

Improving the properties of recycled Polyethylene terephthalate (PET) reinforced with different fibers

Tamam Mahdi Salih^{1*}  and Wafaa Mahdi Salih² 

¹*Chemistry Lab, Ibn Sina University of Medical and Pharmaceucal Sciences, Baghdad, Iraq*

²*Inspection and Characterization of Materials Lab, Materials Engineering Department, University of Technology, Baghdad, Iraq*

*tamam.alnaser@ibnsina.edu.iq

Abstract

The accumulation of plastic waste, especially polyethylene terephthalate (PET), is a major environmental concern. This research focuses on the use of recycled polyethylene terephthalate (r-PET) as a building material in concrete, and studies the improvement of its properties by reinforcing it with natural and synthetic fibers. The effect of adding hemp fibers on the mechanical and physical properties of PET composites was investigated. Results after curing each sample for 7, 14, and 28 days showed that reinforcing r-PET with fibers significantly increased compressive strength, flexural strength, and density, making it a suitable option as a complement or partial replacement for conventional concrete. Furthermore, the use of hemp fibers, as a renewable and biodegradable resource, enhances the sustainability of the resulting materials. It contributes to the production of high-performance, environmentally friendly building materials, reduces plastic waste, supports the economy, and can be applied in semi-structural concrete to promote sustainable construction techniques.

Keywords: *building materials, cement concrete, polyethylene terephthalate (PET), hemp fiber, recycling.*

Data Availability: Research data is available upon request from the corresponding author.

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1. Introduction

The relentless accumulation of plastic waste, coupled with the absence of effective disposal methods, has precipitated a critical and unprecedented crisis. This crisis manifests as plastic waste choking our water resources and waterways, overwhelming landfills, seeping into the soil, and dispersing through the air, thereby contaminating every natural facet of our environment. Despite the longevity that makes plastic a durable material, it becomes a detriment to safe disposal, as plastic never truly degrades but instead breaks down into smaller fragments over centuries. According to a report from the United Nations Environment Programme, a staggering 300 million tonnes of plastic waste is generated globally each year, with a meager 9% being recycled. UNEP's executive director, Inger Andersen, grimly projects a future scenario where approximately a billion metric tons of plastic will occupy our landfills by 2050. This alarming forecast underscores the urgent need for a paradigm shift in our approach to plastic waste management^[1]. There are many factors that contribute to the growth of plastic waste in the environment, such as the way it affects aquatic organisms^[2,3]. The use of plastic waste in construction applications, such as building mixtures, has recently received a great deal of attention in a lot of modern studies^[4]. As a result of waste plastics' organic and inorganic contents, these investigations revealed challenges in recycling^[5]. There is significant

potential in using plastic waste as a raw material in concrete^[6]. To accomplish this, plastic waste can be ground into a fine powder or mixed into different-sized granules^[7]. In addition to reducing plastic waste, this method makes sustainable construction materials^[8].

In conventional concrete, 12% cement is used along with 80% sand and gravel, requiring an abundance of natural resources to produce^[9]. A brick or concrete block produced using this mixture will have a great deal of weight, and it will not be suitable for most uses.

As sustainable manufacturing processes become more popular, they include recycling, non-traditional methods, and reutilization of waste to create new materials. As sustainability goals are being strived for, the use of non-traditional brick production methods, such as repurposing industrial waste, has gained momentum in recent years. This creative approach to brick production has been explored in several studies. Among the potential alternatives is plastic waste, which is considered to be one of the greatest substantial solid non-degradable contaminants^[10]. Recyclable polyethylene terephthalate (PET) enhances water conservation, reduces environmental impact, and promotes a circular economy by enabling the production of new items, such as construction and automobiles, from used polyethylene products^[8].

