same tensile strength enhancement. The difficulty of achieving a uniform distribution of long fibres (100 mm) coupled with the reduction in workability could be the reason for the decline in strength. 50 mm long fibres do not provide enough length for pull out resistance and hence the reduced strength compared to 75 mm long fibres.

Flexural Strength

Figure 18 shows a similar trend to that of split tensile strength results where the flexural strength of concrete increased by 9.79, 12.49, and 11.61% on incorporating 50, 75, and 100 mm long fibres, respectively. Similar reasons for this behavior are explained above. Table 5 compares the percentage change in the split tensile and flexural strength results of this study to those obtained in other studies.

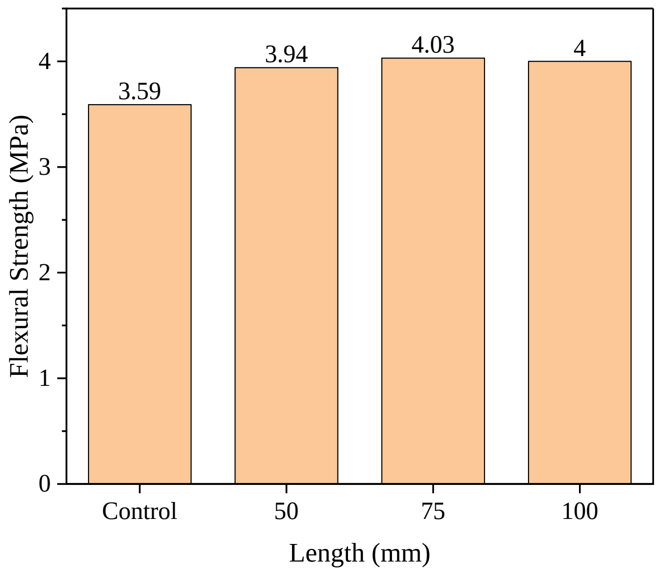


Figure 18. Flexural strength results for varying fibre length

Table 5. Comparison of percentage change in the split and flexural strength results

Author(s)	Fibre length (mm)	Fibre content	Percentage change compared to control mix (%)	
			Split Tensile Strength	Flexural Strength
Current Study	50	1.0% by weight of cement	4.98	9.79
	75		9.49	12.49
	100		13.76	11.61
Sharma et al. (2014) [60]	30	0.5% by weight of cement	5.34	1.46
	60		10.32	6.80
	90		13.17	9.71
	120		3.56	0.73
Ninan et al. (2018) [59]	20	1.0% by weight of cement	55.79	34.10
	80		57.94	44.10
Meza et al. (2021) [18]	53.5	2 kg/m^3	- 10.47	- 6.05
		10 kg/m^3	- 14.73	- 0.36
	85.6	6 kg/m^3	- 17.05	- 3.56
	117.8	2 kg/m^3	- 9.3	- 6.05
		10 kg/m^3	- 12.4	3.2
Merli et al. (2020) [61]	30	0.5% by volume of concrete mix	8	3
	50		13	10
	70		1	- 3
	90		- 9	- 20
	110		- 15	- 31

Increasing the length of the fibre increases the surface area in contact with the matrix, limiting crack propagation and eventual failure. However, if the fibres have a sufficient bond strength, a shorter length of fibre provides an equivalent strength enhancement as observed in this study. Fibres with a length of 75 mm gave excellent results in terms of tensile and flexural strengths. These were therefore selected to study their optimum dosage in concrete.

3.2.3. Effect of Varying Fibre Percentage on Concrete Properties

The content of the sand-coated fibres in the mix was varied from 0.75% to 1.5% at an increment of 0.25% to assess their effects on the fresh and hardened properties of concrete.

Workability

Figure 19 shows the effect of PET fibre content on the workability of fresh concrete mix at a constant w/c ratio.

