Optimization of recycled polyethylene terephthalate plastic bottle fibers in grasscrete

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Abstract. Cement and concrete production account for between 5% to 8% of global CO2. Waste PET plastic and glass waste have also brought about rapid environmental degradation. Glasscrete was developed with glass powder of fewer than 75 microns (has pozzolanic properties) that performed 14% better than concrete at 90 days. So, to further this effort, this experimental research considered the glass create C20 (at 10% cement replacement) and added PET fibers (of aspect ratio 25) at different percentages of 1%, 2%, 3%, and 4% the weight of cement in a bid to optimize the grasscrete performance and its ability to absorb PET waste. Glasscrete being extremely brittle alone, failed by cracking at all percentage PET additions, thus improving its safety factor. A 1% PET fiber addition to grasscrete exhibited the highest strength properties compared to other percentage additions while having a durability of 1.5% better than concrete. It is thus recommended for structural uses as it outperforms concrete. Despite this, a 1% fiber addition decreased grasscrete's compressive strength by at least 3.5% at 28 days and 6% at 90 days but improved the flexural strength by 5.4% at 28 days and 0.8% at 90 days testing.

1. Introduction
Globally, fourteen million tons of waste glass and three hundred and eighty-one tons of waste plastic are disposed of annually [1]. 11 billion tonnes of concrete are consumed annually, making it the most used construction material in the world and contributes between 5% and 8% global CO2 emissions [2]. To conserve the environment, engineers have constantly developed various ways to utilize recycled materials such as glass and plastics in various civil engineering applications. Studies have employed recycled polyethylene terephthalate bottles (PET) fibers in concrete and have recorded significant improvements in their mechanical properties [3]–[5].

This research will focus on finding improvements in the mechanical properties of grasscrete by the addition of recycled PET plastic fibers. So, engineers can better understand its performance in the field, especially in structural members. It will increase not only the recycling capacity of grasscrete but also its sustainability.
2. Methodology
The primary constituents used include water, cement, fine and coarse aggregates, glass, and plastic bottle fibers. Concrete of class 20 with mixing ratios as per mix design was adopted. Also, the addition of the plastic bottle fibers to grasscrete was studied. A naming system and mix design for the samples, as shown in table 1, was used.

Table 1. Mix design for 1 m³ of concrete.

| Batch | Cement (kg) | Sand (kg) | Coarse Aggregates (kg) | Water (kg) | PET Fibres (kg) | Glass Powder (kg) |
|-------|-------------|-----------|------------------------|------------|-----------------|-------------------|
| CON   | 254.5       | 375.1     | 712.4                  | 127.3      | -               | -                 |
| G10   | 229.1       | 375.1     | 712.4                  | 127.3      | -               | 25.5              |
| F1    | 229.1       | 375.1     | 712.4                  | 127.3      | 2.5             | 25.5              |
| F2    | 229.1       | 375.1     | 712.4                  | 127.3      | 5.1             | 25.5              |
| F3    | 229.1       | 375.1     | 712.4                  | 127.3      | 7.6             | 25.5              |
| F4    | 229.1       | 375.1     | 712.4                  | 127.3      | 10.2            | 25.5              |

where;
- G10: Glasscrete with 10% cement replacement with glass powder <75µm as reference
- CON: Concrete C20
- F1: G10 with 1% PET fibre addition
- F2: G10 with 2% PET fibre addition
- F3: G10 with 3% PET fibre addition
- F4: G10 with 4% PET fibre addition

From a concrete C20 (CON) of mix design in table 2, a modification of 10% cement replacement with glass powder <75µm (G10) is derived as the reference. G10 is further modified with PET fiber addition in varying percentages from F1 to F4. All these simulate a possible substitution of the concrete (CON) with grasscrete (G10) or a fiber-reinforced grasscrete F (1-4) without any change in fine or coarse aggregates quantities.

