Materials Research Express

Effects of hybrid polyethylene terephthalate fibre and fly ash on mechanical properties of concrete

N Z Nkomo, L M Masu and P K Nziu
Department of Industrial & Operations Management and Mechanical Engineering, Vaal University of Technology, Vanderbijlpark, South Africa
E-mail: zintinkomo@gmail.com

Abstract
Cracked concrete is a problem due to several factors such as poor maintenance, insufficient reinforcement or steel corrosion leading to crack propagation. There is a need to increase the load-bearing capacity of concrete and increase its life span. The use of waste polyethylene terephthalate fibres and fly ash in a hybrid concrete composite dramatically alleviates the problem of crack propagation and failure sustainably. This study aimed to optimize a waste polyethylene terephthalate fibre/fly ash hybrid cement composite. The concrete test specimens were fabricated using polyethylene terephthalate fibres and fly ash following a full factorial experimental design. The developed specimens were then tested to ascertain their workability and material strength properties. The combined effect of fibre addition and fly ash showed a general decreasing slump value for all quantities of fly ash content. The combined optimum compressive strength for fibre and fly ash was at 0.5% and 15%, respectively, with a strength of 15.54 N mm$^{-2}$. The optimum split tensile strength of 2.79 N mm$^{-2}$ was realised at 0.5% fibre and 20% fly ash mass fractions. The optimum flexural strength for fibre and fly ash mass fractions was obtained at 0.5% and 30%, respectively. The trend observed by the rebound number followed that of the compressive strength. However, the non-destructive rebound hammer method gave significantly lower strength values than the destructive test method.

1. Introduction
Concrete is relatively strong under compression but weak in tension and brittle [1]. The weakness in tension of concrete can be overcome through the use of reinforcement materials. The reinforcement can take the form of fibres which improve the toughness of the concrete and give resistance to crack propagation [2]. The use of synthetic fibres such as recycled polyethylene terephthalate provides an effective and relatively inexpensive reinforcement material for concrete [3]. Furthermore, the use of fibres in concrete reduces the concrete water absorption and improves the mechanical strength properties [4]. Concrete is susceptible to shearing forces that can cause the formation of cracks which can compromise the structure of the concrete. Reinforced concrete assist to maintain the structural integrity of the concrete structure [5]. Optimization of the fibre properties and volume fraction in reinforced concrete results in stronger concrete with lower reinforcement costs.

Plastic pollution is perceived as a universal threat to the ecology. This threat is largely attributed to the resilient nature of plastics against degradation. Plastic illegally dumped in the environment are a threat to wildlife and domestic animals through entanglement and ingestion of the waste plastic [6, 7]. Plastics despite the challenge of pollution are very popular due to their lightweight, durability, and being inexpensive. However, plastics after use, find their way into the environment as they tend to be single-use items [8]. This lack of recycling necessitates study and research into innovative and imaginative ways of reusing plastics. Furthermore, the scarcity of landfill space and the cost of managing such sites makes it necessary to find alternative methods to deal with plastic waste [9]. Plastic production worldwide has increased from 2 million metric tons a year in 1950 to well over 380 million tons by 2015 and this figure is expected to double by 2050 [10, 11]. The use of waste...
polyethylene terephthalate (PET) plastic in the reinforcement of concrete is one sustainable method for the disposal of plastic materials.

The use of fly ash in concrete has gained increased popularity over the past years. This is because of the improved durability, workability, and ecological benefits of using concrete containing fly ash in the mixture. Furthermore, advancements in thermal power station processes have also improved the quality of fly ash obtained, making it more suitable for cement composites [12]. Fly ash increases the durability of concrete by mitigating the alkali-silica reactions, increasing resistance to sulphate attack and reduced ingress of chloride and water [13]. Fly ash is normally used in volume fractions of between 0% – 30% in concrete mixtures [14]. Fly ash in concrete has been shown to reduce the quantity of water required in the concrete paste [15]. Additionally, due to the spherical nature of fly ash particles they act as a lubricant to the aggregates interface, reducing friction and increasing the workability of the fresh concrete. Generally, the higher the volume fraction of fly ash, the better the workability of the concrete mixture [16]. The workability of concrete is also linked to the water content. Moreover, fly ash lowers the required amount of water in the manufacture of concrete. Thomas (2007) [15] study established that partial replacement of cement with fly ash reduces the slump of concrete. The lower slump loss of concrete mixture containing fly ash can be attributed to the lower amount of water in the concrete containing fly ash.

The addition of synthetic fibres in concrete can significantly improve its mechanical properties without altering its density drastically [17, 18]. Therefore, synthetic fibre reinforced concrete is now favoured by many engineers. This is due to its strength to weight ratio and the favourable economics offered by reinforced concrete. Synthetic polymer reinforced concrete is suitable for domestic and industrial applications such as suspended slabs [19]. The advantages of the fabricated PET reinforced concrete in the present study are comparable to that found in other fibre reinforced polymer materials: lightweight, high strength, non-corrosive and non-magnetic [20]. Not much research has been done on the use of waste PET extruded fibres in process flow followed in the production of textile grade fibres and use of fly ash on concrete. Much research has been done on filaments and fibres produced by either simple shredding or cutting up PET bottles to use as reinforcement of concrete [21–23]. The present study evaluates the effect of hybridization of both fly ash and PET fibres in a fibre reinforced concrete composite (FRCC) and ascertains the mechanical strength effects of varying the mass fractions of these. The split tensile strength, compressive and flexural strength of the FRCC is studied in this research as well as the workability of the concrete mixture.