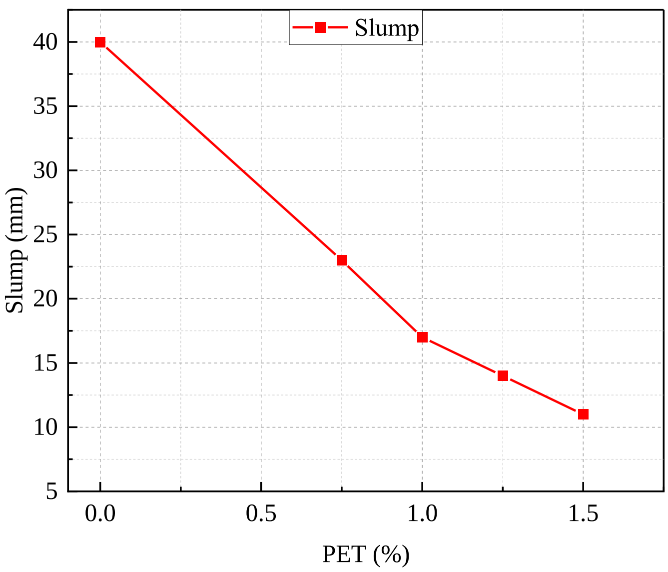


Figure 19. Slump values for varying fibre content

Compared to the control mix, there was a 42.5, 57.5, 65, and 72.5% reduction in slump when 0.75, 1.0, 1.25, and 1.5% fibre content were added, respectively. The addition of 1.5% PET fibres by weight of cement resulted in the slowest slump of 11 mm. This shows that an increase in the content of sand-coated PET fibres affects the workability of concrete negatively. Ninan et al. (2018) [59] noted a 30.8, 38.5, 69.2, 76.9% and 96.2% reduction in slump values when 0.5, 0.75, 1.0, 1.25, and 1.5% fibre content (by weight of cement) were added. The rough surface of the fibres adheres to the concrete ingredients restraining their movement. Al-Hadithi & Abbas (2018) [13] noted that the sharp edges and the length of fibres compared with the aggregates restrained the movement of the mix materials, hence lowering the workability. In this study, this adherence is amplified by the rough surface of the fibres in use. The higher the content, the lower the workability, which increases the compaction effort and reduces the compressive strength.

Compressive Strength

Figure 20 shows the effect of varying the fibre content on the compressive strength of concrete. There was a subsequent reduction in strength from 0.75 to 1.5% fibre content compared to the control. The highest reduction in strength of 26.84 MPa was observed at 1.5% fibre content, corresponding to a 23% reduction compared to the control. 0.75, 1, and 1.25% fibre contents reduced the strength at 4.2, 16.9, and 15.2% respectively, compared to the control mix at 28 days.