2.1. Water
The experiment tried to mimic the natural condition on-site, and therefore ordinary tap water was utilized. Water was batched a few minutes before it prevents massive evaporation. The water flowed steadily during the mixing process to allow for a constant temperature for a particular mix.

2.2. Cement
Grade 32 PPC was used throughout the experiments. This was sourced from a local cement factory.

2.3. Fine aggregates
All the sand used throughout this experiment conformed to BS 812:1992 for fine aggregates in concrete. All the sand used in this experiment was locally sourced.

2.4. Coarse aggregates
All the aggregates to coarse aggregates used conformed to the BS 882:1992 for 20 mm type aggregates in concrete. Their maximum size was 20 mm and the minimum 5mm. Anything smaller was expelled using the wet sieving procedure. All aggregates were sourced from locally crushed limestone.
2.5. Glass
The waste glass used was primarily obtained from glass soda bottles and sourced from a local Beverages company. It was crushed, as shown in figures 1 and 2.

Once collected, these bottles were adequately washed and crushed using a fabricated steel mortar and pestle to achieve a glass particle size of ≤75µm that could act as a cement replacement with pozzolanic properties. This glass was continually crushed and sieved until the desired size was obtained.
2.6. Recycled PET plastic bottle fibers
PET plastic bottles were collected from used plastic soda bottles in homes and a local beverages company stockpile, then recycled to fibers, as shown in figure 3.

![Image of PET waste bottle and fibers]

**Figure 3.** Waste PET bottle shred stages.

After the PET bottles were washed, they were rolled through a workshop fabricated cutting machine blade to make 5mm wide thread rolls of 300 mm circumference. These rolls were then cut at three arches of 100 mm, each achieving a size aspect ratio of 25, which is the main focus of this study.

2.7. Moulds and curing tank
After the material acquisition, molds were hired from the laboratory using 150x150x150 mm for cubes and 150x150x450 mm for beams. A 10,000-litre concrete curing tank of the laboratory was used to cure the cubes and beams. All curing was done by complete water submersion until testing time.

2.8. Tests
The testing cubes were cast following acceptable international standards, maintained at 20±5°C (ASTM C 31), protected from moisture loss, and then moved to the testing laboratory after a minimum of 20 hours of curing.

The tests were carried out on the concrete at 0 hours, 7 days, 14 days, 28 days, and 90 days accordingly, as shown in table 2.
Table 2. Test performed and their timing.

| Tests               | Machine/Instrument used                  | Days |
|---------------------|----------------------------------------|------|
| Fresh Properties    |                                        | 0    | 7   | 14  | 28  | 90  |
| Slump               | Slump cone test set                     |      |     |     |     |     |
| Hardened Properties |                                        |      |     |     |     |     |
| Compressive         | Universal testing machine              |      | *   |     |     |     |
| Flexural            | Universal testing machine              |      | *   |     |     |     |
| Durability          | Sorptivity (ASTM C1585-04)             |      | *   |     |     |     |

2.8.1. Slump. With a guided procedure from ASTM C143/C143M-15a, under laboratory conditions with strict control of concrete materials and apparatus, the slump of each batch mix was determined.

2.8.2. Compressive strength test. An average of seven 150x150x150mm cubes was tested from each mix batch on each test day. The procedure followed is as specified in BS EN 12390-3:2019. The universal testing machine with continuous loading of 140kg/cm² was used on the cubes until the specimens failed.

2.8.3. Flexural strength test. The procedure followed with a universal testing machine is detailed in ASTM C293/C293M – 16 for center-point loading. 150x150x450 mm concrete beams were loaded till failure.

2.8.4. Sorptivity test. As concrete dries, the water within leaves behind cavities that are capillary pathways. These relate directly to concrete’s permeability and porosity which are a measure of durability. This test measures the rate of absorption by capillary suction as detailed in ASTM C 1585-04. Cubes of 150x150x150 mm were used at 28-day curing [6], as shown in figure 4. With a timer, weight measurements of the cubes were taken at various times following tolerances specified in table 3.

