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A Step towards Sustainable Concrete with Substitution of Plastic Waste in Concrete: Overview on Mechanical, Durability and Microstructure Analysis

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Citation: Ahmad, J.; Majdi, A.; Babeker Elhag, A.; Deifalla, A.F.; Soomro, M.; Isleem, H.F.; Qaidi, S. A Step towards Sustainable Concrete with Substitution of Plastic Waste in Concrete: Overview on Mechanical, Durability and Microstructure Analysis. *Crystals* **2022**, *12*, 944. https://doi.org/10.3390/cryst12070944

Academic Editors: Yurii Barabanshchikov and José L. García

Received: 25 May 2022
Accepted: 29 June 2022
Published: 5 July 2022

Abstract: Plastics have become an essential part of our daily lives, and global plastic production has increased dramatically in the past 50 years. This has significantly increased the amount of plastic garbage produced. Researchers have recently been interested in using trash and recyclable plastics in concrete as an ecologically acceptable building material. A large number of publications have been published that describe the behavior of concrete, containing waste and recovered plastic com ponents. However, information is scattered, and no one knows how plastic trash behaves as concrete materials. This research examines the use of plastic waste (PW) as aggregate or fiber in cement mortar and concrete manufacturing. The article reviewed the three most significant features of concrete: fresh properties, mechanical strength, and durability. PW and cement connections were also studied using microstructure analysis (scan electronic microscopy). The results showed that PW, as a fiber, enhanced mechanical performance, but PW, as a coarse aggregate, impaired concrete performance owing to poor bonding. The assessment also identified research needs in order to enhance the performance of PW-based concrete in the future.

Keywords: plastic waste; sustainable concrete; mechanical strength; durability and microstructure analysis

1. Introduction

Cement, sand, coarse aggregate, water, and admixtures are used to make concrete. After water, concrete is the second most used material in the building construction [1–3]. The quality of aggregates, which make up 65–80 percent of the total quantity of concrete, have a significant impact on concrete strength [4]. By the end of 2025, the global materials construction industry expected a 59 percent growth in aggregate demand [5]. Due to the constant manufacture of concrete, natural resources are depleting, resulting in severe environmental consequences [6–9]. Fast economic growth and the emergence of a throw-away culture, on the other hand, have resulted in challenges in garbage managing and its dumping. To address this difficult issue, scholars have started looking at possible alternatives to replace natural aggregates and binding materials [10–14].

Various research studies have been done recently to substitute natural aggregate with waste by-products from manufacturing businesses, vehicles, and electrical items. Plastic's widespread usage and manufacturing reached a total of 359 million tons in 2018 [15]. Acrylonitrile butadiene styrene (ABS) is a thick plastic composed of polycarbonate and acrylonitrile butadiene styrene [4].

China makes more plastic than any other nation, accounting for 15% of the world output. Figure 1 shows the worldwide production of plastics. Plastics, which are already a widespread element of daily life, are becoming more dependent on changes in social attitudes. As new materials are developed, policymakers are faced with new hurdles in controlling their negative impacts. Regulatory tools aimed at reducing the negative impacts of plastics on human health and the ecosystem require adaptations to the manufacturing process, the use of plastics, and the disposal patterns for plastics [16].

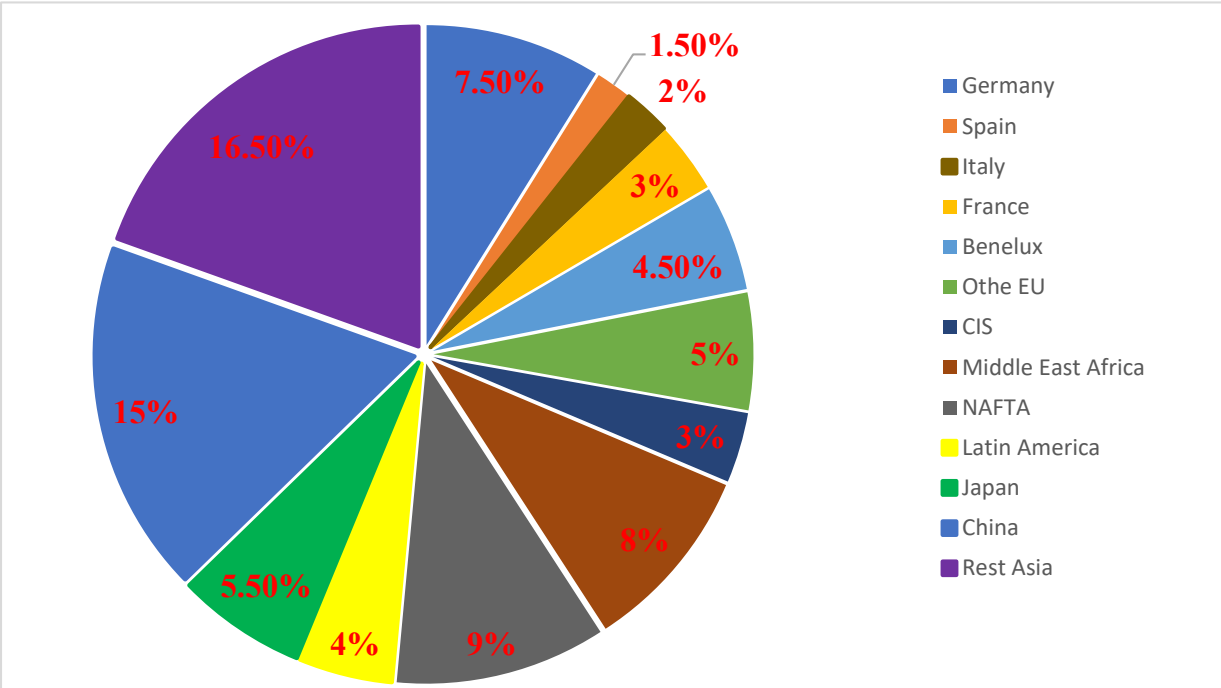

Figure 1. Global Production of Plastics: Data Source [17].

As a result of its adaptability, flexibility, and durability, plastic is employed in various parts of life, involving home and manufacturing usages. Due to its being lighter in weight than metal, plastic has gained prominence in electrical gadgets, packaging materials, and cars. However, as the world's population grows and industrialization accelerates, so does the production of plastic garbage, which presents a huge environmental challenge. To lessen the negative environmental effects of plastic trash, it is critical to recycle and reuse it.

Studies from the 1990s to the current year, have been carried out on the use of plastic fibers to strengthen concrete, which were then followed by studies on the use of polymeric resins and, more recently, plastic aggregates [18]. Recycling garbage into mortar or concrete aggregates provides a number of environmental advantages, although their characteristics are often inferior to those of natural aggregates. This presents the question of determining the best substitution ratio to reduce undesirable substitution effects or enhance mortar properties [18]. Weight and density decline, reduction in absorption, improved toughness, improved ductility and impact resistance, improved acoustic and thermal insulation capacity, and so on, are all benefits of adding polymer waste to concrete in filler or fibers. Along with the foregoing enhancements, and depending on the sort of addition, undesirable consequences, such as those on material compressive strength or durability, might be detected owing to various processes [19,20].

Furthermore, waste plastic's inherent qualities, such as poor fire resistance, surface roughness, and form, may dramatically affect the properties of concrete. As a consequence, substantial study into the influence of waste plastics in concrete has been conducted over the past three decades, as shown in Figure 2. It is clear that the quantity of papers has roughly grown tenfold over this time. Several concerns, however, remain unresolved.

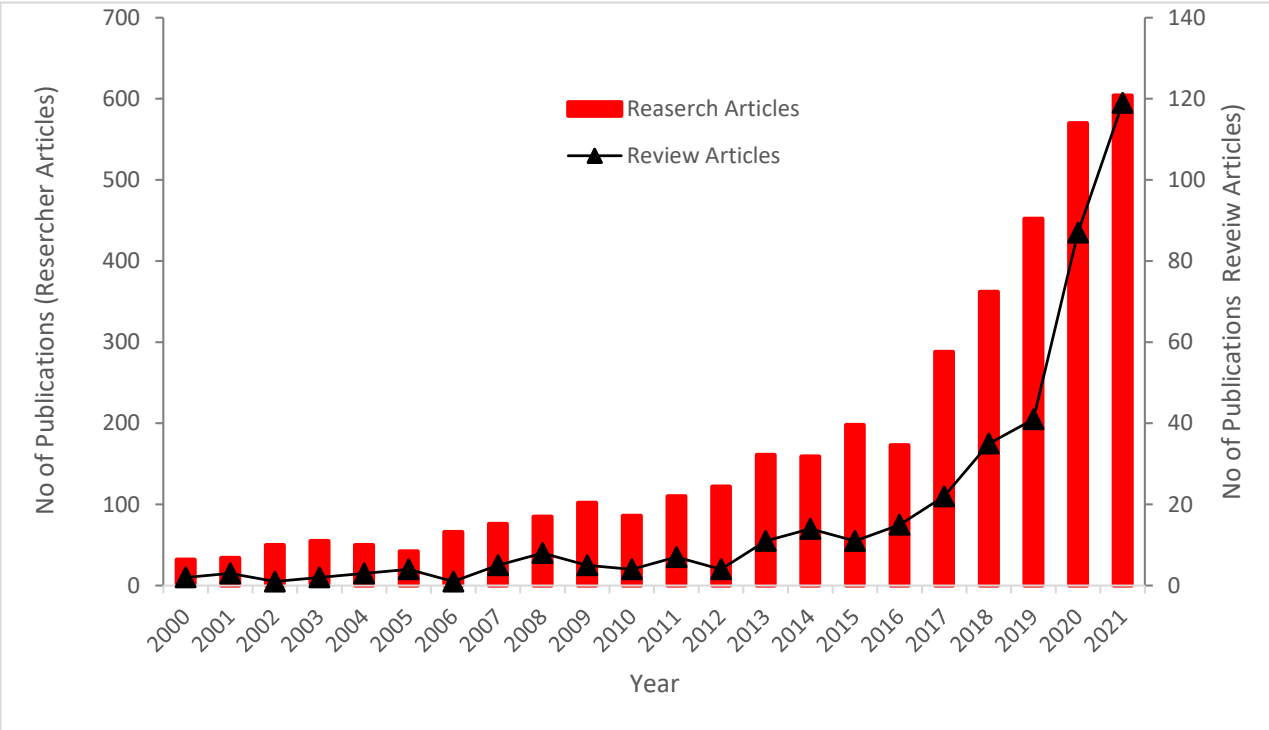

Figure 2. No of the Articles published from 2000 to 2021 on Recycling Plastic Waste: Data source [21].

