

Strength Properties of Recycled Waste Plastic and Quarry Dust as Substitute to Coarse Aggregates: An Experimental Methodology

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Strength properties of recycled waste plastic and quarry dust as a substitute to coarse aggregates; an experimental methodology

Abstract

Plastic waste disposal is a significant environmental concern due to its low degradability and management practices, especially in developing countries. Plastic recycling is considered the most effective disposal method, which minimizes environmental impacts. This paper discusses the use of Poly(ethylene terephthalate) (PET), High-Density Polyethylene (HDPE), and Polypropylene (PP) plastic as aggregates in the concrete industry by incorporating quarry dust as a base material. An experimental mix design series was carried out, followed by a deoxygenated heat treatment on each mixture for optimum bonding. Compressive strength, specific gravity, and water absorption properties were then investigated in each mixture. Although the specific gravity of PET plastic was 30% lower than the natural aggregates, the specific gravity of PET plastic aggregates was higher than the HDPE or PP waste plastic aggregates. Therefore, the proposed method is ideal for low-strength concrete components.

Graphical Abstract

Keywords: Coarse Aggregates, Compressive Strength, Plastic Waste, Recycled aggregates, Sustainable Concrete

1. Introduction

World plastic production has increased from two million tons to 380 million tons since the 1950s' If the current growth trends continue, global production of plastics is forecasted to reach 1,100 million tons by 2050 [1]. Packaging, building, and construction sectors are the dominant users of primary plastics, responsible for half of the total global plastics [2]. Currently, 49% of plastic waste accumulates in landfills, 19% is combusted for energy recovery, only 9% is recycled, and 22% is for mismanaged or uncollected litter [3]. Moreover, due to COVID-19, healthcare plastic products and plastic product usage have drastically increased, which further surpluses plastic waste accumulation [4], [5], [6]. This is becoming a critical case, especially in developing countries, due to the lack of standards and poor waste management practices [7]. Also, due to its slow degradability, plastic poses a significant limitation on its recyclability and disposal methods. Therefore, many novel applications were introduced and implemented to manage plastics sustainably [8].

Recycling plastic waste will reduce the environmental impact and add value to the various applications of the circular economy. The use of plastic waste in the packaging industry has been broadly explored [9],[10]. Plastic waste in the construction industry is still being researched extensively. Although, the construction industry is found to be the ideal application to achieve its sustainability objectives and reduce its energy consumption.

The use of plastic waste as a replacement or partial replacement for raw materials in the construction industry is an area of increasing interest, with the potential to reduce waste and greenhouse gas emissions. However, the extent to which different plastic types have been studied for this application remains unclear. In this study, we conducted a cross-tabulation analysis using several vital keywords, including fine aggregates, coarse aggregates, and flakes, in ScienceDirect and Google Scholar for the past ten years. This analysis aimed to identify which plastic types have been studied more or less frequently, providing insights to guide future research efforts and to identify patterns or trends in the literature for a broader understanding of the field. Overall, our findings suggest that certain plastic types have been more extensively researched for use in construction applications than others (i.e. Polypropylene (PP) and Poly(ethylene terephthalate) (PET) while Low-Density Polyethylene (LDPE) was the least). These results can inform future research efforts and provide guidance on which plastic types are most promising for further exploration in this context (see Figure 1). The previous studies have highlighted the drawbacks of using plastic waste directly in concrete, but the current study takes a different approach by integrating plastic waste with waste material to obtain the necessary surface roughness for the coarse aggregate. It is important to note that in low-strength concrete, the Inter Transition Zone (ITZ) is the primary factor that contributes to the strength properties.

Aggregates are one of the most accessible components to substitute in the concrete mix design. Generally, fine and coarse aggregates are classified on their diameter. The most common fine aggregate in reinforced concrete is sand, and gravel is coarse. When considering the strength properties of a concrete mixture, coarse aggregate determines the final strength of the concrete. Due to the depletion of natural resources, an alternative solution should be considered for the construction industry.