2. Materials and methods

2.1. Materials
The properties of the raw materials used in this study which include the fly ash, aggregates, PET fibres and fly ash are outlined in the following subsections. The water used in the manufacture of the fibre reinforced concrete was clean water from municipality treatment.

2.1.1. Cement
Suretech Portland cement CEM I 52,5N was used in this study and table 1 shows the important properties of the cement.

| Parameter                           | Physical properties | Result |
|-------------------------------------|---------------------|--------|
| Setting time:                       | Initial (mins)      | 125    |
|                                     | Final (hours)       | 2.5    |
|                                     | Specific Area       | 400    |
| (Blaine): m² kg⁻¹                   |                     |        |
| Compressive strength (mortar prism EN 196–1) | At 2 days (MPa)     | 28     |
|                                     | Relative density    | ±3.14  |
| Densities                           | Bulk density, aerated, kg m⁻³ | 1100–1300 |
|                                     | Bulk density, as packed, kg m⁻³ | ±1500  |
2.1.2. Polyethylene terephthalate fibres

Recycled PET fibres from Pet bottles were used in this study as shown in figure 1. The PET fibres were produced by recycling PET bottles and extruding the fibres through textile grade spinnerets and the fibre length restricted to 12 mm. The fibres used had the properties shown in table 2.

### Table 2. Properties of PET fibres [25].

| Property                  | Specification                                      |
|---------------------------|----------------------------------------------------|
| Description               | Thermoplastic fibre, round and uncrimped            |
| Fibre diameter            | 18 μm                                              |
| Fibre count per gram      | 231.4 for 12 mm fibre                              |
| Specific density          | 1.34–1.4                                           |
| Moisture regain           | 0.5%                                               |
| Tenacity at break         | 45 cN/Tex (+/− 5)                                  |
| Elongation at break       | 40% (+/−)                                          |
| Fibre tenacity at 10%     | >10 cN/Tex                                         |
| elongation                |                                                    |

**Figure 1.** Recycled PET fibres.

**Figure 2.** SEM image of fly ash particles.
2.1.3. Fly ash

The fly ash had a dark grey colour, with moisture regain of 0.5695%, which was considered low for Class F fly ash. The SEM morphology study showed that the fly ash had predominantly spherically shaped particles as shown in figure 2. This was expected to improve the workability of the concrete.

The fly ash particle sizes analysed by the particle size distribution machine (PSD) had sizes that ranged from 0.31 μm to 800 μm. Chemical analysis using EDS showed that the fly ash contained Ca, Al, P, Si, and trace amounts of Ti and Mg. The XRD pattern showed the presence of a large number of crystalline minerals like mullite (Al₆Si₂O₁₃) and quartz (SiO₂).

2.1.4. Fine aggregates

The fine aggregate characterisation showed that the river sand had a fineness modulus of 3.69, which is considered coarse sand. The river sand showed uniform particle size distribution with a uniformity coefficient of 4.007. The specific gravity of the river sand was calculated as 2.15, which was considered a bit low for fine aggregate.

2.1.5. Coarse aggregates

The coarse aggregate characterisation revealed that the size of the aggregate particle was between 9.5 mm and 13 mm. The coarse aggregate had a uniformity coefficient of 4.007, which implied the aggregate was well graded. The coarse aggregate had a high flakiness index of 74.82% and an acceptable elongation index of 46.72%. The water absorption of the coarse aggregate used was 0.80% with a specific gravity of 2.609, which is typical for coarse aggregates.

2.2. Mix design

A 2 factor and 5 level full factorial experimental design was used to ascertain the effect of mass fraction of the PET fibres and fly ash on mechanical properties of the concrete composite slab. A total of 25 experimental runs were generated using the full factorial experimental design of response surface methodology. The full factorial experimental design can be used to predict dependent variables, also known as responses by using a small number of experimental data points, with all the parameters varied within a preferred and set range. 5 level experimental design with two factors, namely mass fraction of the PET fibres and fly ash, was developed using

![Figure 3. Test specimens submerged in curing tank.](image)

**Table 3.** Composite experimental design with values X₀ of the independent variables.

| Variable | Parameters | Levels |
|----------|------------|--------|
| X₁       | PET Fibre Mass Fraction (%) | 0.0% 0.5% 1% 1.5% 2.0% |
| X₂       | Fly ash Mass Fraction (%)   | 0.0% 15% 20% 25% 30% |
Minitab Software Version 17. Each factor was varied over five levels as shown in table 3. The dependent variables included the slump value, compressive strength, flexural strength and split tensile strength.

Minitab software was then used to generate the multilevel full factorial experimental design followed in generating the test samples as shown in table 4.

The water to cementitious materials ratio was held constant throughout the mix design at 0.6 in order to ensure acceptable workability of the concrete mixture with fibre addition.

2.3. Fresh concrete mixture

The fresh concrete was mixed in accordance with SANS5861–1 [26]. The ambient temperature for the storage of raw materials was maintained between 22 °C and 25 °C. The Portland cement and sand was measured and blended for 3 min to obtain a homogeneous mixture. The fly ash and weighed PET fibres were then added to the mixture. Water was constantly added to the mixture until there was equal distribution. The concrete mix was then placed in an appropriate mould suitable for the various tests. The samples were covered with a damp hessian sack for 24 h and then demoulded and put into temperature-controlled water tanks at 23 °C ±/−2 °C for 28 days as shown in figure 3.

2.4. Experiments

2.4.1. Slump test

A representative composite sample was obtained in line with SANS 5861–2 [27] from the freshly mixed concrete sample. The slump test mould was then filled and tampered with a metal rod in accordance with the standard. The slump after demoulding was measured to the nearest 5 mm in accordance with the SANS standard.