The review provides a compressive overview of the utilization of PW in concrete. The review concentrates on the main characteristics of concrete, such as fresh properties (slump flow and fresh density), strength properties (compressive strength (CMS), split tensile strength (STS) and flexural strength (FLS)) and durability (water absorption, dry shrinkage and carbonation depth). Microstructure analyses were also considered to study PW and paste bonding. The successful review provides a guideline for researchers to understand the behaviors of PE as a concrete ingredient.

2. Physical Properties

The majority of the published research assessed the qualities of PW to be utilized in concrete. The physical qualities data of PW used by various researchers are organized in Table 1. It should be noted that PW has a near-zero absorption capacity, which will increase concrete flowability. It is also worth noting that the researchers reported varied outcomes. Some of them are rather different. The apparent density, for example, ranges from 350 to 1315 kg/m^3. Changes in the source and kinds of PW might explain the disparity in findings.

Table 1. Properties of Plastic Waste (PW) Used in concrete.

Reference	[22]	[23]	[24]	[18]
Specific gravity	-	-	0.97	-
Water Absorption (%)	0.01	-	0%	0.13
Fineness Modulus	-	2.8	-	-
Moisture Content (%)	-	-	-	-
Apparent density (kg/m^3)	560	350	-	1315
Specific surface (m^2 /kg)	1.67	450	-	-
Bulk Density (kg/m^3)	-	-	620	261.4
Plastic Type	Polyethylene Terephthalate	Low Density Polyethylene	E-Waste	Polycarbonate

Bottles, laptops, LCDs, monitors, and printers were among the plastic garbage collected, and the kind of plastic recovered was acrylonitrile butadiene styrene plastic. The plastic aggregates in this research are made by going through four processing steps. The PW was first washed to remove any dust or clay particles. The E-waste plastic was then crushed in an electric crusher into tiny flakes or shredded particles in the second phase. E-waste flakes were melted in a kiln in the third step. Acrylonitrile butadiene styrene plastic melts at roughly 105 degrees Celsius. Nevertheless, the kiln heat was raised to 200 degrees Celsius to assure optimal melting. Plastic flakes were melted and then chilled in water to make plastic rocks which were crushed to pebbles. Finally, plastic aggregates were created by crushing the plastic rocks. Figure 3 depicts a schematic design of aggregate manufacture. Figure 4 depicts the microstructure of plastic particles, which were non-uniform in shape and size. The non-uniform shape decreased the fluidity of concrete by increasing the friction among concrete constituents.

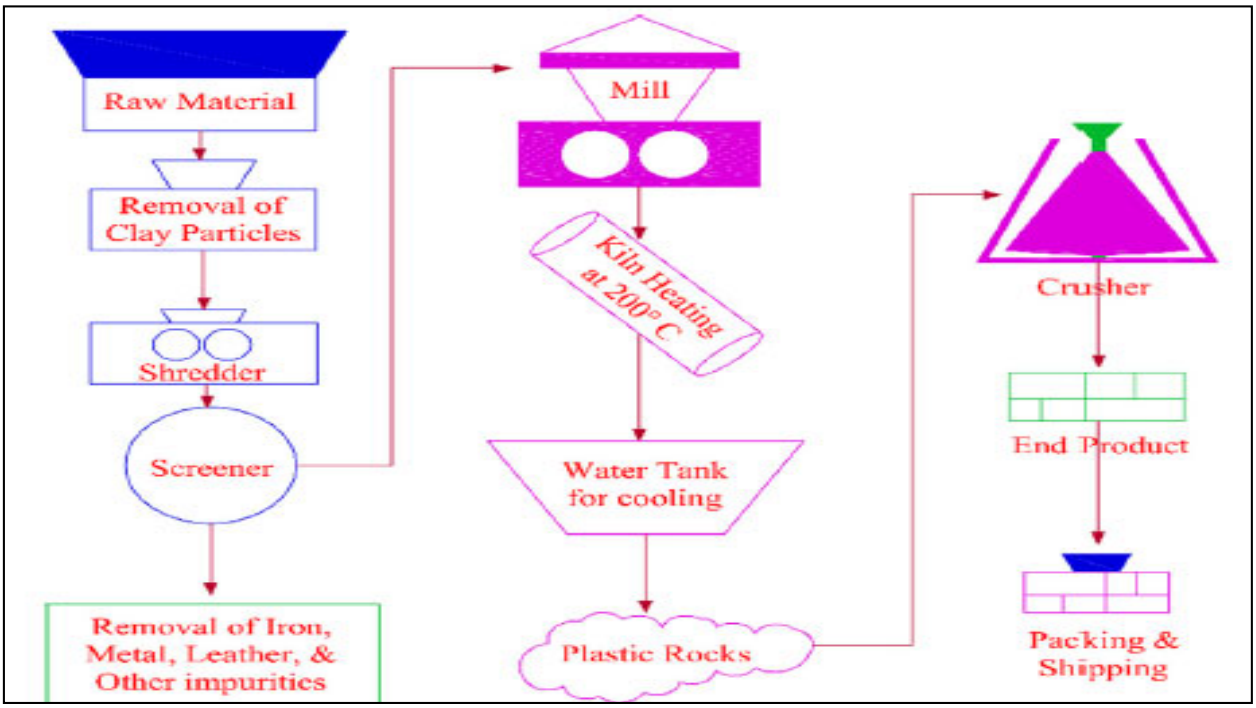

Figure 3. Manufacturing Process of Plastic Aggregates: Used as per Elsevier Permission [24].

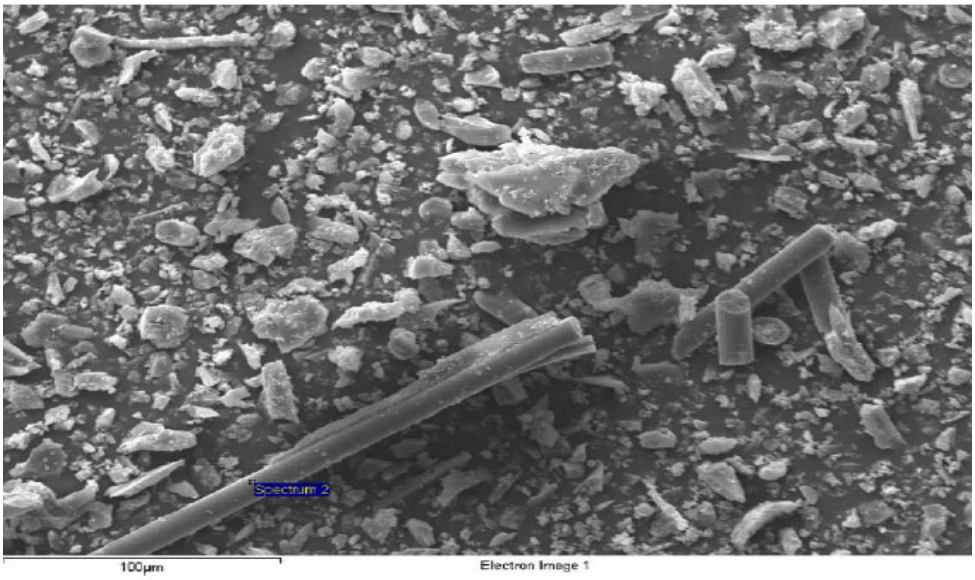

Figure 4. Scan Electronic Microscopy of Plastic Waste: Used as per Elsevier Permission [25].

3. Fresh Properties

Workability

The slump values of different combinations of PW in concrete are shown in Table 2 and Figure 5. Figure 5 shows that, as compared to the control concrete, the slump of concrete mixes decreased as the amount of fine plastic aggregate increased.