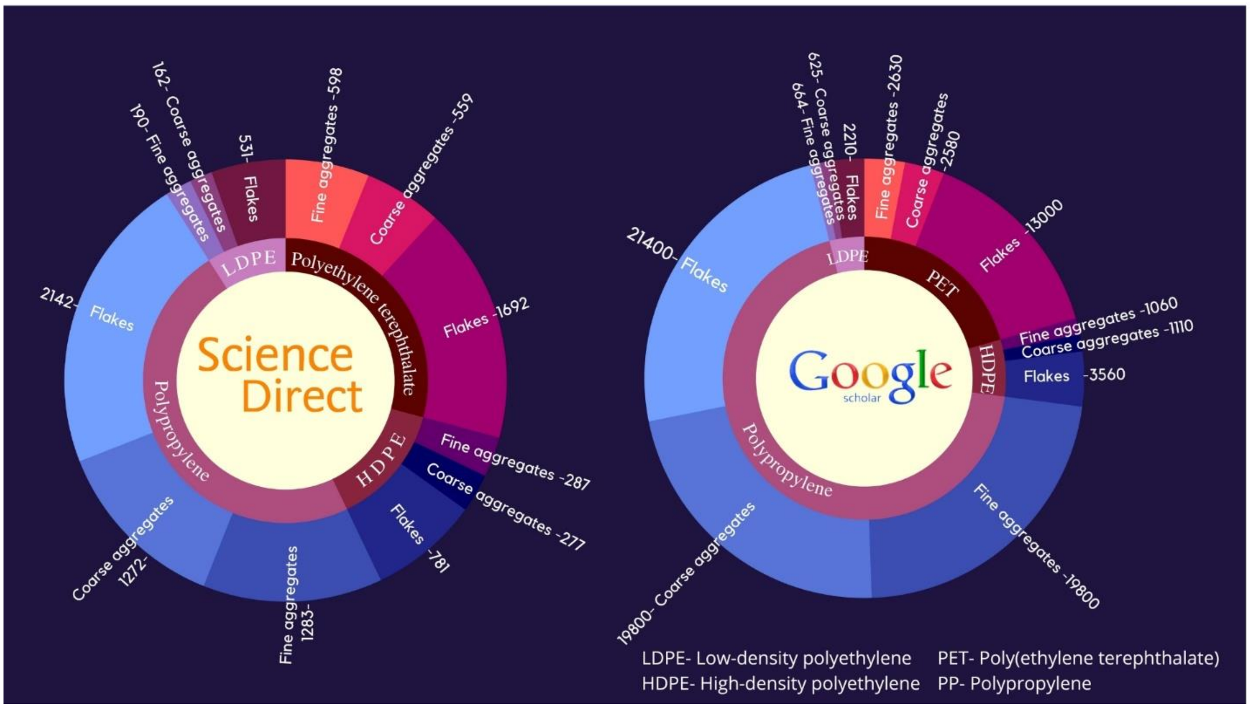


Figure 1:Number of publications on plastic waste in construction (ScienceDirect and Google scholar 2002 -2022)

This study investigated the physical properties produced by waste plastic aggregates and quarry dust. The comprehensive review of the previous studies revealed that plastic waste was added to the concrete as plastic flakes or pallets. It was ideal for low-strength concrete due to its lower strength parameters. As a substitute, this study aims to develop a coarse aggregate that incorporates quarry dust (a by-product of crushing natural aggregates) and plastic waste to replace or partially replace the natural aggregates in concrete. Accordingly, the plastic aggregates' physical and mechanical properties were studied using several plastic waste types (i.e. HDPE, PP, and PET plastics). Current applications and methods utilized for recycling plastic waste are shown in Table 1. This was developed using an in-depth literature review.