Building materials such as concrete are widely used around the world. Although it is heavy, it does not absorb much energy, and it has low ductility and poor tensile strength. For these attributes, civil engineers have been using conventional strengthening to increase concrete's tensile strength and ductility^[11]. A cement composite is typically used in architecture because of its numerous benefits, including close availability, superior compressive strength, good stiffness, and sturdiness^[12]. However, the low tensile strength of these composites makes them prone to cracking impairment, forming structural perils in practice^[13]. Thus, fibers are commonly utilized to strengthen cement matrices to prevent cracks from forming and propagating^[14,15]. The use of a variety of fibers in cement matrices has been reported, comprising basalt fibers^[12,16], glass fibers^[17], carbon fibers^[18,19], graphene fibers^[20], steel fibers^[21], plastic fibers^[22–24], and natural fibers^[25,26]. The sustainability and environmental friendliness of natural fibers such as coconut fibers^[27] and flax fibers^[28] make them competitive alternatives to other types. Plants of the hemp family are perfectly suitable in a wide range of soil and environmental circumstances, making them grow in many locations throughout the world. The plantations of hemp has been developed extensively in Europe, producing high-quality industrial fiber crops^[29,30]. Europe's hemp cultivation area had expanded to 33020 ha in 2022, reference to European agriculture and rural development^[31]. A total of 179020 tonnes of hemp were produced in the meantime. Thus, Hemp fiber (HF), which is extracted from the stem of the Cannabis Sativa plant, therefore has a greater rate of production. Additionally, HF exhibits relatively good mechanical strength and stiffness^[32]. Thus, the vast use of HF in cement composites may substantially improve the composite's ductile strength. Because HF is renewable, affordable, and biodegradable, it additionally endorses the objectives of the creation of green and long-lasting cement composites. The effects of HF on improving cement composites conduct, including pastes and mortars, have been demonstrated in previous studies as Li et al.^[33].

To protect the environment, researchers have modified cement mixtures with recycled plastic bottle waste to make them environmentally friendly. In the next section, some of the research being conducted on using this environmentally friendly material in different applications was discussed.

Fahad Amin et al.^[34], stated that the Coronavirus (COVID-19) pandemic has an environmental threat as well as its global health. This study intends to investigate an inventive approach to handle the concern of the extra waste produced due to the epidemic. Particularly, the investigation aims to explore the use of recycled concrete aggregate (RCA) and silica fume (SFM) in civil constructions using discarded face masks. The ear loops and nose strips were taken off the disposable face masks, and they were then chopped into tiny fibers that have a length of 20 mm, width of 5 mm, and thickness of 0.46 mm, giving a 24 aspect ratio. The concrete mix was formulated with different ratios of SFM and RCA, with a concentration on assessing its durability, compressive strength, and split tensile strength. Results revealed that as a result of adding SFM, both compressive and split tensile strength improved, but durability did not improve significantly.

Gonzalez Laria et al.^[35], researched the development of a new technology for the production of a new CM based on two types of recycled plastic (PE/PET) with high availability. The proposed procedure is easy to apply and requires low cost. The main physical and mechanical properties were studied. Components manufactured with this plastic compound comply with non-structural materials regulations based on CIRSOC standards.

Mishra^[11] endeavored to reduce trash and reduce the negative ecological effects due to growing economic and industrial expansion. A summary of the experimental exertions on the usage of PET in the construction of roads and cement concrete is provided in this study. Investigations show that adding waste PET to cement and bituminous concrete mixes improved several of the mixture's features and lowered expenses. PET can be utilized as a building material to reduce the use of new polymeric materials that have negative environmental impacts.

This study intends to employ reclaimed PET bottles to make amended cement building mixes. These changed mixtures should be enhanced concerning durability, permeability, drainage, abrasion, and stability. The importance of using damaged materials and making use of them, as well as connecting them with natural fibers to resist heat and flames.