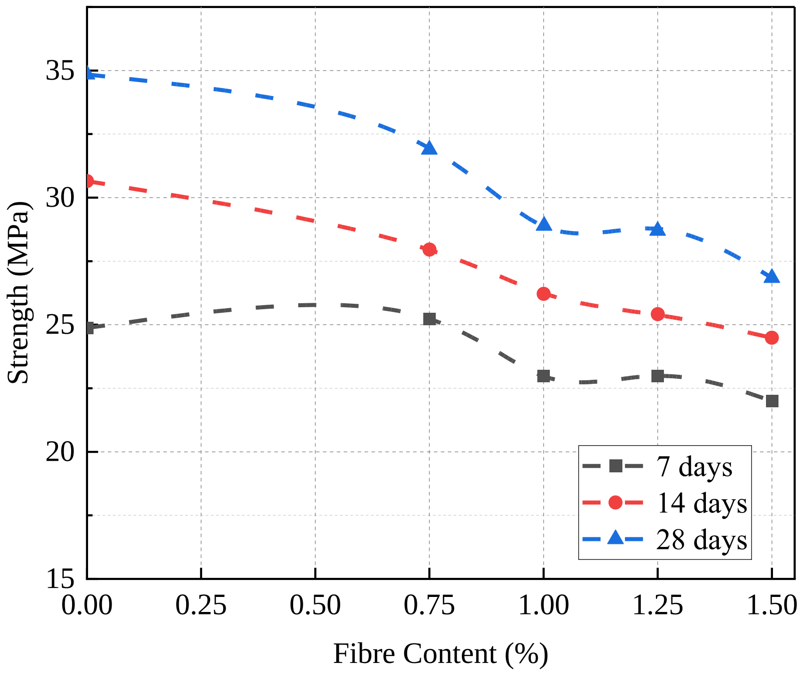


Figure 20. Compressive strength values for varying fibre content

Ninan et al. (2018) [59] observed a similar reduction in compressive strength as the fibre content increased for 80 mm fibre lengths with 1.5% fibres, showing a reduction of 24.9% in strength. Incorporating sand-coated fibres reduced the concrete compressive strength owing to the subsequent reduction in workability as the fibre content increases. Despite the good bonding of sand-coated fibres, increasing their content makes the concrete matrix more porous and their low elastic modulus offers no resistance to the compressive forces compared to say steel fibres. Most of the studies that report an improvement in the compressive strength of concrete on the inclusion of fibres use consistently short fibres (within a range of 15–50 mm) [13, 56, 62] and this improvement only occurs at low fibre dosages.

Split Tensile Strength

Splitting tensile strength tests for standard cylinders (100 by 200 mm) were carried out at 7, 14, and 28 days for all PET fibre contents. The fibre content of 0.75% did not show any considerable increment in strength at 28 days. However, a 13.76, 15.49, and 11.08% respective increment for 1, 1.25, and 1.5% content of fibres was observed compared to the control as shown in Figure 21.

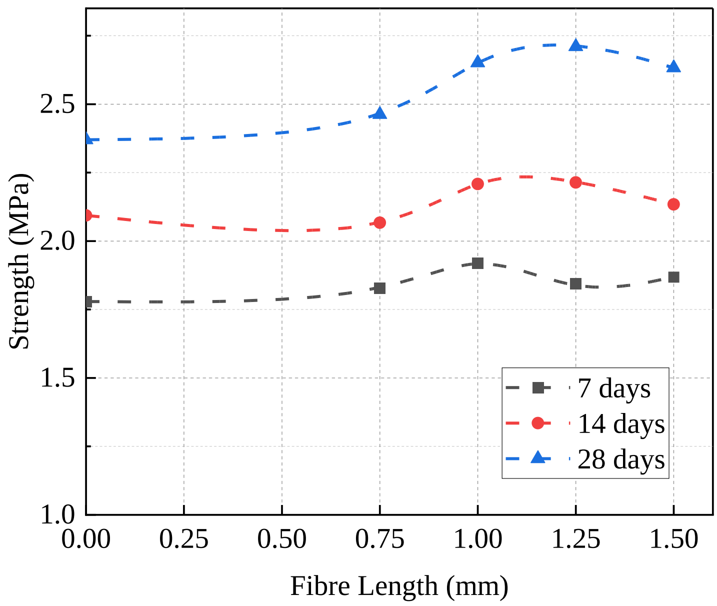


Figure 21. Split tensile strength values for varying fibre content

As the content of the fibres increases, compaction and uniform distribution become a challenge, explaining the decline in split tensile strength at 1.5% fibre content. The optimum percentage of sand-coated fibres from this study in terms of the split tensile test is 1.25% by weight of cement with an increment of 15.49% in strength compared to the control. The increment in strength was attributed to the bridging effect of the fibres where on cracking of the concrete matrix, the stresses were transferred to the fibres, which increased the resistance to fracture and prolonged the time of failure, hence improving the ductility of the concrete. Failure of fibre specimens was not sudden as compared to the control specimens and the fibres held the concrete together even after failure.

Flexural Strength

Figure 22 shows the flexural strength results for the varying fibre content. The flexural strength of the concrete increases by 1.74, 12.49, 17.26, and 2.58% for 0.75, 1, 1.25, and 1.5% fibre content, respectively. At 1.5% fibre content, the compressive strength reduces by 23% compared to the control mix. The resistance of concrete to flexure is a function of its compressive and tensile strength. Fibres improve the tensile strength of the concrete but reduce the compressive strength of concrete. This explains the decline in flexural strength when a high fibre content (1.5%) is utilized in concrete. Borg et al. (2016) [10], Mohammad et al. [11], and Meza et al. (2021) [18] have noted 7%, 15% and 21% improvement in the flexural strength of concrete. Ninan et al. (2018) [59] further noted that the flexural strength increased up to 0.75% fibre content (by weight of cement) after which the strength decreases.