Using plastic waste directly as coarse aggregates may result in low strength parameters due to its surface smoothness [11]. This process focuses on achieving adequate surface roughness to the aggregates for better bonding properties. Also, the process uses only the quarry dust as base material. River sand would be ideal as a base material to achieve the surface roughness the aggregate required. However, quarry dust was selected as a substitution for the base material to minimize the environmental impact. Further studies should need to be conducted incorporating other base materials. Integrating industrial waste as a substitution for the base material would further reduce the carbon footprint.

Table 1: Methods of recycling -different plastic waste types in the construction industry

Used plastic type/s	Application	Type of substitution	Methods	References
PET	Walling material	Bricks	PET bottles with filling materials (e.g., sand, mud, soil, or any waste materials)	[12][13][14][15]
PET	Concrete	Fine aggregate	Waste plastic granulate into fine powder	[16][17][18][19][20]
	Concrete	Coarse aggregate	Shredded PET plastic waste melted and chopped	[21][22][23]
	Mortar	Fine aggregate	Powdered PET mixed in cement paste	[24][25][26][27]
PP	Waling material	Bricks	Melting and casting bricks	[28][29]
	Concrete	Fine aggregate	Powdered waste plastic used as fine aggregates	[18][20]
	Concrete	Coarse aggregate	Melted and crushed into coarse aggregates	[29][30]
HDPE	Waling material	Bricks	Melting and casting bricks	[28][31]
	Concrete	Fine aggregate	Powdered waste plastic used as fine aggregates	[32][33][34]
	Concrete	Coarse aggregate	Crushed plastics are added to the mixture as coarse aggregates	[34][33][35]
	Mortar	Fine aggregate	Powdered waste plastic mixed with cement paste	[36][37][38][39]

2. Materials

2.1. Waste plastics as a binder

Shredded waste PET, HDPE, and PP plastics were cleaned, categorised, and collected from the plastic waste recycling centre, in Matale, Sri Lanka. The shredding was conducted at the centre using separate machines to avoid mixing any plastic types. The waste plastics were washed and dried for 24 hours in the open air. Waste plastic particles that passed the 5mm sieve size were taken for the mix design.

2.2. Quarry dust as a base material

Quarry dust was acquired from a local construction material supplier. Quarry dust is a readily available construction material in Sri Lanka since it has been used to replace sand in construction. For the mix design, quarry dust that passed through a 2.36mm sieve, was selected by ASTM D2487 standards.

2.3. Mix Design and Production Process

Sets of cubes were cast with different mixed proportions by combining each shredded plastic waste with quarry dust (see Table 2).

Table 2: Mix proportions selected for the study

Plastic type	Mix proportion		Plastic type	Mix proportion		Plastic type	Mix proportion	
	Plastic	Quarry dust		Plastic	Quarry dust		Plastic	Quarry dust
PET	30%	70%	HDPE	-	-	PP	-	-
PET	40%	60%	HDPE	40%	60%	PP	40%	60%
PET	50%	50%	HDPE	50%	50%	PP	50%	50%
PET	60%	40%	HDPE	60%	40%	PP	60%	40%

The production process of plastic waste aggregates is illustrated in Figure 2. Initially, selected plastic wastes are shredded into 5 -10mm and cleaned. Base material (quarry dust) is then mixed with shredded plastic waste. Each mixture was heated to its plastic melting point and kept heated for another 10 minutes. The melting points of PET, HDPE, and PP were 260^{0}C, 120^{0}C, and 160^{0}C, respectively. The heating process was conducted without oxygen to omit the foul gas released from the mixing. The heated mixture was then poured into 75mm x 75mm x75mm moulds and allowed to cool and hardened. The hardened blocks were then crushed. The resulting aggregates were sorted using sieves, and fine and coarse aggregates were separated. Since the study only focused on coarse aggregates, the remaining fine aggregates were added and reused at the heating stage.