2. Materials and Methods

2.1 Polyethylene Terephthalate (PET)

PET is thermoplastic in origin, it is likewise termed as "polyester," which is frequently confused owing to polyester resins being thermosetting materials. Despite its transparency, PET has good mechanical properties and good dimensional stability when subjected to varying loads. PET is also a proper gas barricade and chemically resistant material. PET's aforementioned properties have led to its use in electrical components, bottles, and thermally stabilized films (e.g. recording tapes, film bases, graphics, capacitors, etc.). Textile fibers can also be produced using PET, which has many uses in the industry. PET is a thermoplastic that has superior physical characteristics. The PET market consumes around 30% of the global PET demand, which constitutes 18% of the entire polymers yielded globally. Above 60% of its production goes into manufactured fibers and bottles. Table 1 presents an overview of the key attributes associated with PET plastics. rPET powder was manufactured through the following sequential procedures: PET water bottles were subjected to a cleaning and drying process. In this experiment, the bottle underwent a shredding process and was then turned into a powder using an industrial stainless steel grinder. Figure 1 depicts the above method.

Table 1. PET plastic characteristics^[36].

| Property | Value |
|---------------------|------------------------|
| Melting temperature | 250 °C |
| Density | 1.38 g/cm ³ |
| Molar weight | 192.2 g/mol |

The mortar mixtures used ordinary Portland cement CEMI 52.5 R in combination with standard sand according to UNE-EN 1961^[37]. As shown in Table 2, hemp fibers with a 5 mm length, their geometry characteristics, and their composition are described.

2.2 Mixture preparation

Based on Table 3's mixing ratios, different mixtures were made using resistant cement. Sand; The proportions of components in the first sample were (cement, sand, water / 1, 0.5, 0.5) and all materials were mixed according to ASTM C305 practice^[39]. Then different percentages of recycled polyethylene terephthalate (rPET/0.01, 0.02, 0.03) were added. Fixed proportions of hemp fiber (0.01) were

added. Manual mixing was performed until a homogeneous mixture was obtained. As a side note, each mixture of PET pellets was made separately to ensure its precise proportion and weight. Produced bricks are made uniformly composed and have mechanical properties through detailed preparation of raw materials.

2.3 Specimens characteristics

In the present section, Tables 4, 5 and 6 provide the number and characteristics of the specimens made. The manufactured specimens are categorized into three classes of compressive specimens as per ASTM C39^[40]. Flexural and standard specimens according to ASTM D790-03^[41]. Standard and bulk density specimens according to ASTM C567^[42].

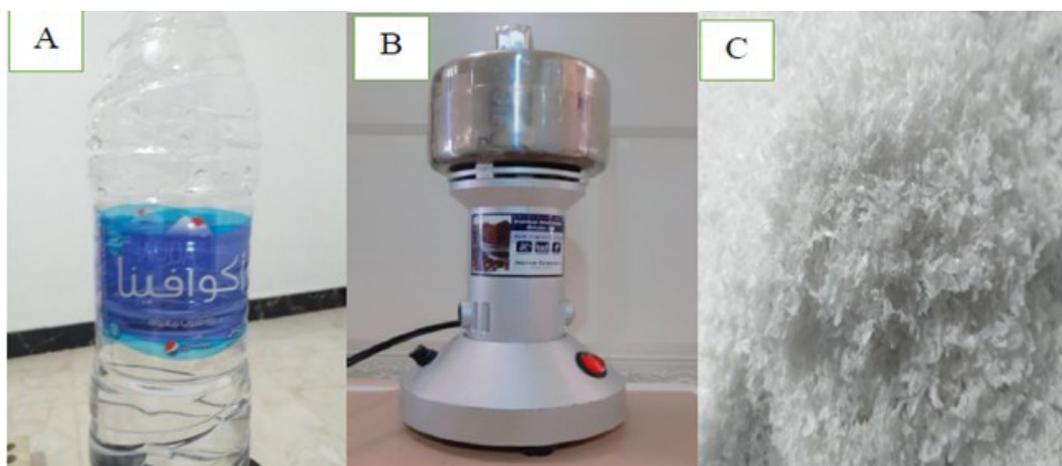


Figure 1. (A) Materials used in this research study of waste PET plastic, used for bottle milling (C) plastic after grinding.