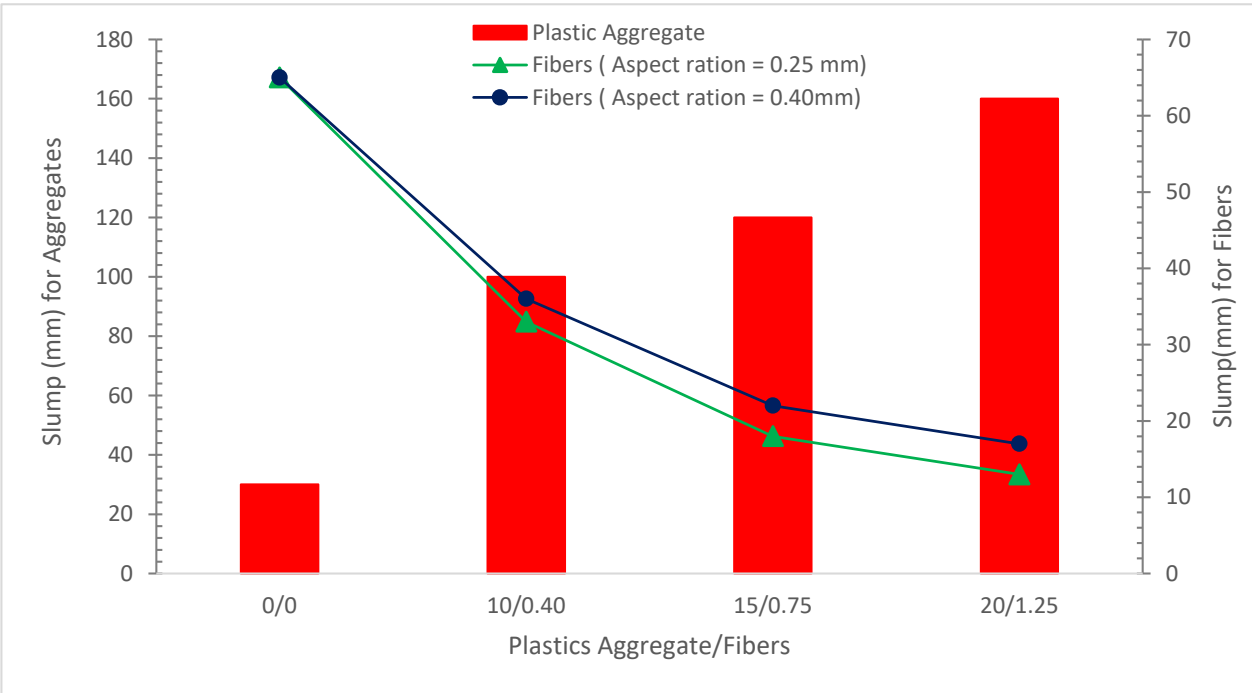

Figure 5. Slump Flow: Data Source [24,26].

The decreased is regardless of type, and these results were comparable with those of previous research [27]. However, plastic waste as fibers reduced the flowability of concrete. The decrease in flowability with fibers was due to a larger surface area which required a larger quantity to cover the surface areas [28,29]. Also, fiber enhanced the friction among concrete components which resulted in decreased flowability. Various researchers

claimed that fibers reduce the flowability of concrete [30–35]. However, plastic waste as aggregate caused an increase in the flowability of concrete. The uneven angular form of the plastic elements contrasted with the smoothed shape of the sand grains caused this drop, which raised particle friction and lowered the workability of the combination. The circular structure of the particles enhanced flowability in general, but the rough sharp shape of the particles reduced the concrete slump [36]. It should be noted, however, that plastic trash may enhance the flowability of concrete. In comparison to sand, the plastic garbage employed in this research had little weight and a small particle size. Furthermore, as compared to sand, the waste had a smaller specific surface area. This aided in the mass gain of the waste generated by mortars. Also, compared to sand, it takes less water to wet the waste surface, which has a significant impact on the fluidity of the mortar [22]. In contrast to natural aggregates, plastic does not absorb water when mixed, according to Saikia et al. [5]. Their results demonstrated that adding PFA to concrete improves its workability. The lower water absorption capacity of plastic sand compared to natural aggregates, the comparatively smooth surface texture of plastic sand, and the correct gradation of PFA-like natural sand all contribute to the greater workability of concrete [24]. This improvement in flowability with the addition of plastic aggregate to concrete has also been reported in previous investigations when the plastic aggregate had a smooth surface [37]. The amount of water needed depends on the aggregate's particular area and water absorption. The overall specific surface of the changed aggregates was smaller than predicted if a further substitution was undertaken, and, hence, might not offset the plastic's non-absorbent qualities, resulting in slight increase in free water and workability [38]. As a result, the assessment suggests that additional research into the flowability qualities of concrete containing plastic trash be conducted.

Table 2. Workability of Concrete with Substitution of Plastic Waste.

Reference	Plastic Waste	Slump (mm)
[24]	0%, 10%, 15% and 20%	30, 100, 120 and 160
[39]	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50%	120, 100, 80 and 60
	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50%	120, 100, 70 and 55
[40]	Plastic fibers (0.25 mm) 0%, 0.40%, 0.75% and 1.25%	65, 33, 18 and 13
	Plastic fibers (0.40 mm) 0%, 0.40%, 0.75% and 1.25%	65, 36, 22 and 17
[41]	0%, 2%, 4%, 6%, 8% and 10%	132, 126, 102, 80, 52 and 14
[23]	Plastic fibers powder content (%) 0%, 10%, 20%, 30% and 40%	70, 80, 90, 105 and 120

4. Mechanical Strength

4.1. Compressive Strength (CMS)

Concrete's compressive strength (CMS) is one of its most essential and useful qualities. Concrete is used as a building material to withstand compressive forces. The CMS is utilized to determine the needed property at sites where tensile strength or shear strength is of main concern. As a result, CMS of concrete and cement mortar is a key feature that is carefully explored in practically all plastic aggregate research.

The CMS of concrete using PW as aggregate, or fibers, is shown in Figure 6 and Table 3. PW as fiber increased the CMS of concrete, whereas PW as aggregate lowered it.

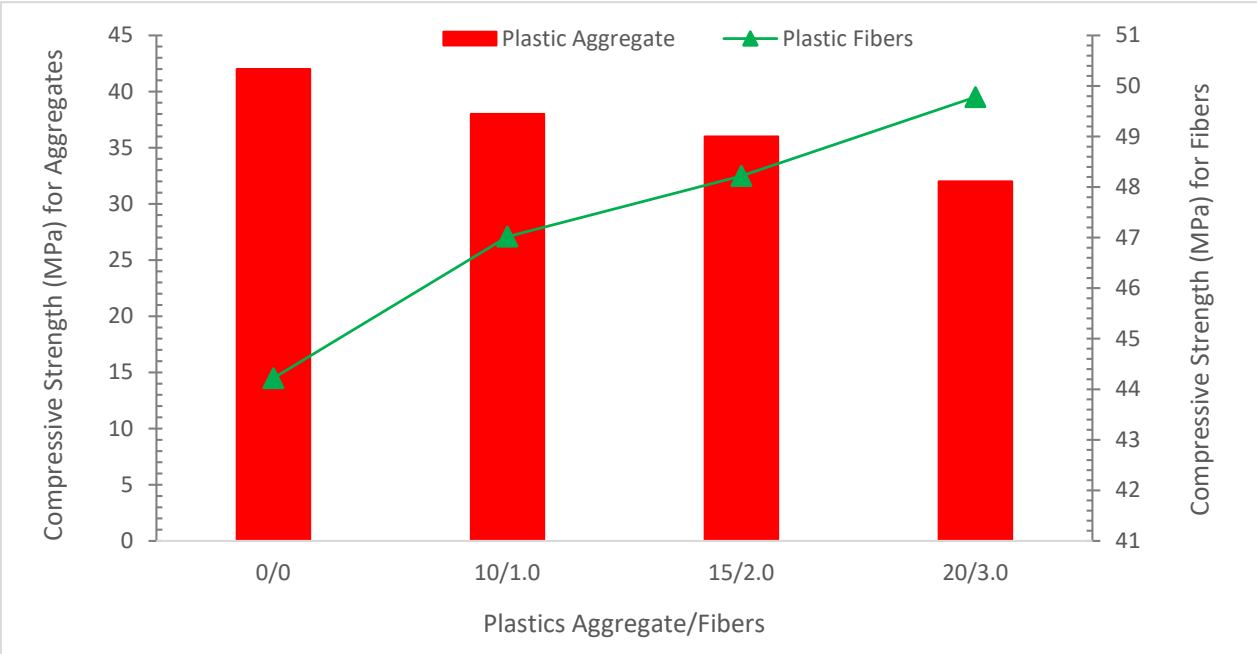

Figure 6. Compressive Strength: Data Source [24,26].

The 28-day CMS of concrete may be reduced by up to 70% when 20 to 100 percent virgin sand is replaced with plastic aggregate [42]. Plastic fiber enhances CMS significantly. The supplement of 3% fiber improves the CMS of standard concrete specimens by 12.5 percent [26]. In comparison to other contents ranging from 0% to 2%, adding 1.5 percent plastic fibers increased CMS [43]. Hama et al. [44] employed three distinct forms of plastic trash to substitute sand in self-compacting concrete and found that rise in plastic content affects self-compacting concrete's CMS. The CMS of concrete is reduced as the size of the plastic sand increases. Fine plastic, coarse plastic, and mixed plastic have CMSs of 47, 37 and 42 MPa, respectively, when 12.5 percent of natural sand is replaced with fine plastic. This is because of the poor bonding among mortar and plastic aggregate [42]. The hydrophobic nature of plastic aggregate and the poor interaction of plastic sand with the cement might explain the reduction in CMS. Plastic aggregates absorb very little water according to research [45], causing extra water in the mix. The extra water causes a film to develop around the aggregates, which produces poor interaction among the aggregates and the cement. SEM observations indicated obvious fractures between the cement matrix and plastic aggregates, as well as a water film around the aggregates, according to Pezzi et al. [46]. According to previous study [47], the fundamental cause of loss of strength is a weak interaction between plastic materials and cement. Despite the kind of plastic aggregate used or the curing time, the CMS of PET aggregate reduces as the replacement of plastic aggregate raises. After 28 days, the CMS of PP-containing concrete at all replacement levels, as well as concrete containing 5% PF, was more than 75% that of reference concrete. Although the rate of degradation was generally moderate, the CMS of concrete continued to worsen as the quantity of plastic fragments grew. The introduction of plastic components may have lowered bonding strength [48].