The slump was calculated using equation (1) [27].

\[ \text{Slump} = h_m - h_s \]  

Where:

- \( h_m \) — Height of the mould in mm
- \( h_s \) — Height of the slumped test specimen in mm

| PET fibre mass fraction (%) | Fly ash mass fraction (%) | Design materials for FRCC |
|---------------------------|--------------------------|--------------------------|
|                           |                          | Cement Kg m\(^{-3}\) | Fine aggregate Kg m\(^{-3}\) | Coarse aggregate Kg m\(^{-3}\) | Fly ash Kg m\(^{-3}\) | Fibre Kg m\(^{-3}\) |
| 0                         | 0                        | 346.50                   | 519.75                       | 1093.50                      | 0.00                   | 0.00                     | 207.90 |
| 0                         | 15                       | 294.53                   | 546.75                       | 1093.50                      | 51.98                   | 0.00                     | 176.72 |
| 0                         | 20                       | 277.20                   | 546.75                       | 1093.50                      | 69.30                   | 0.00                     | 166.32 |
| 0                         | 25                       | 259.88                   | 546.75                       | 1093.50                      | 86.63                   | 0.00                     | 155.93 |
| 0                         | 30                       | 242.55                   | 546.75                       | 1093.50                      | 103.95                  | 0.00                     | 145.53 |
| 0.5                       | 0                        | 346.50                   | 546.75                       | 1093.50                      | 0.00                    | 9.93                     | 207.90 |
| 0.5                       | 15                       | 294.53                   | 546.75                       | 1093.50                      | 51.98                   | 9.93                     | 176.72 |
| 0.5                       | 20                       | 277.20                   | 546.75                       | 1093.50                      | 69.30                   | 9.93                     | 166.32 |
| 0.5                       | 25                       | 259.88                   | 546.75                       | 1093.50                      | 86.63                   | 9.93                     | 155.93 |
| 1.0                       | 0                        | 346.50                   | 546.75                       | 1093.50                      | 0.00                    | 19.87                    | 207.90 |
| 1.0                       | 15                       | 294.53                   | 546.75                       | 1093.50                      | 51.98                   | 19.87                    | 176.72 |
| 1.0                       | 20                       | 277.20                   | 546.75                       | 1093.50                      | 69.30                   | 19.87                    | 166.32 |
| 1.0                       | 25                       | 259.88                   | 546.75                       | 1093.50                      | 86.63                   | 19.87                    | 155.93 |
| 1.0                       | 30                       | 242.55                   | 546.75                       | 1093.50                      | 103.95                  | 19.87                    | 145.53 |
| 1.5                       | 0                        | 346.50                   | 546.75                       | 1093.50                      | 0.00                    | 29.80                    | 207.90 |
| 1.5                       | 15                       | 294.53                   | 546.75                       | 1093.50                      | 51.98                   | 29.80                    | 176.72 |
| 1.5                       | 20                       | 277.20                   | 546.75                       | 1093.50                      | 69.30                   | 29.80                    | 166.32 |
| 1.5                       | 25                       | 259.88                   | 546.75                       | 1093.50                      | 86.63                   | 29.80                    | 155.93 |
| 1.5                       | 30                       | 242.55                   | 546.75                       | 1093.50                      | 103.95                  | 29.80                    | 145.53 |
| 2.0                       | 0                        | 346.50                   | 546.75                       | 1093.50                      | 0.00                    | 39.74                    | 207.90 |
| 2.0                       | 15                       | 294.53                   | 546.75                       | 1093.50                      | 51.98                   | 39.74                    | 176.72 |
| 2.0                       | 20                       | 277.20                   | 546.75                       | 1093.50                      | 69.30                   | 39.74                    | 166.32 |
| 2.0                       | 25                       | 259.88                   | 546.75                       | 1093.50                      | 86.63                   | 39.74                    | 155.93 |
| 2.0                       | 30                       | 242.55                   | 546.75                       | 1093.50                      | 103.95                  | 39.74                    | 145.53 |
2.4.2. Rebound hammer test
A Rebound hammer test was carried out in accordance with ASTM C806–02 [28] using a Schmidt rebound hammer shown in figure 4. The test area was prepared before testing by grinding the surface flat. The test was then carried out by placing the plunger perpendicular to the test surface. Ten readings were taken from each test area on two opposite faces in the non-casting direction and the average calculated.

2.4.3. Compressive strength test
A compressive test was carried out in accordance with SANS 5836:2006 [29]. Steel cube moulds of dimensions 150 mm × 150 mm × 150 mm were used to cast the test specimens. The samples were cured for 28 days in the water tank and thereafter tested. Testing of the cubes was done on an ELE 1887B0001 compressive testing machine.

2.4.4. Flexural Strength test
The FRCC flexural strength and modulus was determined on a Versa beam press machine. ASTM C78 standard [30] was followed and a four-point loading flexural test was carried out. The beams cast for this test had dimensions of 150 mm × 150 mm × 510 mm.