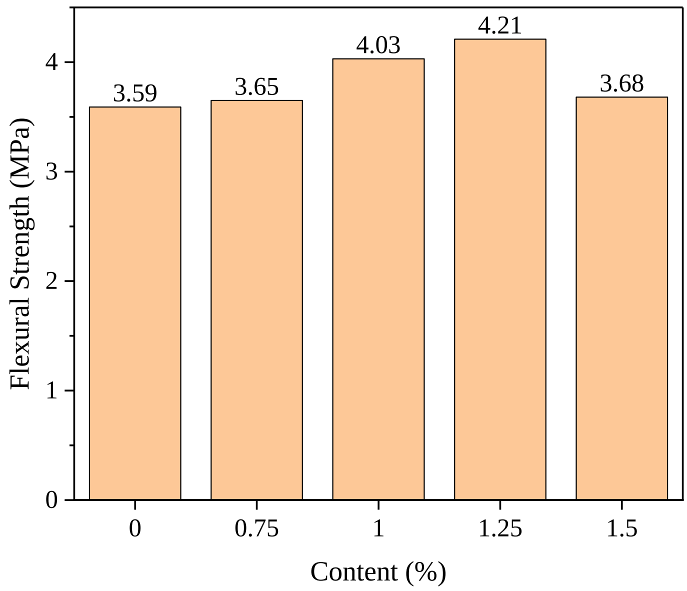


Figure 22. Flexural strength results for varying fibre content

At 1.25% fibre content, sand-coated fibres gave excellent results in terms of split tensile and flexural strength, with a slight reduction in the compressive strength of concrete. The following section gives the conclusions and recommendations for future research.

4. Conclusions

The following conclusions were derived from this study:

- This study presents a new way of modifying the bond properties of virgin PET fibres with superior tensile strength and elasticity. The performance of these fibres in concrete was superior to that of other surface-modified fibres based on tensile and flexural strength results. The split tensile strength improved by 9.49% while the flexural strength improved by 11.61% compared to the control mix. This can be attributed to their increased bonding capacity and elasticity.
- Sand-coated fibres reduced the workability of concrete compared to the other types of fibres, which reduces the compressive strength of concrete. A subsequent reduction was also noted with the increase in fibre length and fibre content. Superplasticizers should be used to improve the workability of PET fibre concrete to achieve maximum compaction and favourable strength.
- The optimum length for sand-coated fibres in terms of split tensile and flexural strength was 75 mm, with an increment of 13.76% and 12.49%, respectively. Fibre content of 1.25% showed the highest split tensile and flexural strength increments of 15.49% and 17.26%, respectively.
- However, at this fibre content, there is a 15.2% reduction in the compressive strength compared to the control and a 1.5% reduction compared to the lower limit of Grade 30 concrete. The use of these fibres should therefore be guided by the structural member of interest. Their use can be restricted to the tension zone of concrete members to avoid losses in the compressive capacity of structures.
- When determining the optimum fibre length, the fibre dosage was held constant, posing a limitation to the effect of varying fibre length and dosage at the same time. A correlation study can be carried out to predict the relationship between fibre length and dosage.

A microstructure study on the interaction of this new surface modified fibre is highly recommended to understand the interaction between the fibres and the cement paste in comparison with other types of fibres. Additional tests can be carried out to characterize the fibres, especially fibre pull out tests. Durability tests are also highly recommended for concrete samples made of these fibres to assess their performance under exposure to temperature, chloride ion penetration, and water permeability, among others.

5. Declarations

5.1. Author Contributions

Conceptualization, M.M.M., C.K., and N.G.; methodology, M.M.M.; formal analysis, M.M.M.; writing—original draft preparation, M.M.M.; writing—review and editing, C.K. and N.G.; supervision, C.K., and N.G.; All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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