Table 3. Summary of Compressive Strength (CMS).

Reference	Plastic Waste	Compression Strength (MPa)
[49]	PF 0%, 10%, 15% and 20% PC 20%	7 Days 21.5, 19.6, 18.16 and 16.6 28 Days 30.5, 27.5, 25.3 and 26
[24]	0%,10%,15% and 20%	28 Days 42, 38, 36 and 32
[25]	0%, 5% and 15%	WC 61.45, 70.25 and 65.21 OC 54.80, 66.17 and 59.77
[18]	0%, 7.5% and 15%	7 Days 33, 27 and 25 28 Days 37, 32 and 33 56 Days 45, 40 and 35
[39]	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50% Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50%	16, 15, 14 and 13 16, 14, 13 and 12
[40]	Plastic fibers (0.25 mm) 0%, 0.40%, 0.75% and 1.25% Plastic fibers (0.40 mm) 0%, 0.40%, 0.75% and 1.25%	23.3, 24.1, 26.6 and 23.5 23.3, 26.2, 24.1,.23.4
[50]	0%, 5%, 15% and 25%	28 Days 47.31, 20.65, 4.28 and 1.63
[22]	0%, 10%, 20%, 30% and 50%	3 Days 22, 18, 15, 15 and 17 7 Days 26, 22, 20, 18and 16 14 Days 32, 29, 25, 17 and 16 28 Days 60, 58, 52, 42 and 40.
[51]	2 mm fibers 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%	28 Days 82, 81, 80, 77, 72, 70, 68, 66 and 65
[52]	0%, 10%, 20%, 30% and 40%	28 Days 27, 24, 20, 18 and 15
[53]	PVC 0%, 2.5%, 5%, 10% and 20%	60 Days 32, 27, 20, 14 and 08 120 Days 40, 35, 22, 14 and 09
[41]	0%, 2%, 4%, 6%, 8% and 10%	7 Days 23.20, 21.2, 19.66, 15.33, 13 and 12.20 28 Days 35.05, 34.86, 32.46, 29.80, 22.73, 22.73 and 17.33
[54]	PP plastic in fraction volume (%) 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%	7 Days 17, 18, 19, 16, 13, 12 and 11 28 Days 24, 23, 21, 20, 19, 18 and 18

Table 3. *Cont.*

Reference	Plastic Waste	Compression Strength (MPa)
[26]	0%,1%,2% and 3%	7 Days 34.67, 36.00, 39.11 and 41.78 14 Days 38.36, 40.22, 43.78 and 46.04 28 Days 44.22, 47.02, 48.22 and 49.78
[55]	0%, 2%, 4%, 6%, 8% and 10%	28 Days 21.26, 13.29, 14.43, 11.50, 6.60 and 5.70
[56]	0%, 5%, 10% and 15%	PP 3.7, 3.5, 3.4 and 3.0 PF 3.7, 3.6, 2.0 and 1.9
[57]	0%, 15%, 30%, 45%, 60% and 75%	28 Days 35.0, 42.0, 38.0, 32.8, 29.5 and 20.0
[23]	0%, 10%, 20%, 30% and 40%	28 Days 20, 25, 26, 22 and 21

Oven Curing = OC. Water curing =WC. Plastic fine Aggregate = PF. Plastic Coarse Aggregate = PC. Polyvinylchloride = PVC. Plastic pellets = PP. Plastic flakes = PF.

A study [56] looked at the usage of plastic aggregates in the preparation of mortars. Substitution ratios of 5, 10 and 15% were examined, but only with sand measuring 1–2 mm in size. The CMS and FLS dropped as a result, which may be ascribed to the cementitious matrix weak interaction with the PET particles. It is important to remember that the shape and number of recycled particles used in mortars are significant factors to consider since they may create significant differences in mortar performance [56]. Owing to the inadequate connection among the aggregates and the cement matrix, CMS reduced when waste aggregate plastic was added. The majority of plastic particles in the concrete did not fail after reaching maximum strength. However, alternatively they de-bonded from the cement, demonstrating insufficient binding, as shown in Figure 7.

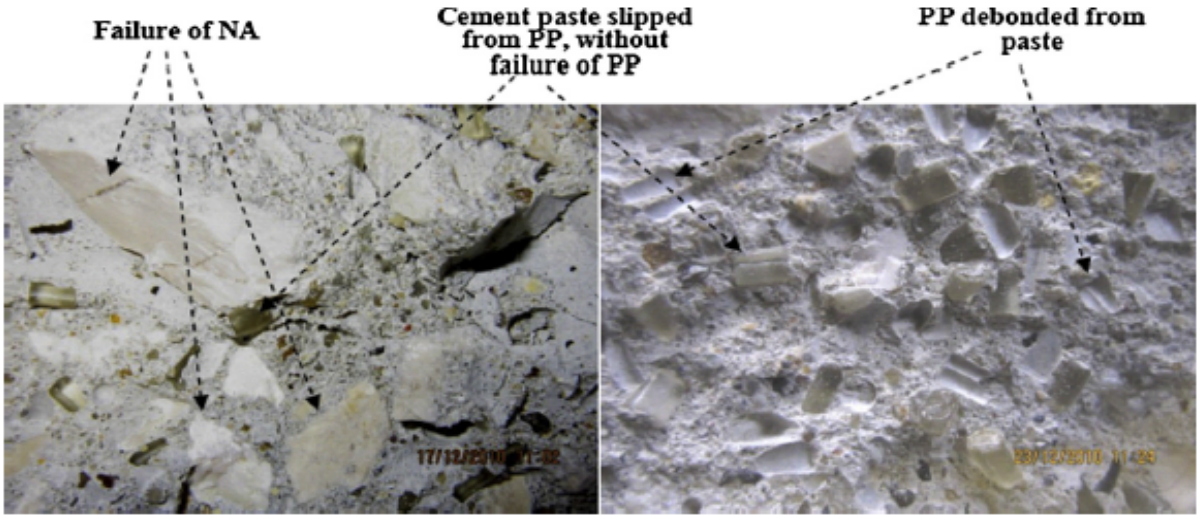

Figure 7. Poor Bond between Plastic and Cement Paste [58].

4.2. Flexural Strength (FLS)

Flexural strength is assessed in terms of stress and is described as a material's capacity to withstand deformation under FLS load. At the collapse load, it reflects the greatest stress

encountered inside the material. The most common test is the transverse bending test, with a three- or four-point FLS test procedure.

The FLS of concrete using PW as aggregate or fibers is shown in Figure 8 and Table 4. PW as fiber enhanced FLS of concrete in the same way as it did for CMS, while PW as aggregate reduced FLS. FLS ranged between 9 and 15 MPa. The FLS differences between PW concrete and conventional concrete were minimal. The plastic trash did not have strong, interlocking connections with the cement, as seen by the surface of the cracked samples [59]. The same rationale applies to the FLS behavior of concrete as it does to the loss of CMS, STS and the decrease of the modulus of elasticity caused by the integration of PET aggregate. After failure, the reference specimen separated into two parts, while the concrete beams combining PET concrete beam and plastic fiber did not. During the test, the PET concrete beam and plastic fiber particles bridged the fracture and saved the specimen from brittle failure [58]. Increased ductility and post-crack flexural toughness of concrete, resulted in almost comparable mechanical qualities (including impact resistance) to equivalent concrete reinforced with polypropylene and high-modulus polyethene fibers [60]. Using plastic cut from scrap plastic containers, concrete specimens containing 0.2–1.0 percent volume fractions of HDPE fibers were tested. The strength tests revealed that using HDPE fibers in a volume of 0.6 percent could boost concrete's CMS, STS, FLS and impact strengths by up to 15 percent, 23 percent, 22 percent, and 200 percent, respectively, with only minor gains when increasing the fiber volumes to 0.8 percent and 1.0 percent [61]. The findings showed that adding PET fibers to mortars enhanced FLS while also increasing mortar toughness [39]. Various researchers have claimed that fibers improved the FLS of concrete due to crack prevention [62–66].As little as 0.75–1.25 percent of additional HDPE fibers (by volume) may keep concrete's post-cracking tensile capability at 30–40 percent of its peak FLS capacity [40]. FLS improved with a rise in PF content of up to 1.75 percent by volume, according to research. Due to the uneven distribution of PFs, increasing the PF concentration reduced the strength, although the value was still greater than the control combination [43]. Other studies revealed similar outcomes for the same kinds of PF and contents [67].