The flexural strength of the fibre reinforced concrete sample was then ascertained by subjecting the sample to flexure under transverse load at a loading rate of 6.3 kN min⁻¹ until the sample failed. The modulus of rupture was calculated as shown in equation 2.

\[ R = \frac{PL}{bd^2} \] (2)

Where
- \( R \)—The modulus of rupture (MPa)
- \( P \)—The maximum applied load indicated by the testing machine (N)
- \( L \)—Span length (mm)
- \( b \)—The width of the specimen in millimetres (mm)
- \( d \)—The depth of the specimen in millimetres (mm)

2.4.5. Split tensile strength test
The split tensile test was carried out on Model number 1887B0001 ELE machine in accordance with ASTM C 496–96 [31]. The split tensile strength test applied a compressive force diametrically along the length of the concrete cylinder until failure. This force resulted in the load inducing tensile stresses on the plane with the load and high compressive stresses in the area surrounding the applied load. Thus, tensile failure of the specimen occurred rather than compressive failure. Metal strips on which the force was applied were placed on top and below the concrete cylinder using marked diametric lines. The rate of loading used was 690 kPa min⁻¹, and the splitting tensile strength was calculated using equation 3.
Where:
- \( T \) — Splitting tensile strength (N mm\(^{-2}\))
- \( P \) — Maximum applied load indicated by the testing machine (kN)
- \( l \) — Length in (m)
- \( d \) — Diameter in (m)

3. Results and discussion

3.1. Effect of PET fibre and fly ash on concrete workability

The graph in figure 5 shows the combined effect of PET fibre and fly ash on the slump value in fresh FRCC mixture.

As observed in figure 5 the slump value dropped drastically from the control specimen with an increase in fibre content regardless of the quantity of fly ash added to the concrete mixture. However, the mixture containing a lower fly ash content had a slightly higher slump value compared to corresponding higher fly ash content for 0.5% fibre content. The mixture containing 15% fly ash content recorded a slump value of 15.00 mm. The mixtures containing 20%, 25% and 30% fly ash recorded slump values of 12.00 mm, 11.00 mm, 10 mm respectively for 0.5% PET fibre content. However, upon the addition of 1% fibre content regardless of the fly ash content, the slump value dropped to zero. Any further addition of fibre beyond 1% resulted in an insignificant slump value.

As expected, the lower slump values realised with the addition of fibre resulted in reduced workability of the concrete mixture and made placing of the concrete increasingly difficult with higher fibre content. From 1% addition of PET fibre, the workability became a significant problem. The FRCC containing 2% fibre addition gave a very harsh concrete mixture that was extremely difficult to work with coupled with significant fibre clumping. Fibre clumping started being a significant problem from 1.5% fibre addition. The results obtained for all levels of fly ash addition show decreased workability with increase in the fibre loading percentage. This conclusion has been reached in previous studies [32–37]. Adding incremental fibres into the concrete mixture enhances the internal friction between the concrete ingredients leading to reduced workability. Furthermore, the use of PET fibres increases the surface area that is required to be covered by the concrete paste. Research by Daewood et al (2021) [21] attributed the decrease in slump value with incremental fibre to the large surface area of the PET fibres leading to saturation of the PET fibre surface with water. This phenomenon leads to drying out of the concrete mixture and reduces its workability. This increase in surface area reduces the workability of the concrete drastically at fibre mass fractions above 1.0%. A study by Ahmad et al (2021) [38] reported a similar trend with the slump value of the concrete paste dropping drastically above 0.5% and necessitating adjustment to the water/cement ratio to increase the workability. A study by Wang et al (2019) [39] also concluded that workability decreased drastically from 0.40% fibre mass fraction addition. Slump value can be increased by adding more water or other additives. However, the addition of more water compromises the ultimate strength.

\[
T = \frac{2P}{\pi ld}
\]
properties of the concrete. Furthermore, the addition of more water into the mixture tends to result in aggregate separation.

3.2. Effect of PET fibre and fly ash on rebound number

The graph in figure 6 shows the effects of PET fibre and fly ash on the FRCC rebound number.

The rebound number for the FRCC containing 25% fly ash has the highest rebound number of 21.5 at 0.5% PET fibre addition which is marginally higher than that of the control specimen, which had a rebound number of 21.1. Thereafter, there is a sharp drop in the rebound number with 1.0% fibre addition to the lowest rebound number for 25% fly ash content of 12.5. Further addition of PET fibre results in a drastic increase in the rebound number to 21.4 at 1.5% fibre addition. Addition of 2.0% fibre results in another drop in the rebound number to 14.7.

The specimen containing 20% fly ash had a steady drop in the rebound number with the addition of fibre up to 1.0%. Further addition of fibre content to 1.5% resulted in a drop in rebound number from 17.0 to 16.9. On the other hand, the addition of fibre to 2.0% resulted in a slight increase in rebound number to 17.3.

The specimen containing 30% fly ash had a similar trend to the sample with 20% fly ash. The rebound number dropped with the addition of fibre to 16.0 for 0.5% fibre content. Thereafter, the addition of 1.0% fibre
content slightly decreased the rebound number to 15.6. In contrast, further addition of fibre gave an increase in rebound number to 16.6 and thereafter a decrease with further addition of fibre.

The specimen containing 15% had a decreasing trend with an increase in fibre content. This trend was different to that observed in other specimens containing higher quantities of fly ash which had a fluctuation in the trend at 1.5% fibre addition. The specimen containing 15% fly ash had a decrease in rebound number to 20.0 for 0.5% fibre content which was identical to the rebound number obtained for 0.5% fibre addition with 30% fly ash content. Thereafter, the rebound number dropped to 15.6 for 1.0% fibre content, which was lower than the rebound number realised for 1.0% fibre addition for 30% fly ash content FRCC. Further, the addition of PET fibre resulted in a steady decline in rebound numbers to 13.8 and 11.9 for PET fibre content 1.5% and 2.0%, respectively.

The rebound number has a correlation to the concrete compressive strength. However, the trend observed for rebound number varied with that of the destructive compressive strength test. This variation could be attributed to the randomly distributed fibre content as well as the air voids created within the concrete especially at higher fibre percentages. Research by Kazemi et al (2020) [40] reported a similar variation in fibre reinforced concrete rebound number compared to the destructive compressive strength test. Furthermore, the rebound calculated compressive strength is consistently lower than the actual destructive compressive strength for the same reasons.