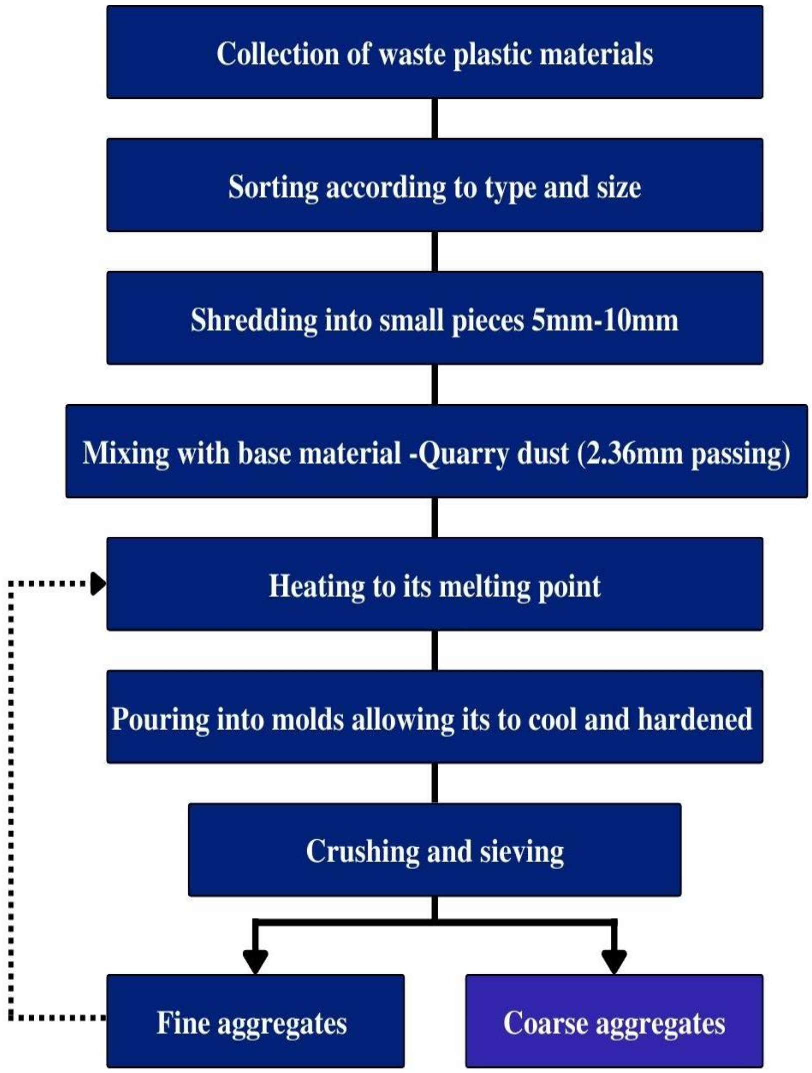


Figure 2: Manufacturing process of the recycled plastic aggregates

3. Results and Discussion

3.1. Compressive strength

The compressive strength of the samples was tested at two different temperatures, 30^{0}C and 50^{0}C. Each sample was soaked in a water bath incubator for 24 hours before the testing. It was identified that, compared with other plastic types, PET plastic aggregates have a higher compressive strength than other plastic aggregates. Similar trends were also observed with reduced strengths at 50^{0}C temperature (see Figure 3).