Table 2. The geometry characteristics composition of hemp fibers (HF)^[38].

| HF | Length (mm) | Diameter (µm) | Density (g/cm ³) |
|----|-------------|---------------|------------------------------|
| | 5 | 125 | 1.32 |

Table 3. Plastic brick preparation raw materials mixing ratios.

| Specimens | rPET% | HEMP | Cement | Sand | water |
|-----------|-------|------|--------|------|-------|
| 1 | 0 | 0 | 1 | 0.5 | 0.5 |
| 2 | 0.01 | 0 | 0.99 | 0.99 | 0.99 |
| 3 | 0 | 0.01 | 0.99 | 0.99 | 0.99 |
| 4 | 0.01 | 0.01 | 0.98 | 0.98 | 0.98 |
| 5 | 0.02 | 0.01 | 0.97 | 0.97 | 0.97 |
| 6 | 0.03 | 0.01 | 0.96 | 0.96 | 0.96 |

Table 4. The Flexural strength of concrete with and without rPET and hemp.

| 28-days | 14-days | 7-days | samples |
|---------|---------|--------|---------|
| 4.2 | 3.43 | 2.821 | 1 |
| 4.98 | 3.78 | 3.194 | 2 |
| 5.21 | 3.98 | 3.52 | 3 |
| 5.51 | 4.13 | 3.65 | 4 |
| 5.76 | 4.31 | 3.68 | 5 |
| 5.87 | 4.54 | 3.69 | 6 |

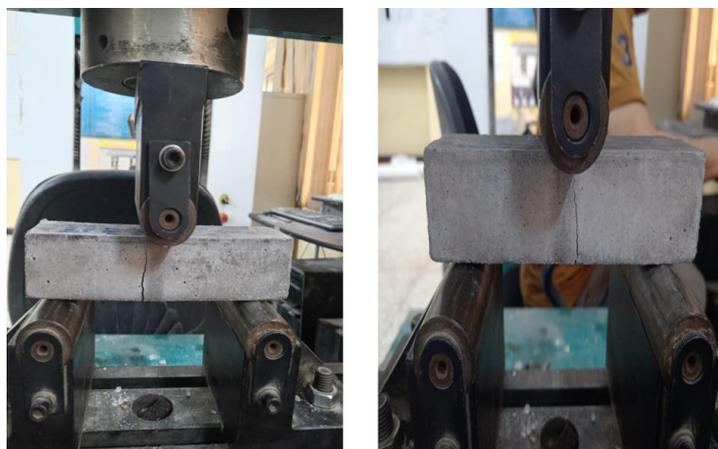


Figure 2. Types of failures presented in the prismatic beams containing rPET particles in the flexure strength test.

Table 5. The compressive strength of concrete with and without rPET and hemp.

| Curing time (28 days) | Curing time (14 days) | Curing time (7 days) | samples |
|-----------------------|-----------------------|----------------------|---------|
| 35.8 | 23.5 | 18.8 | 1 |
| 37.7 | 25.1 | 19.2 | 2 |
| 37.9 | 25.6 | 19.9 | 3 |
| 37.1 | 25.2 | 19.4 | 4 |
| 36.7 | 24.6 | 18.4 | 5 |
| 35.2 | 23.8 | 17.3 | 6 |

2.3.1 Flexural test

In order to determine the flexural strength of the plastic bricks, ASTM D790-03 was followed. Figure 2 illustrates how the test was conducted using a universal inspecting machine with a 100 kNA loading capacity. The test was conducted when specimens were placed on two support points 120 mm apart and loaded at 0.05 mm/min until failure was reached by exerting a load at its center. The strength of flexion was computed using the typical equation after the maximum load that the specimen underwent was registered. The average value was reported.

2.3.2 Compression test

The plastic bricks were tested for compression strength using a compression testing machine to comply with ASTM C39. The testing machine's lower plate was filled with bricks, which were compressed until failure happened. Located at Resistance Lab of the University of the Materials Engineering Department University of Technology - Iraq. As per ASTM standards, the loading rate was kept at 3.5 MPa/min. To conduct the test samples were reserved under standard laboratory conditions at room temperature before testing. Tests were performed on moist cured specimens after 7, 14, and 28 days. Plastic bricks were evaluated for their suitability for construction applications according to the compression test results.