### 3.3. Effect of PET fibre and fly ash on composite compressive strength

The graph in figure 7 shows the effect of PET fibre addition on various fixed percentages of fly ash and the relationship with the 28-day compressive strength.

The addition of both fibre and fly ash in the FRCC had an adverse effect on the compressive strength. For all samples in the experimental design, the combined addition of fly ash and PET fibre decreased the ultimate compressive strength.

The FRCC containing 15% fly ash had a sharp decline in compressive strength of 34.8% within the first 0.5% fibre addition, with strength dropping from the control of 23.84 N mm⁻² to 15.54 N mm⁻². After that, there was a marginal 5.9% drop in compressive strength between 0.5% and 1.0%. There was a constant decline in compressive strength from 1.0% to 2%.

The FRCC containing 20% fly ash had an almost constant decline in compressive strength up to 1.0% fibre addition. However, this composition had the best overall compressive strength compared to the other samples with different fly ash content. There was a drastic decrease in compressive strength between 1.0% and 1.5% from 15.96 N mm⁻² to 8.50 N mm⁻², respectively. However, the compressive strength picked up with the addition of more fibre with 2.0% fibre addition having a strength of 15.53 N mm⁻².

The FRCC containing 25% ash exhibited a similar trend to that containing 20% up to 1.0% fibre content. This was the third strongest mix design containing fly ash. From 1.0% to 2.0% fibre addition, there was an almost constant and marginal decrease in compressive strength.

The FRCC containing 30% exhibited the lowest compressive strength at 0.5% fibre addition of all the specimens. However, from 0.5% to 1.5%, there was an increase in compressive strength, which surpassed that of
mix design with 25% at 0.5% and was greater than all other mix designs at 1.5%. But, from 1.5%, there was a decline in compressive strength to 7.44 N mm$^{-2}$.

The graph in figure 8 shows the combined effect of fibre and fly ash on the compressive material stress of the specimens.

The trend observed for the stress on the FRCC was like that of the compressive strength in figure 7. The results show that the addition of PET fibres has an adverse effect on the compressive strength regardless of the fly ash quantity used. This conclusion is reasonable as several researchers [41–44] have reported a similar decrease or lack of improved compressive strength concrete with the addition of polymeric and natural fibres. The poor compressive strength with PET fibre reinforced concrete can be attributed to a poor interfacial bond between the fibre and cement matrix. Furthermore, the increase in porosity in the concrete mixture can be a significant contributing factor, as stated in Jiang et al (2014) [45] study. A study by Ahmad et al (2021) [38] attributed the decrease in compressive strength to decrease in workability adversely affecting the compaction process leading to pores in the hardening concrete. This phenomenon was observed in the current study with addition of fibres above 0.5% leading to voids forming in the hardening concrete. However, the addition of steel fibres into the concrete slightly increases the compression strength. This increase in strength can be attributed to the stiffness of the steel fibres compared to flexible polymeric fibres. Another study by Prahallada and Prakash (2013) [46] investigated the effect of waste fibre reinforced concrete and fly ash on the compressive strength of concrete. The study reported that there was a decrease in compressive strength with all combinations, and this agreed with the results obtained in this study. There is a need to study the effect of a hybrid FRCC containing both steel fibres and PET fibres to ascertain the improvement, if any, in the compressive strength of the composite.

3.4. Effect of PET fibre and fly ash on composite flexural strength

The graph in figure 9 shows the combined effects of fly ash and PET fibre on the FRCC flexural strength.

The FRCC containing 15% cement replacement with fly ash showed the highest flexural strength at 0.5% PET fibre addition of 3.220 N mm$^{-2}$. Further addition of PET fibre decreased flexural strength with 1% PET fibre addition giving 2.825 N mm$^{-2}$. This strength was still greater than the control specimen flexural strength of 2.820 N mm$^{-2}$. Further addition of PET fibre to 1.5% resulted in a slight increase in flexural strength to 1.960 N mm$^{-2}$. The addition of PET fibre to 2.0% resulted in a drastic decrease in flexural strength to 2.335 N mm$^{-2}$ which was less than observed in the control specimen.

PET fibre addition of 0.5% and 20% fly ash content resulted in all the specimens lowest flexural strength. However, the flexural strength obtained of 3.125 N mm$^{-2}$ was still greater than the control specimen of 2.820 N mm$^{-2}$. There was a slight increase in flexural strength with 1.0% PET fibre. The addition of 1.5% PET fibre resulted in a slight decrease in flexural strength to 2.930 N mm$^{-2}$. However, the addition of 2.0% PET fibre resulted in a significant increase in flexural strength to 3.995 N mm$^{-2}$. This magnitude was the highest flexural strength realised for the 20% fly ash composite.

The specimen containing 25% fly ash had the second-highest flexural strength at 0.5% PET fibre addition of 3.625 N mm$^{-2}$. There was a slight increase in flexural strength with 1.0% PET fibre to 3.70 N mm$^{-2}$. After that, any further addition of PET fibre resulted in a decline in flexural strength with 1.5% PET fibre addition giving
flexural strength of $2.20 \text{ N mm}^{-2}$. This magnitude was less than the control specimen, which had a flexural strength of $2.820 \text{ N mm}^{-2}$. Besides, the addition of 2.0% PET fibre gave flexural strength of $1.885 \text{ N mm}^{-2}$. The FRCC containing 30% fly ash had the highest flexural strength of $4.47 \text{ N mm}^{-2}$ with 0.5% PET fibre addition. Further addition of PET fibre resulted in a decrease in flexural strength with 1.0% PET fibre addition giving flexural strength of $3.72 \text{ N mm}^{-2}$. In contrast, the addition of 1.5% fibre gave a moderate increase in flexural strength to $3.84 \text{ N mm}^{-2}$. Further addition of 2.0% fibre content drastically decreased flexural strength to $2.25 \text{ N mm}^{-2}$.