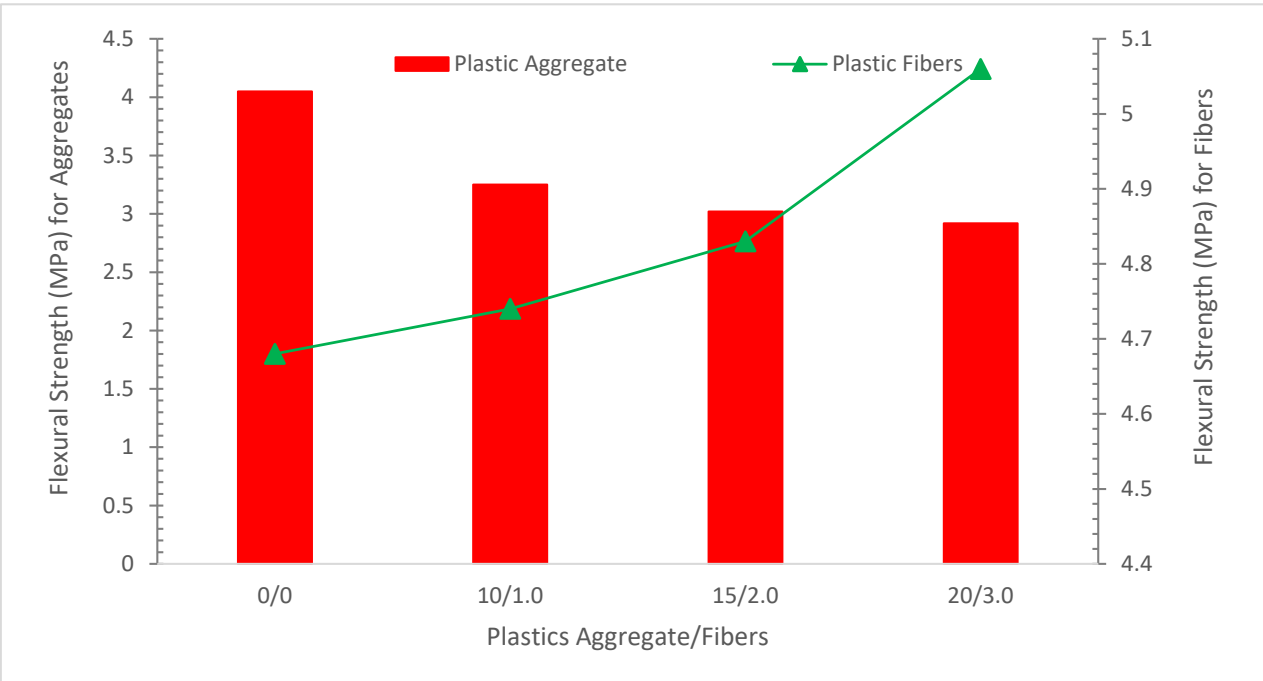

Figure 8. Flexural Strength (FLS): Data Source [26,49].

Table 4. Summary of Flexural Strength (FLS).

Reference	Plastic Waste	Flexure Strength (MPa)
[49]	PF 0%, 10%, 15% and 20% PC 20%	7 Days 2.35, 2.12, 2.17 and 1.72 28 Days 4.05, 3.25, 3.03 and 2.92
[50]	0%, 5%, 15% and 25%	28 Days 15.45, 8.08, 1.95 and 0.29
[22]	0%, 10%, 20%, 30% and 40%	3 Days 6.0, 4.5, 4.5, 4.6 and 4.4 7 Days 6.5, 5.5, 5.0, 4.8 and 4.5 14 Days 7.5, 6.0, 6.0, 58 and 4.7 28 Days 10.5, 8.5, 6.5, 7 and 5.8
[51]	2 mm fibers 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%	28 Days 10.5, 9.5, 8.5, 7.5, 6.5, 6.4, 6.3, 6.2 and 6.1
[52]	0%, 10%, 20%, 30% and 40%	28 Days 4.8, 4.5, 4.2, 3.8 and 3.2
[53]	PVC 0%, 2.5%, 5%, 10% and 20%	60 Days 7.0, 5.8, 5.3, 5.0 and 2.0 120 Days 7.0, 5.8, 4.1, 5.0, 2.0
[41]	0%, 2%, 4% and 6% 10% Fly Ash 0%, 2%, 4% and 6%	28 days 7.0, 7.2, 7.0 and 5.6 7.4, 7.6, 7.2 and 5.2
[54]	0%, 0.1%, 0.2%, 0.3%, 0.5%, 0.7 and 1.0%	28 Days 4.28, 4.17, 4.24, 4.15, 4.62, 5.02 and 4.84
[26]	% of plastic content 0%, 1%, 2% and 3%	7 Days 4.00, 4.24, 4.38 and 4.52 14 Days 4.46, 4.54, 4.69 and 4.72 28 Days 4.68, 4.74, 4.83 and 5.06
[55]	0%, 2%, 4%, 6%, 8% and 10%	28 Days 3.60, 2.70, 2.90, 2.54, 1.77 and 1.72
[56]	0%, 5%, 10% and 15%	PP 1.35, 1.25, 1.20 and 1.18 PF 13.5, 1.25, 0.8 and 0.75
[57]	0%, 15%, 30%, 45%, 60% and 75%	28 Days 3.63, 4.28, 4.00, 3.45, 3.10 and 2.08
[23]	0%, 10%, 20%, 30% and 40%	28 Days 3.5, 4.0, 5.0, 3.7 and 3.9

4.3. Split Tensile Strength (STS)

As mentioned earlier, one of the most important and practical properties of concrete is its CMS. Concrete is a structural material that can sustain compressive pressures. In places where tensile or shear strength is important, compressive strength is used to estimate the required characteristic. The STS of concrete is usually between 10% and 15% of its compressive strength. The STS of concrete using PW as aggregate, or fibers is shown in Figure 9 and Table 5.

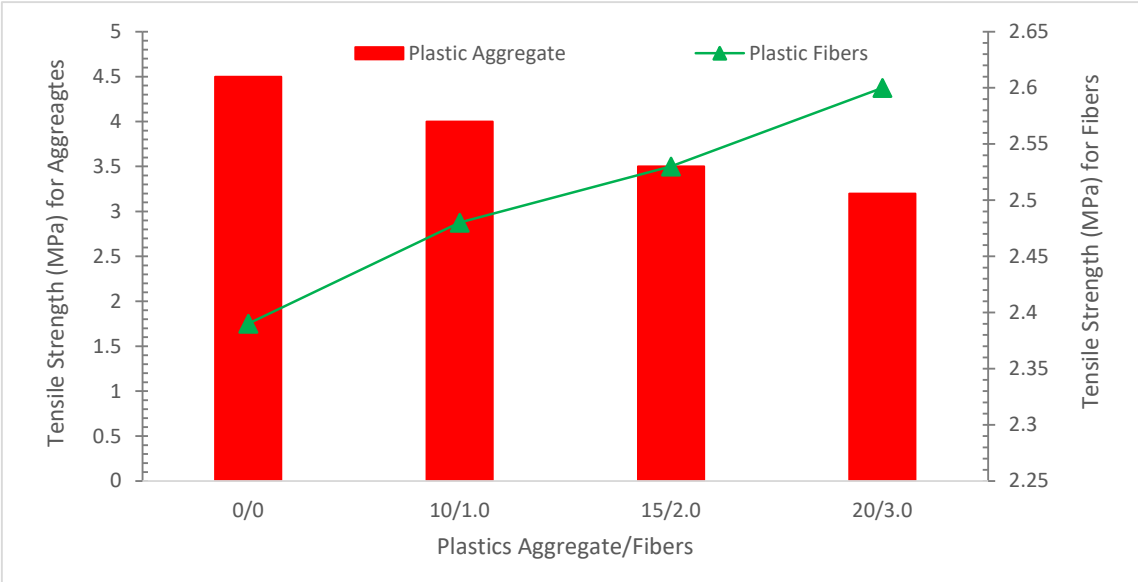

Figure 9. Tensile Strength (STS): Data Source [24,26].

Table 5. Summary of Split Tensile Strength (STS).

Reference	Plastic Waste	Split Tensile Strength (MPa)
[49]	PF 0%, 10%, 15% and 20% PC 20%	7 Days 1.50, 1.46, 1.35 and 1.29 28 Days 2.02, 1.80, 1.73 and 1.69
[24]	0%, 10%, 15% and 20%	28 Days 4.5, 4.0, 3.5 and 3.2
[25]	0%, 5% and 15%	WC 3.85, 4.12 and 4.22 OC 3.23, 3.44 and 4.19
[18]	0%, 7.5% and 15%	28 Days 3.3, 2.7 and 2.5
[39]	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50% Aspect ratio = 2.5 0.10%, 0.25% and 0.50%	1.4, 1.6, 2.1 and 2.2 1.4, 2.0, 2.3 and 2.4
[40]	Plastic fibers (0.25 mm) 0%, 0.40%, 0.75% and 1.25% Plastic fibers (0.40 mm) 0%, 0.40%, 0.75% and 1.25%	2.79, 3.03, 3.93 and 2.88 2.79, 3.08, 2.95 and 2.96
[51]	2 mm fibers 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40%	28 Days 6.5, 6.3, 6.2, 5.8, 5.6, 5.5, 5.3, 5.0 and 4.5
[50]	0%, 5%, 15% and 25%	28 Days 8.19, 4.2, 0.57 and 0.17
[54]	PP plastic in fraction volume (%) 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%	7 Days 2.2, 2.1, 2.3, 2.2, 2.2, 2.1 and 2.1 28 Days 3.0, 2.5, 2.5, 2.4, 2.2, 2.4 and 2.6