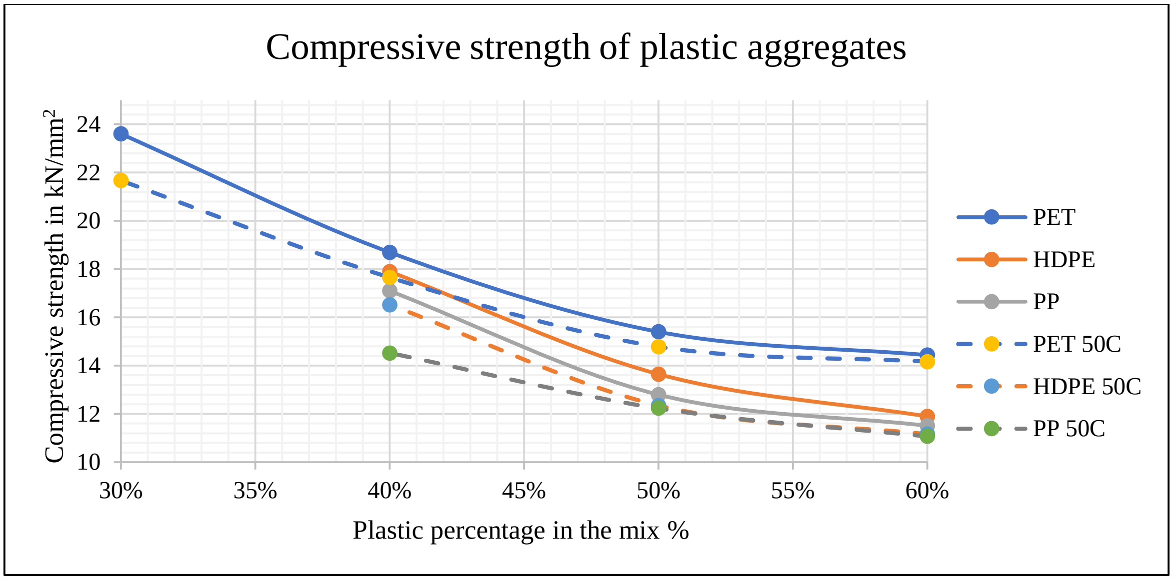


Figure 3: Compressive strength of plastic aggregates

Previous studies only focus on the strength parameters of concrete mixtures with recycled plastic aggregates [40], [41]. No proper studies were conducted only for testing recycling aggregate properties. Compressive strength is increasing with lesser waste plastic content. However, below 40% of mixtures for HDPE and PP were not possible to cast due to inconsistency since the 40% PET plastic mixture strength is more than 18kN/mm^2, which can be ideal to use for low er grade concrete mixtures.

3.2. Specific gravity and water absorption

Specific gravity and water absorption tests were carried out for recycled plastic aggregates according to the specifications. The specific gravity of PET plastics was comparatively higher than the HDPE and PP aggregates. This indicates that higher specific gravity occurs with lower plastic content in the mix design. Also, when considering the water absorption of plastic aggregates, PP has the highest water absorption rate compared to the HDPE and PET aggregates (see Table 3).

Table 3: Summary of the physical properties test results

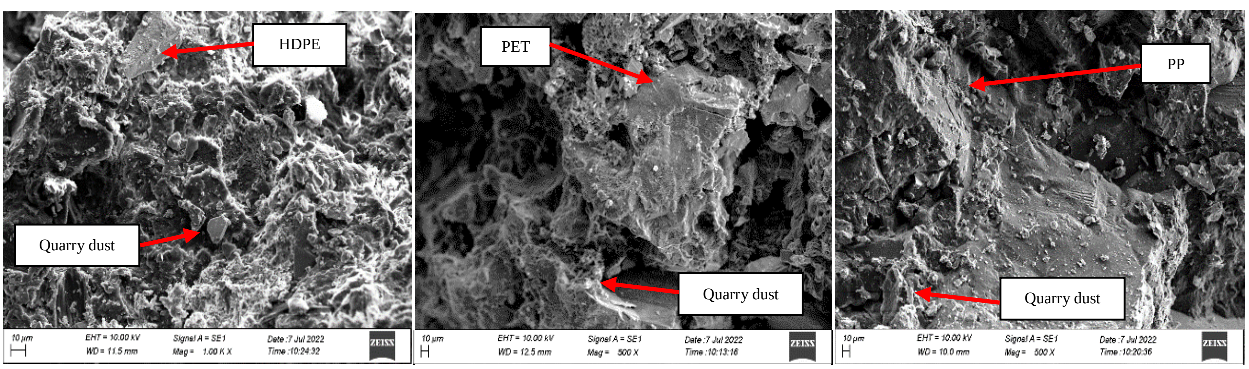
Plastic-type	Mix proportion		Compressive Strength in kN/mm^2		Specific Gravity	Water Absorption %
	Plastic	Quarry dust	30^{0}C	50^{0}C		
PET	60%	40%	14.44	14.17	1.41	2.83
PET	50%	50%	15.40	14.79	1.68	2.27
PET	40%	60%	18.70	17.65	1.80	1.77
PET	30%	70%	23.60	21.67	1.82	1.63