The overall optimum flexural strength was obtained with the specimen containing 30% fly ash at 0.5% PET fibre addition which had a strength of $4.47 \text{ N mm}^{-2}$. This optimum had an increase of 37% in flexural strength over the control specimen. The high quantity of fly ash at 30% increased the workability of the concrete mixture allowing good compaction at 0.5% fibre content resulting in the highest flexural strength at this point. The mixture containing 15% had the lowest flexural strength at all fibre percentages due to the lower workability in comparison to the mixtures containing higher fly ash content. This trend agrees with study by Singh et al (2020) [22] and Kassa et al (2019) [37] who reported a higher flexural strength at high fly ash content and low fibre reinforcement content.

### 3.5. Effect of PET and fly ash on composite split tensile strength

The graph in figure 10 shows the combined effects of fibre and fly ash addition on the split tensile strength of the FRCC.

The FRCC containing 20% fly ash had the highest flexural strength at 0.5% PET fibre addition with a splitting tensile strength of $2.79 \text{ N mm}^{-2}$ compared to the control specimen with the strength of $0.90 \text{ N mm}^{-2}$. However, there was a gradual reduction in the split tensile strength with the further addition of PET fibre. The addition of 1.0% PET fibre gave a split tensile strength of $2.69 \text{ N mm}^{-2}$. Further, the addition of PET fibre reduced the split tensile strength even further, with 1.5% PET fibre addition giving the strength of $2.34 \text{ N mm}^{-2}$ and 2.0% PET fibre giving a strength of $1.11 \text{ N mm}^{-2}$.

The FRCC containing 15% fly ash had a significantly high split tensile strength of $2.70 \text{ N mm}^{-2}$ at 0.5% addition of PET fibre. This FRCC exhibited a similar trend for 0.5% PET fibre addition with the FRCC containing 30% fly ash. Further PET fibre addition to 1.0% resulted in a sharp decrease in the split tensile strength to $1.77 \text{ N mm}^{-2}$. After that, there was a slight decrease in split tensile strength with increased PET fibre content with 2.0% PET fibre content having a split tensile strength of $1.19 \text{ N mm}^{-2}$. However, this split tensile strength was still higher than that observed on the control specimen, which was $0.90 \text{ N mm}^{-2}$.

The FRCC containing 25% fly ash content had a marginal increase in split tensile strength with the addition of 0.5% PET fibre giving a strength of $1.48 \text{ N mm}^{-2}$. After that, a decrease in strength was observed with 1.0% PET fibre content giving a strength of $1.29 \text{ N mm}^{-2}$. There was a sharp decline in strength with 2.0% PET fibre content which gave the strength of $0.44 \text{ N mm}^{-2}$, which was way less than the control specimen split tensile strength of $0.90 \text{ N mm}^{-2}$.

The FRCC containing 30% fly ash had the lowest split tensile strength at PET fibre content of between 1.0% and 1.5%. PET fibre addition of 0.5% yielded the highest strength for the fly ash ratio giving a strength of
1.16 N mm$^{-2}$. After that, the trend was indicative of a steady decline in the split tensile strength with 1.0% PET fibre yielding 1.03 N mm$^{-2}$ and 1.5% PET fibre content giving the strength of 0.98 N mm$^{-2}$. PET fibre addition of 2% gave the lowest split tensile strength of 0.89 N mm$^{-2}$.

The addition of fibres significantly altered the failure pattern of the concrete. The concrete containing fibres had a complex crack propagation due to the bridging and retardation effect of the fibres. This phenomenon made the concrete, despite being weaker to be able to withstand load for longer before failure. This analogy agrees with a study by Truong (2012) [47] and Vu et al (2020) [48], who reported that fibre content is mainly used for crack control and used in percentages less than 0.3. The addition of fibres beyond 0.5% percent regardless of the fly ash quantity resulted in a decrease in split tensile strength. This phenomenon was observed by several researchers [22, 38, 49] and is attributed to the formation of voids or pores within the hardened concrete at high fibre content percentages. These pores create nucleus sites for crack propagation and adversely affect the split tensile strength.

The samples containing the lowest fly ash content gave higher split tensile strength which was in contrast to what was noted for flexural strength. Several researchers [30–55] noted the same trend of reduction in concrete flexural strength with increase in fly ash content. This phenomenon can be attributed to the bond strength of the fly ash compared to the cement that it has replaced. The failure mode observed was mainly fibre pull out at high percentages of fly ash. This drastically affected the strength of the concrete as the fibres were not being utilised to the maximum of their capabilities as reinforcement.

4. Conclusion

The study investigated the effect of addition of varying mass fraction of PET fibre and fly ash on the mechanical properties of concrete slabs. Based on the experimental results carried out in the study the following conclusions can be drawn

i. The combined effect of fibre addition and fly ash showed a general decreasing slump value for all amounts of fly ash content. The use of lower amounts of fibres less than 0.5% gave acceptable workability of the FRCC. Therefore, it is recommended to maintain less than 0.5% fibre content to have acceptable concrete workability.

ii. A comparison between the destructive and non-destructive rebound hammer test was done and showed that the non-destructive test gave significantly lower strength of between 20%–40%. This showed the need to accurately map a relationship between the destructive and non-destructive test to use the rebound hammer test for compressive strength approximation. The rebound number for the FRCC containing both fibre and fly ash followed a similar trend to that of the compressive strength test.