Table 5. *Cont.*

Reference	Plastic Waste	Split Tensile Strength (MPa)
[26]	0%, 1%, 2% and 3%	7 Days 2.26, 2.38, 2.45 and 2.49 14 Days 2.34, 2.41, 2.49 and 2.55 28 Days 2.39, 2.48, 2.53 and 2.60
[55]	0%, 2%, 4%, 6%, 8% and 10%	28 Days 2.85, 1.98, 2.21, 1.86, 1.15 and 1.17
[57]	0%, 15%, 30%, 45%, 60% and 75%	28 Days 3.29, 3.85, 3.69, 3.08, 2.62 and 1.80

PW as fiber enhanced STS concrete similarly to compressive strength, whereas PW as aggregate lowered STS. Although recycled plastic fibers in the concrete mix do not greatly boost CMS and STS, they are nonetheless effective for limiting fractures, particularly those induced by shrinking and giving the concrete greater ductility. The fibers stitch the surfaces where the fissures appear. In other words, they prevent brittle and rapid fracture of a material that may display continued post-peak deformation depending on the kind and quantity of fibers utilized [52]. STS improved substantially, according to research [39]. Plastic fibers function to improve the bonding of concrete components and operate on a concept similar to reinforcing, acting as a conveyor medium for stresses in the cracking region, which explains the rise in STS [39]. The increase in STS is related to the fact that plastic fibers can stop fractures from spreading quickly [68]. The STS of the control mix was 4.47 MPa, whereas concrete containing 10, 15 and 20% plastic sand in lieu of natural sand had STS of 3.96, 3.5 and 3.19 MPa, respectively. When just fine plastic was used, the STS was reduced by 29% at maximum replacement. As previously noted, decreases in STS may be ascribed to the hydrophobic nature of plastic, increased surface area, and poor connection of plastic sand with cement matrix [24]. At 28 days of curing age, the addition of 10%, 20%, 30%, and 40% HIPS granules reduced STS by 5.7 percent, 8.3 percent, 11.5 percent, and 16.6 percent, respectively [69]. The decreased bonding between the plastic and the cement paste, caused the STS to drop [70]. According to one research, as the percentage of sand replaced by PET particles grew, the STS of concrete decreased owing to the increased surface area of the fine plastic. Researchers agreed that, like coarse aggregate, replacement of fine plastic was inversely proportionate to concrete STS [71]. The STS of concrete comprising 10, 15 and 20% substitution of natural sand with plastic sand and cement with silica fume, respectively, were 4.13, 4.3 and 4.42 MPa. The reason for the increase in STS of silica fume-containing concrete mixes was the same as for the increase in compressive strength [37]. Silica fume has been shown to boost the STS of concrete in previous experiments [12,72–77].

5. Durability

5.1. Dry Shrinkage

The quick loss of surface bleed water owing to evaporation, as well as the physical and chemical features of additives, determine the shrinkage qualities of concrete. It has been found that having a proper curing technique and avoiding quick curing will help reduce shrinkage [78].

The findings of the shrinkage test with plastic as fibers or aggregate are shown in Figure 10, allowing for the conclusion that the use of recycled plastic aggregates reduced shrinkage. This drop might be linked to a modest reduction in drying capacity. Due to the rise in stiffness with hydration time, and since water evaporation from the capillaries causes shrinkage, slower evaporation caused slower shrinkage, equating to lessened shrinkage.

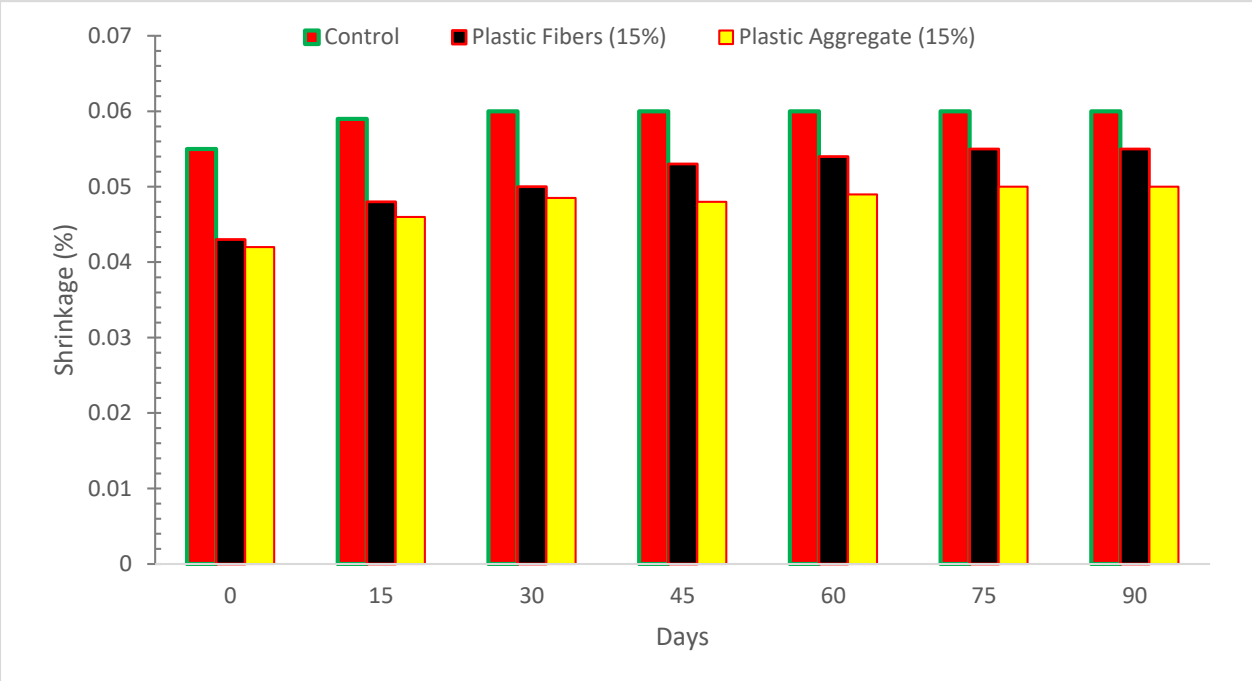

Figure 10. Shrinkage: Data Source [56].

An effort was made to replace 5% of fine concrete aggregate (natural sand) with an equivalent quantity of PET aggregates generated from unwashed PET bottle trash by weight [79]. Kou et al. found that a little increase in drying shrinkage, ranging from 2.3 percent to 2.8 percent. [80] As the number of PVC particles in the mix grew, the drying shrinkage values decreased. After 112 days since demolding the concrete specimens, reductions of 18.1 percent, 31.6 percent, 48.7%, and 72.2 percent were recorded, with replacement rates of 5%, 15%, 30%, and 45 percent, respectively. According to research [81], the addition of plastic flakes may reduce drying shrinkage cracking. It was explored as to whether shredded waste PET bottle grains might be used as aggregate in mortar mixtures [82]. The scientists discovered that mixtures containing solely PET aggregate shrank more when dried than mixes comprising sand and PET. PET fibers' influence on free and restricted shrinking was also investigated [83]. Various studies have shown that fibers reduce shrinkage due to crack prevention [84–86]. Free drying shrinkage strain was larger for recycled PET fiber reinforced concrete specimens than for specimens without fiber reinforcement. When shrinking was restricted, the fibers increased tensile resistance and delayed macro-crack formation. With a volume of 0.40–1.25% high-density plastic fibers added to concrete, crack widths were decreased by more than 50%, indicating that even a little amount of high-density plastic fibers may significantly minimize early plastic shrinkage cracking [40].

5.2. Water Absorption and Porosity

Figure 11 depicts the progression of porosity and water absorption for all mortars over the course of 28 days. The findings show that the porosity of all combinations diminished as the fraction of sand replaced by plastic trash increased.

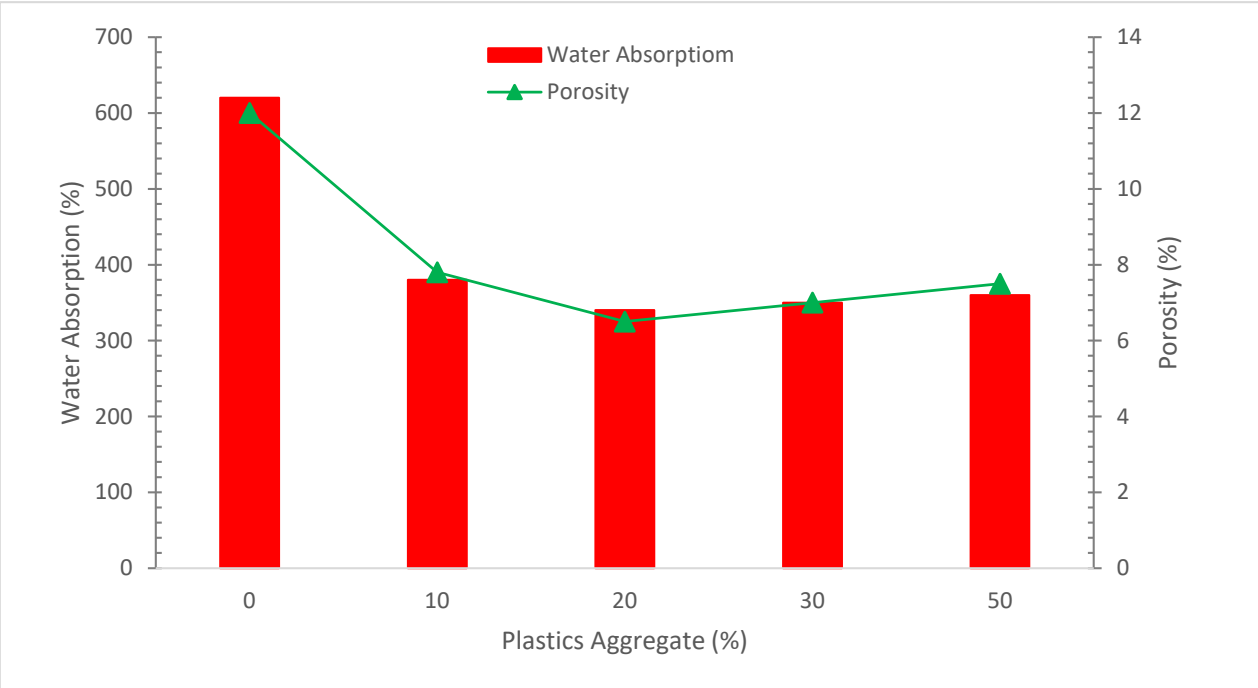

Figure 11. Water Absorption and Porosity: Data Source [22].