2.3.3 Bulk density test

It is a property of a material that expresses how much matter it contains compared to its volume. Different materials have different densities based on their compactness.

Table 6. The bulk density of concrete with and without rPET and hemp.

| bulk density gm/cm ² | samples |
|---------------------------------|---------|
| 2.48 | 1 |
| 2.46 | 2 |
| 2.43 | 3 |
| 2.37 | 4 |
| 2.32 | 5 |
| 2.21 | 6 |

Often, true and apparent density are calculated by dividing a material's mass by its volume, and these can be expressed mathematically as follows:

$$p = \frac{m}{v} \quad (1)$$

where m = material mass, V = materials' bulk volume, true volume, or apparent volume, p = true, apparent or bulk density of the material^[43] testing of bulk density and moist density for different concrete mixes according to ASTM C567^[42].

3. Results and Discussions

3.1 Flexural test

Out of all the tests conducted on concrete, the most crucial one that provides insight into all of its properties is the flexural strength test. This one test allows one to determine if concreting was done correctly or not. Molds with dimensions of 40 mm x 40 mm x 160 mm are frequently used for concrete testing.

The table below shows the results of all specimens evaluated for flexural strength. The average results of the flexural strength test, which was performed at 7 and 28 days of age, are shown in Table 4 and Figure 3. Flexural strength varies depending on the fiber mix ratio. The results show that the flexural strength of conventional concrete reaches its peak after 7 days, but the flexural strength of concrete made with mix (0.03 PET+ 0.01 fiber) reaches its peak at 28 days. It has been found that adding 0.01 fiber to concrete increases its flexural strength compared to normal concrete throughout the course of a 28-day test.

The increase in flexural strength of the samples relative to the control sample can be explained by the fact that rPET granules are less elastic than the coarse blocks and the modulus of elasticity decreases with increasing proportion of recycled PET granules in the mix. The results can also be related to the percentage of rPET replacement concerning the total weight of concrete along with the different gradations, shapes, and sizes of rPET particles^[44]. It was observed that the hemp fiber reinforced concrete shows an increasing trend in flexural strength as in specimens (2, 3, 4, and 5). This may be because at this ratio of 0.01, the fibers may interlock tightly with the rPET and the rest of the mixture resulting in a concrete mass with fewer voids and this is responsible for the higher strength characteristics^[45].

3.2 Compression test

Table 5 and Figure 4 present the results of the compressive strength for the cubic specimens. The compressive strength of concrete without rPET particles is moderate but rises when rPET particles are added at different percentages. Furthermore, the compressive strength values augment gradually between 7-28 days of curing. A reduction in cement hydration may be caused by the existence of non-degradable materials (rPET). Based on results, 7-day compressive strength is lower than 28-day compressive strength. Several techniques are known to improve the strength of materials, including blending, fiber insertion, utilizing fillers, and/or combining these methods. The reinforcement provided by smaller particles is usually greater. Concrete with 0.01 fiber added at 28 days increases by 37% on average in compressive strength, as demonstrated in sample No. 3^[46]. At samples No. 4, 5, and 6 as shown by the experimental results, if we add fibers with increasing proportion of rPET, the compressive strength of the samples decreases^[47,48]. The decrease in compressive strength can be explained by the decrease in adhesion between the fiber surface and rPET and the concrete matrix. Therefore, when the volume of injected fibers increases, the compressive strength decreases^[49]. The decrease in compressive strength can be explained by the decrease in adhesion between the fiber surface and rPET and the concrete matrix. Therefore, when the volume of injected fibers increases, the compressive strength decreases^[49].