iii. The combined addition of PET fibre and fly ash gave the highest compressive strength at 20% fly ash and 0.5% PET fibre addition.

iv. The combined addition of 0.5% PET fibre addition and 20% fly ash gave the highest split tensile strength of 2.7 N mm$^{-2}$. The mix ratio containing 30% fly ash had the lowest split tensile strength at all PET fibre additions.

v. The combined addition of 0.5% PET fibre and 30% fly ash gave the highest flexural strength. However, all the other specimens containing fly ash ranging from 15% to 25% gave satisfactory flexural strength at 0.5% fibre addition. Thereafter, there was a drop in the flexural strength with increased PET fibre addition beyond 0.5%.

vi. Keeping these results in mind, PET and fly ash FRCC can be used in various slabs such as ceiling and floor slabs in low fibre mass fractions of <0.5%. The current study shows the feasibility of recycling PET bottles through chemical textile grade process and extrusion to give fibres that are effective in the reinforcement of concrete. There is, however, need for further research into the use of surface treated PET fibres to increase its bond strength to the concrete paste. Surface treatment of the PET fibres has the possibility of yielding higher FRCC mechanical strength properties.

Acknowledgments

This research work was supported by the Vaal University of Technology. The authors wish to thank the department of Industrial Engineering & Operations Management and Mechanical Engineering at Vaal University of Technology for facilitating this work.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Funding statement

This research was funded by the Vaal University of Technology department of Industrial Engineering & Operations Management and Mechanical Engineering.