HDPE	60%	40%	11.90	11.16	1.27	2.38
HDPE	50%	50%	13.65	12.35	1.37	1.96
HDPE	40%	60%	17.90	16.52	1.44	1.69
HDPE	30%	70%	-	-	-	-
PP	60%	40%	11.51	11.08	1.24	2.76
PP	50%	50%	12.80	12.24	1.28	2.65
PP	40%	60%	17.12	14.52	1.40	2.35
PP	30%	70%	-	-	-	-

According to ASTM C127, water absorption of the aggregates should not exceed 3% or 2% in critical conditions (aggressive chloride or freeze-thaw exposure), and specific gravity is about 2.5-3.0 [42]. Nevertheless, the recycled plastic aggregates have an acceptable water absorption ratio compared with the natural aggregates; low strength parameters can be expected due to the low specific gravity.

3.3. Scanning Electron Microscopic (SEM) analysis

To observe the bonding of the mixture, 50/50 mix designs were further analysed using a scanning electron microscope (SEM) with an accelerating voltage of 10kV (see figure 4).



(a) (b) (c)

Figure 4: Scanning electron microscopic (SEM) analysis for (a) HDPE (b) PET and (c) PP plastic waste aggregates

According to the visual inspection, SEM analysis revealed that the PET plastic blend has homogenous crystallization with quarry dust compared with the HDPE and PP mixtures, resulting in higher mechanical properties in the PET mixture.

4. Conclusion and Recommendation

It was identified that during the manufacturing process (heating and melting), foul gases are released, and PP plastic waste tends to get scorched easily, which may result in environmental, health, and safety issues. To avoid this, heating was conducted without supplying oxygen to mitigate such effects. The specific gravity of PET plastic aggregates (which constituted 60% of the plastic waste mix) is higher than that of HDPE or PP waste plastic aggregates. However, the specific gravity of PET plastic was 30% lower than that of natural aggregates. Water absorption for natural aggregates ranges from 0.6% to 1.0%. However, water absorption varied between 1.69% and 2.83 % for all the plastic aggregates. The water absorption capacity of the aggregates indicates the amount of water that can be absorbed. Therefore, this indicates that plastic waste aggregates have more surface area than natural aggregates, increasing workability. The Inter Transition Zone (ITZ), the region between the surface of the aggregate particles and the cement paste, acts as the dominant factor that contributes to the strength properties, especially in the low-strength concrete mix design. Improving the surface roughness of the recycled aggregate was an essential consideration for the study.

Overall, while there are certainly some drawbacks to using plastic waste in concrete applications directly, there are potential benefits such as reduced carbon footprint, cost saving, environmental benefits and aesthetic appeal etc. Among these plastic waste types, it was identified that PET plastic has the potential to be used for recycled aggregates compared with other types of plastics. Nevertheless, future research and development are needed to optimize the use of plastic waste in concrete to ensure that it is safe and effective for construction applications and to improve the surface roughness of recycled aggregates to enhance the strength properties of low-strength concrete.

Declaration

Conflict of interest:

The authors declare that they have no competing interests.