3.3 Density

The test results of the density of the specimens are presented in Table 5 and Figure 5. It can be seen that the density of concrete decreased with the increment of rPET

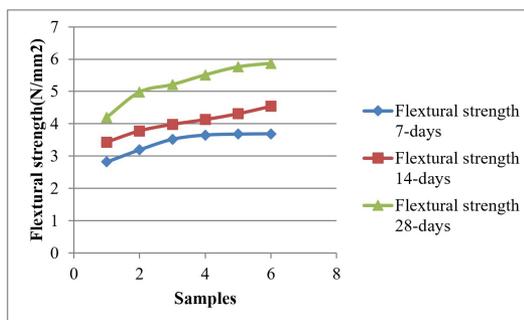


Figure 3. Effect of rPET on 28-day flexural strength.

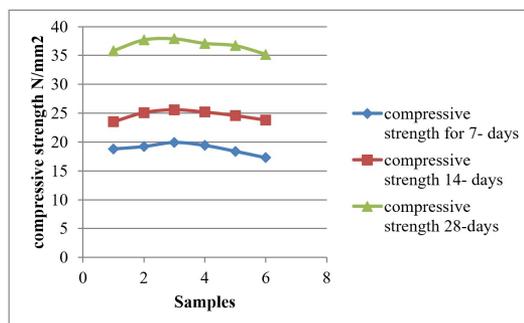


Figure 4. Effect of rPET on 28-day compressive strength.

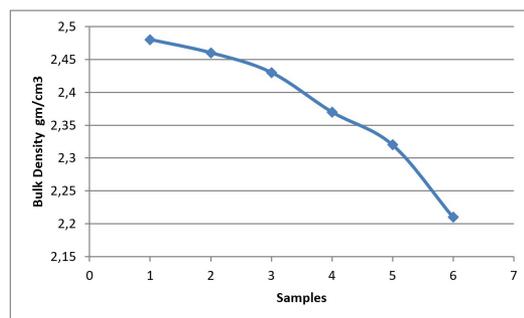


Figure 5. Effect of rPET on 28-day bulk density.

content in concrete. The density for concrete with 0.01, 0.02, and 0.03 ratios was found to be 2.37 gm/cm³, 2.32 gm/cm³ and 2.21 gm/cm³, respectively, which were relatively close to that of the control sample (2.48 gm/cm³). The reason for the decrease in the density of fresh concrete with the increase in the rPET content is that the density of rPET particles is very low compared to the mixed materials^[50].

Alternatively, at 0.01 hemp fiber content, the density value decreased as compared to the reference specimen. The low density of hemp fibers compared to other components of concrete also results in a decline in the value of density in hemp-based concrete due to the high amount of air trapped in the concrete and the high amount of entrapped air^[51].

4. Conclusions

This study examined the mechanical and physical properties of concrete containing rPET and hemp and came to the following conclusions.

1. Concrete samples with different amounts of rPET particle content showed diverse conducts in flexural and compressive strength. In fact, for the rPET content of 0.01, the compressive strength increased by 37.7%. Alternatively, with the ascend of rPET content, the compressive strength reduced. The highest compressive strength was obtained for the hemp particle size of 37.9 mm with a ratio of 0.01 and cured for 28 days.
2. Flexural strength test results. Increasing rPET by up to 0.03 with hemp by up to 0.01 will increase the flexural strength. A spent rPET bottle can be reused as a raw material for concrete if it is in particle form. The concrete will be improved in terms of its mechanical and physical properties, as well as being an environmentally friendly alternative to previously used RPET bottles.

5. Author's Contributions

- **Conceptualization** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Data curation** – Tamam Mahdi Salih.
- **Formal analysis** – Tamam Mahdi Salih.
- **Funding acquisition** – Tamam Mahdi Salih.
- **Investigation** – Tamam Mahdi Salih.
- **Methodology** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Project administration** – Wafaa Mahdi Salih.
- **Resources** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Software** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Supervision** – Wafaa Mahdi Salih.
- **Validation** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Visualization** – Tamam Mahdi Salih; Wafaa Mahdi Salih.
- **Writing – original draft** – Wafaa Mahdi Salih.
- **Writing – review & editing** – Tamam Mahdi Salih; Wafaa Mahdi Salih.

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