Table 3. Times and Tolerances for the Measurements Schedule.

| Time   | 60 s | 5 min | 10 min | 20 min | 30 min | 60 min | Every hour up to 6 h | Once a day up to 3 days | Day 4 to 7 measurements 24 h apart | Day 7 to 9 measurements 1 (one) measurement |
|--------|------|-------|--------|--------|--------|--------|----------------------|--------------------------|---------------------------------------|---------------------------------------------|
| Tolerance | 2 s  | 10 s  | 2 min  | 2 min  | 2 min  | 2 min  | 5 min                | 2 h                      | 2 h                                   | 2 h                                        |

Source: (ASTM C 1585-04)
Figure 4. The cubes are placed 5mm deep in water in sorptivity test at 28-day curing.

3. Results and discussion

3.1. Material characterization

3.1.1. Sand. The percentage of sand passing through the sieve was plotted against the code requirement envelope and found acceptable according to BS 812 specifications, as shown in figure 5.

Figure 5. Sand grading against BS 812 specifications.
3.1.2. **Coarse aggregates.** A plot of particles retained compared to standard limits was plotted, and the coarse aggregates are found to fall in the acceptable envelope, as shown in figure 6.

![Passing coarse aggregates against BS 882 specifications](image)

**Figure 6.** Passing coarse aggregates against BS 882 specifications.

3.2. **Slump**

Each mix batch's slump was determined with a target of the water-cement ratio of 0.5, as shown in figure 7.

![SLUMP](image)

**Figure 7.** Slump test results.

G10 registered the highest slump at 114mm, then CON concrete at 79mm, probably due to the presence of 10% lower quantities of cement. Thus, less water is needed for the hydration process. F1 and F2 slumps are close to the CON by 12mm and 5mm, respectively, probably due to water loss from fiber hydration. 2% PET fiber addition of F2 displays the most superior quality for a slump. The ideal situation is concrete with
the least w/c ratios and the highest possible slump [7]. F3 and F4 had very small slumps of less than <10mm, which indicates their low workability and consistency, as shown in figure 8, most likely due to excessive bleeding of the paste from an excess quantity of PET fiber [8].

Figure 8. The slump of F4 fresh concrete.

3.3. Compressive strength tests
At 7 days, F1 records the highest strength compressive strength. Successive tests days place G10s’ strength over the other batches, registering its highest difference at 6.9MPa gain over CON at 90 days. A graph was plotted to compare growth in strength for each batch at 7, 14, 28, and 90 days as shown in figure 9.

Figure 9. Compressive test averages.
Glasscrete exhibits strength gain over the CON primarily due to the pozzolanic contributions of glass powder <75μm and better packing density of the paste [9]. Due to this, G10, F1, and F2 have more significant strength gain over CON concrete for all the test days. G10 exhibits a 10% higher strength over CON at 28 days and about 14.5% at 90-day testing. The PET fibers in F1 lower compressive strength development of the grasscrete by 3.5% at 28 days and 6% at 90 days from control G10 strength, probably due to its setup in the matrix. Despite this, F1 exhibits a 6.4% strength gain over CON at 28 days and 7.9% at 90 days over CON. Figure 10 shows an F4 cube under compression in the laboratory.

Figure 10. F4 Cube under compression.

3.4. Flexural strength tests
G10 and CON beams were highly brittle and sudden in failure. The presence of PET fibers at all percentages presented failure by cracking the beams first, thus improving the safety factor of the grasscrete, as shown in figure 11. Fibers absorb and distribute the energy of cracks, thus restricting crack growth [10]. On all test days, the flexural strength of the grass creates was higher than the CON.

Figure 11. F1 beam under 3-point test and failed by cracking.
A graph is plotted expressing a clear comparison of the different batch mix flexural strength, as shown in figure 12.