Conflicts of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

ORCID iDs

N Z Nkomo @ https://orcid.org/0000-0002-7085-0276

References

[1] Amit R and Joshi Y P 2014 Applications and properties of fibre reinforced concrete Int. Journal of Engineering Research and Applications 4 123–31
[2] Zainal S M, Hejazi F, Aziz F N and Jaafar M S 2022 The synergetic effects of different types of hybridized synthetic fibers on concrete post-crack residual strength KSCE J. Civ. Eng. 26 131–42
[3] Silgado S S, Valdiviezo L C, Domingo S G and Roca X 2018 Multi-criteria decision analysis to assess the environmental and economic performance of using recycled gypsum cement and recycled aggregate to produce concrete: the case of Catalonia (Spain) Resour. Conserv. Recycl. 133 120–31
[4] Nibadey R N, Nagaralk P B, Parbat D K and Pande A M 2013 A model for compressive strength of PET fibre reinforced concrete American Journal of Engineering Research 2 367–72
[5] Roussan R Z, Alhassan M A and Al-Salman H 2017 Impact resistance of polypropylene fiber reinforced concrete two-way slabs Struct. Eng. Mech. 62 373–80
[6] Signorini C, Marinelli S, Volpini V, Nobili A, Radi E and Rimini B 2022 Performance of concrete reinforced with synthetic fibres obtained from recycling end-of-life sport pitches Journal of Building Engineering 53 1–11
[7] Foti D 2013 Use of recycled waste pet bottle fibers for the reinforcement of concrete Compos. Struct. 96 396–404
[8] Coffin S, Wyer H and Leapman J C 2021 Addressing the environmental and health impacts of microplastics requires open collaboration between diverse sectors PLoS Biol. 19
[9] Ming Y, Chen P, Li L, Gan G and Pan G 2021 A comprehensive review on the utilization of recycled waste fibers in cement-based composites Materials 14 1–28
[10] Geyer R, Jambeck J R and Law K L 2017 Production, use, and fate of all plastics ever made Sci. Adv. 3 1–5
[11] Gross L and Enck J 2021 Confronting plastic pollution to protect environmental and public health PLoS Biol. 19 1–3
[12] Kesharwani K C, Biswas A K, Chaurasiya A and Rabbani A 2017 Experimental study on use of fly ash in concrete International Research Journal of Engineering and Technology 4 1227–30
[13] Hill R L and Folliard K J 2006 Fly ash on air-entrained concrete Concr. in focus 7 51–2
[14] Crouch T L, Hewitt R and Byard B 2007 High volume fly ash concrete High volume fly ash concrete World of Coal Ash (WOCA) 1 (Northern Kentucky, 7–10 May 2007) 1–14
[15] Thomas M 2007 Optimizing the use of fly ash in concrete Portland Cement Association 54 1–24
[16] Zulu S and Aloppi D 2015 Optimising the usage of fly ash in concrete in the construction in the construction of roadworks Proceedings of the 34th Southern African Transport Conference (SATC 2015) 165–74
[17] Yew M K, Mahmoud H B and Ang B C 2015 Influence of different types of polypropylene fibre on the mechanical properties of high-strength oil palm shell lightweight concrete Constr. Build. Mater. 90 36–43
[18] Yap S P, Alangarmur U J and Jumaat M 2013 Enhancement of mechanical properties in polypropylene– and nylon–fibre reinforced oil palm shell concrete Mater. Des. 49 1034–41
[19] Khan M and Ali M 2016 Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks Constr. Build. Mater. 125 800–8
[20] Ebead U and Marzouk H 2004 Fiber-reinforced polymer strengthening of two-way slabs Fibre Plast Con, (Pretoria: South African Bureau of Standards) 14 1–13
[21] Singh A and Khandelwal V 2020 To study the effect of pet fiber (polyethylene terephthalate fiber) on geopolymer concrete by using GBFS and fly ash International Journal of Engineering Research & Technology (IJERT) 9 170–7
[22] Vaccaro P A, Glavin A P, Ayuso J, Barbudo A and Uceda A L 2021 Mechanical performance of concrete made with the addition of recycled macro plastic fibres Appl. Sci. 11
[23] PPC 2018 Product datasheet PPC Sulcarex 55,5N Cement, (Johannesburg: PPC)
[24] Eco Ace 2020 Fibre Plast Con, (Johannesburg: Eco Ace)
[25] SANS5861-1 2006 Mixing of fresh concrete in the laboratory (Pretoria: South African Bureau of Standards)
[26] S. 5861-2:2006 2006 Sampling of freshly mixed concrete, (Pretoria: The South African Bureau of Standards)
[27] ASTM C 606-02 2004 Standard test method for rebound number of hardened concrete (West Conshohocken: ASTM International)
[28] SANS S 836:2006 2006 Concrete tests - Compressive strength of hardened concrete, (Pretoria: The South African Bureau of Standards)
[30] ASTM C78-00 2004 Standard test method for flexural strength of concrete (using simple beam with third point loading) (West Conshohocken: ASTM International)
[31] ASTM C496/C496M-04 2017 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (West Conshohocken: ASTM International)
[32] Ismail Z Z and Al-Hashmi F A 2007 Use of waste plastic in the concrete mixture as aggregate replacement J. Waste Manag 28 2041–7
[33] Albano C, Camacho N, Hernandez M, Mathurs A and Gutierrez A 2009 Influence of content and particle size of per waste bottles on concrete behaviour at different w/c ratio, Waste Manag 29 2707–16
[34] Ashdarpour A M, Nikoudel M R and Taheri M 2016 The effect of using polyethylene terephthalate particles on physical and strength-related properties of concrete; a laboratory evaluation Constr. Build. Mater 109 55–62
[35] Rahman E, Dehestani M, Beryg M H, Allahyarhi H and Nābkī M 2013 On the mechanical properties of concrete containing waste PET particles Constr. Build. Mater 47 1302–8
[36] Almeshal I, Tayeb B A, Alyousef R, Alabduljabbar H and Mohammed A M 2020 Eco-friendly concrete containing recycled plastic as partial replacement for sand J. Mater. Res. Technol 9 4631–43
[37] Kassa R B, Kanali C and Ambassah N 2019 Engineering properties of polyethylene terephthalate fibre reinforced concrete with fly ash as partial cement replacement Civil and Environmental Research 11 25–34
[38] Ahmad J, Aslam F and Garcia M R 2021 Mechanical performance of concrete reinforced with polypropylene fibers (PPFs) J. Eng. Fibers Fabrics 16 1–17
[39] Wang X, He J, Mosallam A S, Li C and Xin H 2019 The effects of fiber length and volume on material properties and crack resistance of basalt fiber reinforced concrete (BFRC) Adv. Mater. Sci. Eng. 1–17
[40] Kazemi M, Haiforoush M, Talebi P K and Li J 2020 In-situ strength estimation of polypropylene fibre reinforced recycled aggregate concrete using schmidt rebound hammer and point load test Journal of Sustainable Cement Based Materials 9 1–33
[41] Exeldin A S and Balaguru P N 1992 Normal and high-strength fiber-reinforced concrete under compression J. Mater. Civil Eng. 4 415–529
[42] Fanella D A and Naaman A E 1985 Stress-strain properties of fiber reinforced mortar in compression ACI J 82 475–83
[43] Shaikh F U and Taweel M 2015 Compressive strength and failure behaviour of fibre reinforced concrete at elevated temperatures Advances in Concrete Construction 3 283–93
[44] Kim S B, Yi N H, Kim H Y, Kim J H and Song Y C 2010 Material and structural performance evaluation of recycled PET fiber reinforced concrete Cem. Concr Compos 32 232–40
[45] Jiang C, Fan K, Wu F and Chen D 2014 Experimental study on the mechanical properties and microstructure of chopped basalt fibre reinforced concrete Mater. Des. 58 187–93
[46] Prahallada M C and Prakash K B 2013 Effect of addition of flyash on the properties of waste plastic fibre reinforced concrete—an experimental investigation International Journal of Scientific Engineering and Technology 2 87–95
[47] Truong D G 2012 An experimental study of the influence of PP fibers used in concrete to limit the crack widths in bending reinforced concrete structures MSC-2012 Conf.
[48] Vu H H, Truong D G and Nguyen T T 2020 The application of polypropylene fiber for reinforced concrete beams and slabs IOP Conference Series: Materials Science and Engineering 869 1–7
[49] Ahmad J, Manan A and Ali A 2020 A study on mechanical and durability aspects of concrete modified with steel fibers (SFs) Civ Eng Archit 8 814–23
[50] Mahajan L and Bhagat S 2021 Effect of fly ash and bottom ash on the ratio of splitting tensile strength to compressive strength of concrete IOP Conf. Series: Materials Science and Engineering 1870 012032
[51] Tipraj R, Guru P M, Prasanna L E, Priyanka A and Hugar P K 2019 Strength characteristics of concrete with partial replacement of cement by fly ash and activated fly ash International Journal of Recent Technology and Engineering (IJRTE) 8 4299–305
[52] Arifi E, Cahya E N and Remayanti C N 2017 Effect of fly ash on the strength of porous concrete using recycled coarse aggregate to replace low-quality natural coarse aggregate J. Adv. Max. Oper. Proc. 1887 1–8
[53] Wong H L 2021 Effect compressive strength and split tensile strength of concrete using aggregate from tana toraja district with fly ash substitution IOP Conf. Ser.: Earth Environ. Sci. 9211 1–9
[54] Madhavi T C, Raju S L and Mathur D 2014 Durability and strength properties of high volume fly ash concrete Journal of Civil Engineering Research 4 7–11
[55] Taberkhani H 2014 An investigation on the properties of the concrete containing waste PET fibers International Journal of Science and Engineering Investigations 3 37–43