A researcher [87] looked at how dry cast concrete blocks with low- and high-density polyethene performed. Water absorption testing revealed that all combinations, including polymer aggregates, had greater results. According to the findings of a study [88] that looked at the physical and mechanical properties of concrete mixes in which different volume fractions of sand were replaced with the same volume of plastic (3 percent, 10%, 20%, and 50%), the water absorption increased as the content of PET aggregates increased. Higher sorptivity coefficient values were reported when natural aggregates were replaced with PET fine aggregates in mortar formulations [37]. A study [89] investigated the impact of various PET aggregate sizes and replacement rates obtained from shredded bottles. When the depth of water penetration was tested, the findings revealed that adding gradually larger sizes and numbers of polymer aggregate fibers decreased the water permeability of concrete by a noteworthy magnitude of 17–42 percent. This demonstrated that HDPE FRC was more durable in use than ordinary concrete. Concrete reinforced with HDPE fibers has less water permeability and plastic shrinkage cracking, which means it will survive longer than plain concrete [40].

5.3. Density

Figure 12 shows the density of concrete made with plastic waste. It can be noted that the density of concrete was reduced with the substitution of plastic waste. Water absorption rose significantly as the quantity of recycled e-plastic components in concrete increased [90]. In comparison to the reference concrete, concrete containing 15% coarse e-plastic absorbed about 100 percent more water. A study [91] found that recycled plastic aggregates may replace natural sand in lightweight foam concrete by 10%, 25%, and 50%, respectively. They found that replacing 10% of the sand with plastic aggregates resulted in roughly the same amount of water absorption. However, this trend did not remain true when the amount of plastic in concrete increased. Plastic aggregates replaced 50 percent of the sand in concrete, increasing water absorption by 117 percent. The increased degree of porosity induced by the plastic particles was responsible for the considerable change in water absorption in concrete [53]. The low density of plastic particles, as well as an increase in porosity, are likely to blame for the drop in concrete density [92]. At 28 days, concrete containing 20%

polyethene (PE) and PVC plastic aggregates increased porosity by roughly 200 percent and 140 percent, respectively [53].

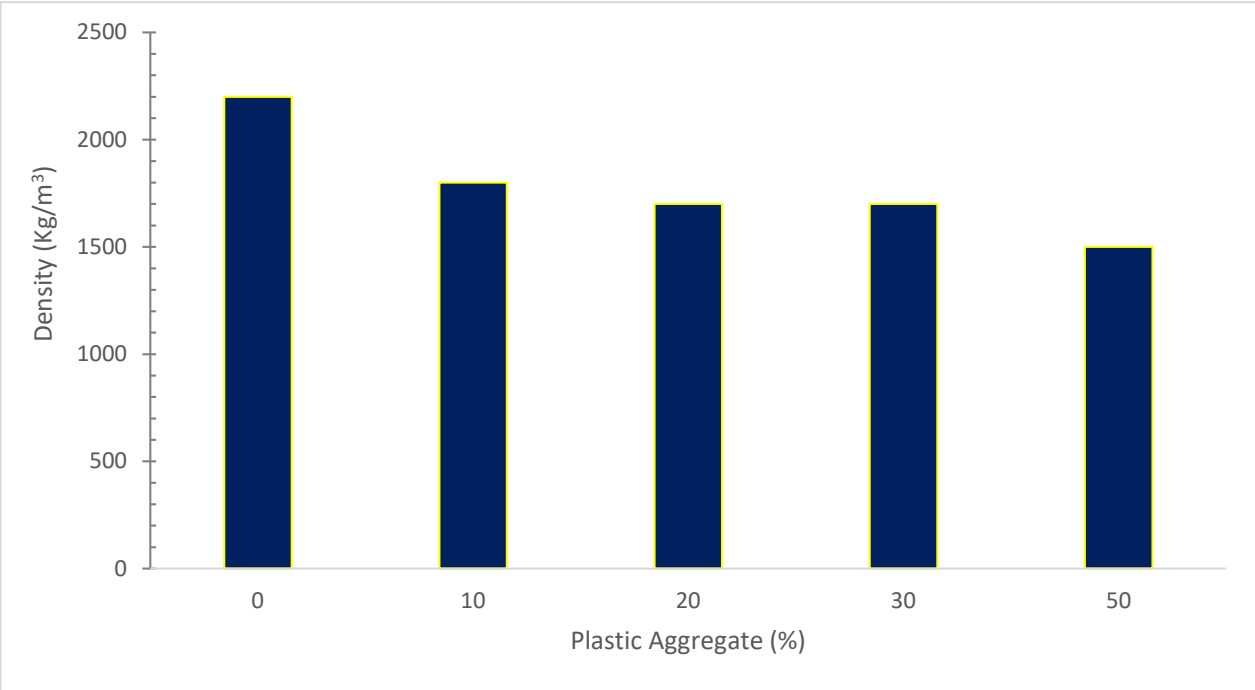

Figure 12. Density: Data Source [22].

5.4. Chloride Penetration

A study [82] investigated the use of PET as a natural aggregate alternative in mortars. Carbonation test findings showed that mortars using solely fine PET aggregates had lower carbonation depths than mixtures including both natural and plastic pebbles. Regarding PVC substituted natural aggregate, Kou et al. [80] observed a rise in chloride diffusion resistance. For concrete mixes with substitution rates of 5%, 15%, 30%, and 45 percent, the total charges passed in coulomb were lowered by 11.9 percent, 19.0 percent, 26.9%, and 36.2 percent, respectively. There is little information available in this area, thus more inquiry is necessary.

6. Scan Electronic Microscopy (SEM)

SEM micrographs of fragmented concrete surfaces with 0:25 mm and 0:40 mm HDPE fibers remaining embedded in 90-day-old concrete are shown in Figure 13. The HDPE fibers' surfaces show no evidence of chemical breakdown, and the observable damage seems to be the consequence of surface friction when fibers were pulled out of concrete during testing.