![Flexural Strength Test Averages](image)

**Figure 12.** Flexural Strength test averages.

PET fibre addition alone in concrete is known to improve its flexural properties [11]. CON’s flexural strength is lower than G10 by 14.9% at 90 days. The PET Fibre contribution to the flexural strength of F1 has it at 15.6% greater than the CON at 90 days. Nonetheless, the Flexural strength of F(2-4) is lowered probably due to the increased presence of the PET fibers, which increases the Interfacial Transition Zone (ITZ) [1]. Despite this, the least performing grasscrete F4 presents a 5.8% higher flexural strength than CON concrete that is not brittle in failure at 90 days. As the concrete ages, its modulus of rupture increases and is more evident in the grasscretes due to the pozzolanic contribution of the glass powder [9]. F1 at 28 days has a higher flexural strength than G10 by 5.4% and 0.8% at 90-days testing. It is mainly due to the grasscrete taking on the flexural strength of the waste PET fibers [12]. Therefore, the presence of PET fibers increases the flexural strength of Glasscrete at a 1% PET addition, beyond which G10's flexural strength is compromised.

### 3.5. Sorptivity tests

After laboratory data is analyzed, the initial absorption rate cannot be determined for F4 because the correlation coefficient is less than 0.98, and points show a systematic curvature. The lower the absorption rate, the more durable the concrete [7]. A graph was plotted in comparison of the rates of absorption, as shown in figure 13.
Figure 13. Rate of absorption comparison with grasscrete.

The presence of glass in concrete offers a closer packing of materials, thus reducing the potential for capillary movement of water in the concrete matrix [6]. It probably explains lower initial absorption rates in G10. The presence of waste PET in the matrix could facilitate the higher initial absorption rates in F1, F2, and F3 by allowing entry points for the water. However, the secondary absorption rate of all the batches does not vary significantly. It could mean the presence of waste PET bottle fibers has no adverse effect on the water ingress resistance of the concrete. The PET fibers could also be a barrier to flow in the pore structure of the grasscrete. The interfacial transitions between the fibers and grasscrete mix are well packed and bonding secured so as not to act as a capillary point for ingress water and harmful substances to concrete [6]. The extra calcium silicate hydrate produced from the reaction of waste glass Silicon Oxide and Ca(OH)$_2$ compensates for the presence of PET fibers making the durability of the grasscrete with fibers similar to concrete [13]. F1 grasscrete exhibits ideal long-term durability characteristics over grasscrete and 1.3% over concrete. Therefore, fiber addition is not recommended where grasscrete compressive strength is of critical importance. Nevertheless, its addition is recommended in improving the flexural strength of grasscrete. A

4. Conclusion
   i. Waste glass in concrete contributes a 14.5% increase in compressive strength and a 14.9% increase in flexural strength at 90 days.
   ii. Glasscrete with a 1% PET fiber addition presented the most optimum mechanical properties with a 15.6% higher compressive strength and 7.9% higher flexural strength than concrete.
   iii. Despite a 0.8% flexural strength gain over grasscrete, 1% PET fibers addition lowered the compressive strength of grasscrete by 6% at 90 days.
   iv. The presence of fibers improves the durability of the grasscrete by about 21.5% over grasscrete and 1.3% over concrete.

Therefore, fiber addition is not recommended where grasscrete compressive strength is of critical importance. Nevertheless, its addition is recommended in improving the flexural strength of grasscrete. A
1% PET fiber addition to grasscrete is thus recommended for structural use and further research development.

In a 1% PET fiber addition to grasscrete, for every 900kg of cement used, 100kg of cement is saved, 10kg of PET waste and 100kg of waste glass can be incorporated into concrete.

It reduces the environmental mining burden of cement, CO₂ emissions of cement production, and the waste of glass and PET plastic in the environment. Adopting a 1% waste fiber addition to grasscrete as concrete gives a substantial possibility and potential for green environmentally friendly concrete.

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