Funding:

The authors received no financial support for the research, authorship, and/or publication of this article

Author’s contributions:

The authors RRR and GPH initiate the main research study and performed testing and manuscript was written by RRR, WPA and MPH while CL, KW and RUH critically reviewed all versions of the manuscript.

Acknowledgement:

The authors would like to acknowledge the support given by the technical officer, Ms W.B.U.Rukma from the Department of Civil Engineering, University of Moratuwa.

Availability of data and materials:

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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<table>
<tr><th>Reviewer Comments</th><th>Author Response</th></tr>
<tr><td colspan="2">Reviewer #1 Comments</td></tr>
<tr><td>When Plastic wastes are used in construction applications, it has some advantages such as lighter weight than competing other materials reducing fuel consumption during transportation, durability and longevity, resistance to chemicals, water, and impact, and excellent electrical insulation properties.

However, some of the disadvantages of using the plastics in concrete are as follows: - They are having low bonding properties so that the concrete strength (such as compressive, tensile and flexural strength) gets reduced.
Another important drawback is that it cannot be used in kitchen or furnaces, as Its melting point is low. Additionally, plastics such as poly(ethylene terephthalate) have the tendency to get hydrolysed into products such as terephthalic acid and ethylene glycol with time. These materials are either toxic or carcinogenic to humans. Even if it is placed in concretes, due to weather, it will get hydrolysed.

Due to the above drawbacks mentioned, the use of plastic wastes in concrete applications is questionable and more work needs to be studied in future. The reviewer has an opinion that it cannot be used in concrete applications.</td><td>The authors of the study would like to address the reviewer's comments point by point:
• The issue of low bonding properties of plastic, which can reduce the strength of concrete - by using plastic in the form of fibers or flakes, which can actually improve the toughness and resistance of concrete. Additionally, chemical additives can be used to improve the bonding between plastic and concrete.
• Although plastic has a low melting point - it can still be used in many other construction industry applications where high temperatures are not a concern, such as small pre-cast applications or floor concrete.
• The issue of plastic waste getting hydrolyzed over time, which can release toxic or carcinogenic byproducts - by encapsulating plastic waste in the concrete matrix or using protective additives to prevent the breakdown of plastic hydrolyzed can be prevented.

The previous studies have highlighted the drawbacks of using plastic waste directly in concrete, but the current study takes a different approach by integrating plastic waste with a waste material to obtain the necessary surface roughness for the coarse aggregate. It is important to note that in low-strength concrete, the Inter Transition Zone (ITZ) is the primary factor that contributes to the strength properties.

While this point was not highlighted in the manuscript, the authors acknowledge the reviewer's feedback and have included in the introduction and discussion section to further explain the connection between the ITZ and surface roughness. The discussion highlights how surface roughness can impact the ITZ and how improving the surface roughness of recycled aggregates can enhance the strength properties of low-strength concrete.</td></tr>
<tr><td>The specific gravity of PET plastic aggregates was higher than the HDPE or PP waste plastic aggregates. Although, the specific gravity of PET plastic was 30% lower than the natural</td><td>Amended</td></tr>
</table>

aggregates. The above sentence can be modified as follows Although the specific gravity of PET plastic was 30% lower than the natural aggregates, but the specific gravity of PET plastic aggregates was higher than the HDPE or PP waste plastic aggregates.	
As per IUPAC nomenclature, Polyethylene Terephthalate (PET) should be written as Poly(ethylene terephthalate)	Amended
In the conclusion section, Therefore, it was identified that PET plastic has the potential to use for recycled aggregates compared with other types of plastics the above sentence has to be changed as follows Therefore, it was identified that PET plastic has the potential to be used for recycled aggregates compared with other types of plastics	Amended
Reviewer #2 Comments	
More references are needed to be added in the Introduction section to validate the line - The use of plastic waste in the packaging industry has been broadly explored (Line 26).	Amended
Need references for - Previous studies only focus on the strength parameters of concrete mixtures with recycled plastic aggregates (Line 52)	Amended