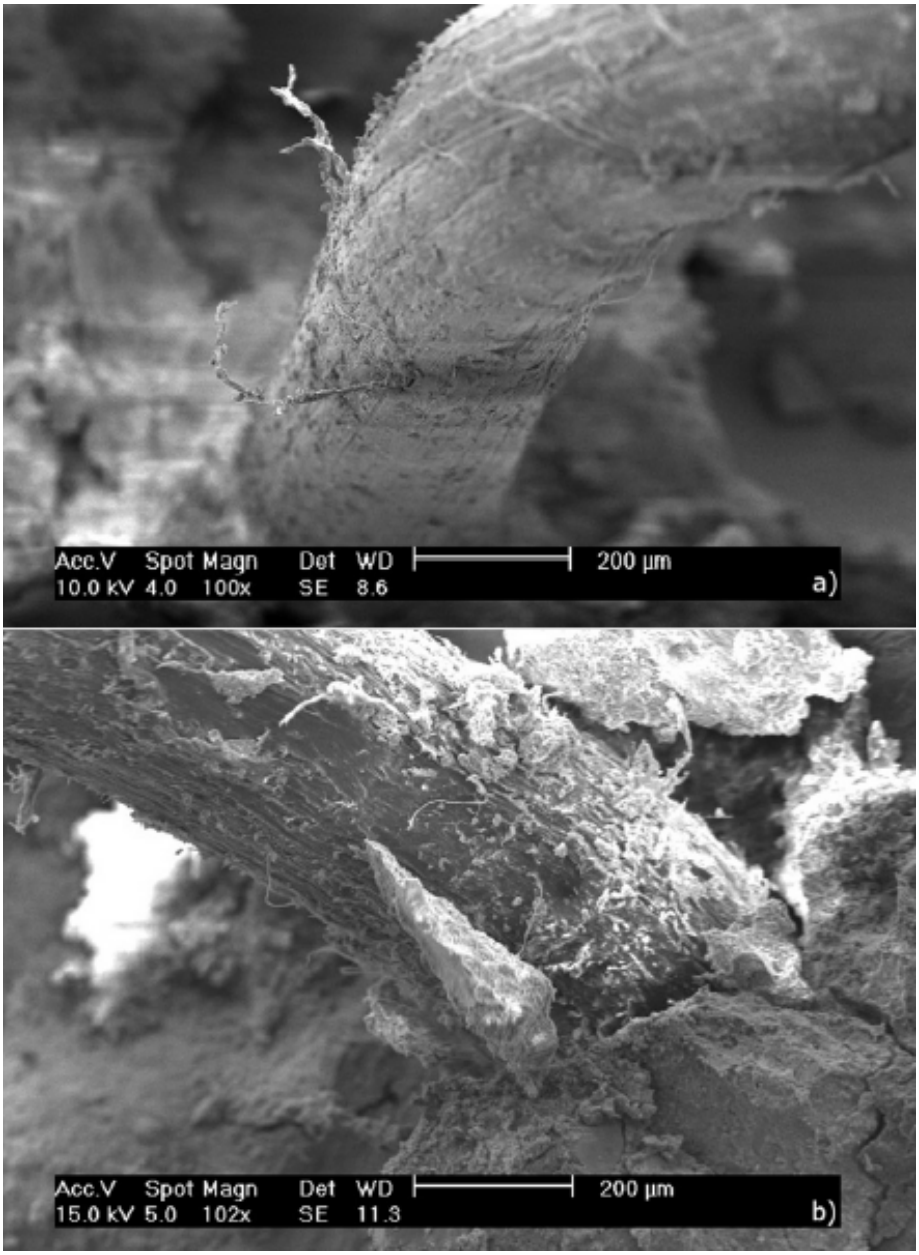

Figure 13. Scan Electronic Microscopy Plastics Waste Fibers (**a**) θ = 0.25 mm and (**b**) θ = 0.40 mm: Used as per Elsevier Permission [40].

Figure 13b illustrates a key flaw with simply extruded HDPE fibers, they do not cling well to concrete and are quickly pulled out when exposed to stress or other deformation when bridging fissures. The binding strength of these recycled HDPE fibers comes only from friction with the surrounding concrete, unlike commercially available PP fibers that have been chemically treated to generate hydrophilic characteristics.

SEM images of plastic aggregate are shown in Figure 14. The interfacial transition zone (ITZ) between plastic aggregate and binder tends to be broader than that between natural aggregate and cement paste. In comparison to the cement matrix and natural aggregates, the SEM study showed a lower adhesion between the cement matrix and PP aggregates. The existence of these pores may cause the compressive strength and unit weight of composite concretes to decrease. According to studies [6,93], poor adhesion between the recycled plastic granulates and the cement matrix causes a loss in the mechanical characteristics of the produced composites. The connection between the cement pastes and the plastic aggregates may be improved by chemically treating the surface of the plastic particles.

A study [47] observed that chemical treatment with Calcium hypochlorite ($Ca(ClO)_2$) increased the binding forces between the cementitious matrix and PET aggregates. As a result, the compressive strength increased.

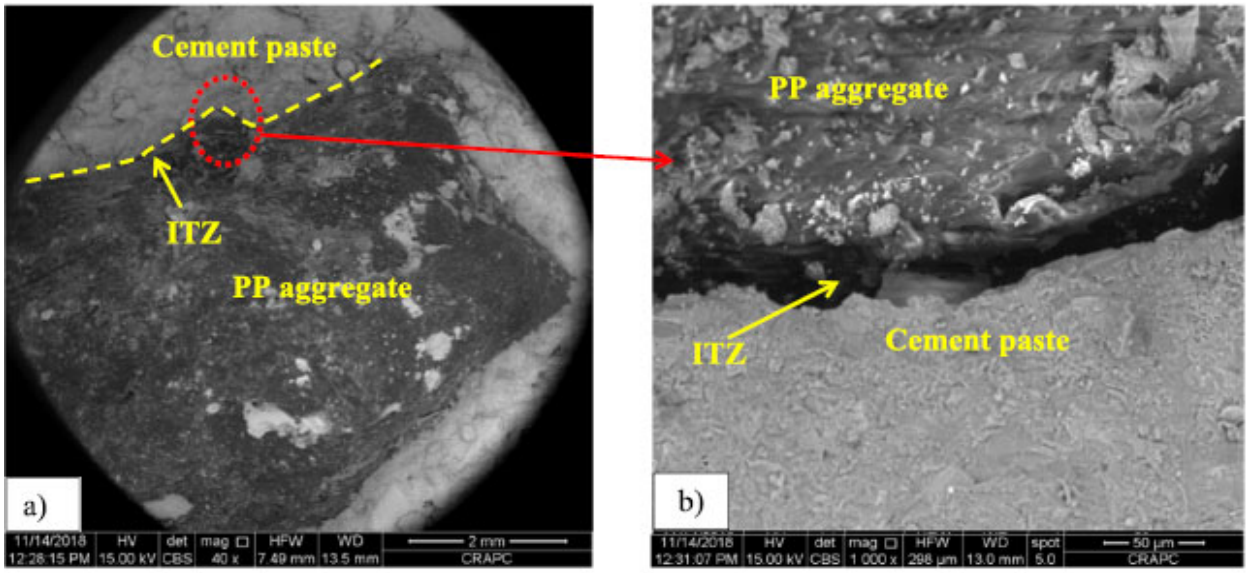

Figure 14. Scan Electronic Microscopy Plastics Waste Aggregate: Used as per Elsevier Permission [92].

7. Environmental Impacts

Plastics, synthetic fabrics, tires and rubber, as well as the PW employed in this study [92], are all products of the petrochemical industry. This form of garbage greatly adds to greenhouse gas emissions. The principal end product of the oxidation of carbon compounds in an incinerator is carbon dioxide (CO^2). As a result, estimating the carbon dioxide emissions from the carbon content of burned garbage is reasonable. In the literature, the mass balance (or material balance) calculation approach is the most often mentioned. This method requires knowledge about the quantity of fossil carbon burned as well as the oxidation rate, which indicates the incineration efficiency.

The greenhouse gas emission variables for various PWs during incineration are summarized in Table 6. According to the research, the combustion of plastic trash emits a significant quantity of carbon dioxide. PE incineration emitted about 813 kg eq C/t, whereas PP incineration emitted approximately 812 kg eq C/t. In comparison to PE and PP, the burning of PVC produced the least quantity of carbon dioxide. Recycling plastic trash in concrete mixes is regarded as one of the most effective ways to reduce pollution caused by energy use, global warming and trash disposal.

Table 6. Release of Corban Dioxide of Plastic: Used as per Elsevier Permission [92].

Plastics	CO_2 (%)	Fossil CO_2	Oxidize	Corbon
PE	85.6%	100%	95%	813 kg eq C/t
PP	85.5%	100%	95%	812 kg eq C/t
PVC	40.1%	100%	95%	381 kg eq C/t

8. Conclusions

A comprehensive review of existing research on the performance of recycled waste plastic in concrete was carried out. The effect of recycled waste plastics in the form of aggregate (fine or coarse) and fiber on the fresh, mechanical, and durability aspects of concrete has been studied. The detailed conclusions are provided below:

- Flowability of concrete decreased with plastics fiber, due to the larger surface area. However, an increase in flowability was observed with plastic waste as aggregates

due to less water absorption. Depending on the particle form, size, roughness, water-cement ratio, and volume of cement paste, the flowability of concrete may improve as the amount of fine recycled waste plastic aggregate rises.

- Mechanical strength, such as compressive, flexural and tensile strength, decreased with plastic aggregate. The decrease in mechanical strength with plastic aggregate is because of a weak bonding between the plastic and the cement paste. Nevertheless, plastic fibers improved mechanical strength, due to crack prevention in a similar way to the other types of fibers.
- The durability of concrete decreased with plastic aggregate while plastic fibers improved the durability of concrete. However, less information is available on the durability of concrete with plastic waste.
- SEM results show that the poor bond of cement paste and aggregate adversely affects the durability and mechanical strength.
- In addition, adding recycled PW into concrete mixes is seen as a viable method for minimizing plastic's environmental effects in terms of pollution, energy consumption, trash disposal, and global warming.

9. Recommendation

- The poor bond between cement paste and plastic aggregate can be improved with pozzolanic or filler materials. Therefore, the review recommends a detailed investigation of plastic-based aggregate with pozzolanic or filler materials.
- Chemical treatment with Calcium hypochlorite ($Ca(ClO)_2$) increased the binding between the cementitious matrix and plastic aggregates, according to Lee et al. [47]. However, there is not a lot of information, and a detailed investigation should be conducted.
- The thermal properties and long-term durability of plastic-based aggregate concrete should be explored before being used practically.

Author Contributions: Writing—original draft preparation, J.A.; Conceptualization, J.A., A.M. and M.S.; methodology, J.A.; software, A.B.E.; validation, A.F.D., A.M. and S.Q.; formal analysis, H.F.I.; investigation, M.S.; resources, A.M.; data curation, S.Q. and H.F.I.; writing—original draft preparation, J.A.; writing—review and editing, A.F.D. and A.M.; visualization, A.F.D. and H.F.I.; supervision, H.F.I. and A.B.E.; project administration, J.A.; funding acquisition, A.F.D. and M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This paper is funded by the deanship of King Khalid University under grant number RGP. RGP.2/152/43.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data are available in manuscript.

Acknowledgments: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Large Groups Project under grant number RGP.2/152/43.

Conflicts of Interest: The authors have no conflict interest.

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