PLASTIC WASTE IN CONSTRUCTION FOR SUSTAINABLE DEVELOPMENT: A COMPREHENSIVE REVIEW

Saniul Haque Mahi[1], Md. Faiag Ahmed Nibir*[2], Tanjun Ashravi Ridoy[3], Saisob Debnath[4] and Sabbir Ahmed Siddiki[5]

[1]Lecturer, Department of Civil Engineering, Dhaka International University, Bangladesh,
e-mail: saniulmahice@gmail.com
[2] Graduate Student, Department of Civil Engineering, Dhaka International University, Bangladesh,
e-mail: muhammadnibir855@gmail.com
[3] Lecturer, Department of Civil Engineering, Dhaka International University, Bangladesh,
e-mail: tanjunashravi41@gmail.com
[4] Graduate Student, Department of Civil Engineering, Dhaka International University, Bangladesh,
e-mail: saisob77d@gmail.com
[5] Graduate Student, Department of Civil Engineering, Dhaka International University, Bangladesh,
e-mail: siddiki.sabbir44@gmail.com

***Corresponding Author**

ABSTRACT

Plastic waste is a major global concern due to its resistance to degradation and limited biodegradability. This type of waste poses a serious threat to the environment by contaminating water bodies, land, and oceans. Nonetheless, the versatile qualities of plastic, including its lightweight, flexibility, strength, moisture resistance, and affordability, make it a potential substitute or alternative to various existing composite materials like concrete. In recent years, researchers have explored the substitution of plastic waste for aggregates in concrete to address environmental challenges. This endeavor aims to mitigate issues by incorporating different types of plastic into concrete formulations, taking advantage of their extended lifespan and reduced weight. This article presents an overview of prior research endeavors investigating the utilization of diverse plastic waste forms in concrete blends. Additionally, it offers a global outlook on how plastic waste impacts concrete's fresh characteristics. It extensively examines the effects of adding plastic waste on the mechanical properties and durability of concrete.

***Keywords**: Plastic waste, plastic fiber, plastic aggregate, mechanical and durability properties, construction material.*

1. INTRODUCTION

The gradual build-up of plastic waste over time, coupled with the absence of effective disposal methods, has led to a critical and unprecedented situation. This crisis manifests in the obstruction of our water resources and waterways, the overflow of landfills, the seepage into the soil, and the airborne transfer, thereby contaminating every natural element in our environment. Despite the advantageous durability of plastic, its prolonged existence becomes a detrimental factor in its proper disposal. In reality plastic materials do not undergo complete degradation but instead break down into smaller fragments over centuries. According to a report from the United Nations Environment Programme (UNEP), the global generation of plastic waste reaches approximately 300 million metric tons annually (Bajracharya, R. M. et al., 2014). While only 9% of plastic waste is currently being recycled, UNEP executive director Inger Andersen warns that by 2050, our landfills could accumulate around a billion metric tons of plastic. Andersen emphasizes the urgent need for a significant shift in our approach to address this impending issue (Ragaert, K. et al., 2017).

To mitigate the adverse environmental impact of plastic waste, it is crucial to engage in recycling and reusing efforts. The use of plastic fibers to reinforce concrete has been the subject of research from the 1990s to the present. Subsequently, studies on the use of polymeric resins and, more recently, plastic aggregates have been done. (Ferreira, L. et al., 2012). Transforming waste into mortar or concrete aggregates offers environmental advantages, even though their characteristics often do not match those of natural aggregates. This prompts the question of determining the optimal substitution ratio to minimize undesirable effects or enhance mortar properties (Ferreira, L. et al., 2012).

The review presents a comprehensive overview of the incorporation of plastic waste in concrete. It focuses on key concrete characteristics including fresh properties (slump flow), strength properties (compressive strength, split tensile strength, and flexural strength) and durability (water absorption, dry shrinkage, and carbonation depth). Microstructure analyses were also considered to examine the bonding between PW and paste. This thorough review serves as a guideline for researchers offering insights into the behaviors of PW (plastic waste) as a concrete ingredient.

2. PHYSICAL PROPERTIES

Most of the available research examines the properties of Plastic Waste (PW) for its potential use in concrete. Table 1 compiles the physical features data of PW as examined by several researchers. It is important to highlight that PW exhibits nearly zero absorption capacity, contributing to increased concrete flowability. Additionally, it's noteworthy that the reported outcomes by researchers vary, with some differences being quite pronounced. For instance, the apparent density ranges from 350 to 1315 kg/m^3. The differences in findings could potentially be attributed to variations in the source and types of PW.

Table 1: Properties of plastic waste (PW) used in concrete.

Reference	(Safi, B. et al., 2013)	(Guendouz, M. et al., 2016)	**(**Ali, K.et al., 2021)	(Ferreira, L et al., 2012**)**
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	PETE	LDPE	E-Waste	Polycarbonate

3. FRESH PROPERTIES

3.1. Workability

Table 2 and Figure 1 present the slump values for various combinations of plastic waste (PW) in concrete. Figure 1 illustrates that, in comparison to the control concrete, the slump of concrete mixes declined with an increase in the quantity of fine plastic aggregates.

Table 2: Slump value of plastic waste (PW) used in concrete.

Reference	Plastic Waste	Slump (mm)
(Ali, K. et al.,2021)	0%, 10%, 15% and 20%	30, 100, 120 and 160
(Khatab, H.R. et al., 2019)	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50%	120, 100, 60 and 60
	Aspect ratio = 2.5 0%, 0.10%, 0.25% and 0.50%	120, 100, 70 and 55
(Peši´c, N. et al 2016)	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
(Kumari, B. et al., 2016)	0%, 2%, 4%, 6%, 8% and 10%	132, 126, 102, 60 and 14
(Guendouz, M. et al., 2016)	Plastic fibers powder content (%) 0%, 10%, 20%, 30% and 40%	70, 80, 90, 105 and 120

The decrease is consistent across types, and these findings align with those from earlier studies **(**Batayneh, M. et al., 2007). Nevertheless, when used as fibers, plastic waste diminished the flowability of concrete. This reduction in flowability with fibers can be attributed to the larger surface area, necessitating a greater quantity to cover those surfaces **(**Figueiredo, A. D.D. et al., 2015; Hung, C. et al., 2020). Additionally, the fibers increased friction among concrete components, leading to a decrease in flowability. Several researchers have contended that the inclusion of fibers in concrete diminishes its flowability **(**Ahmad, J. et al., 2021; Said, A. et al., 2022; Ahmad, J. et al., 2020; Das, G., & Biswas, S. 2016; & Fediuk, R. 2016).

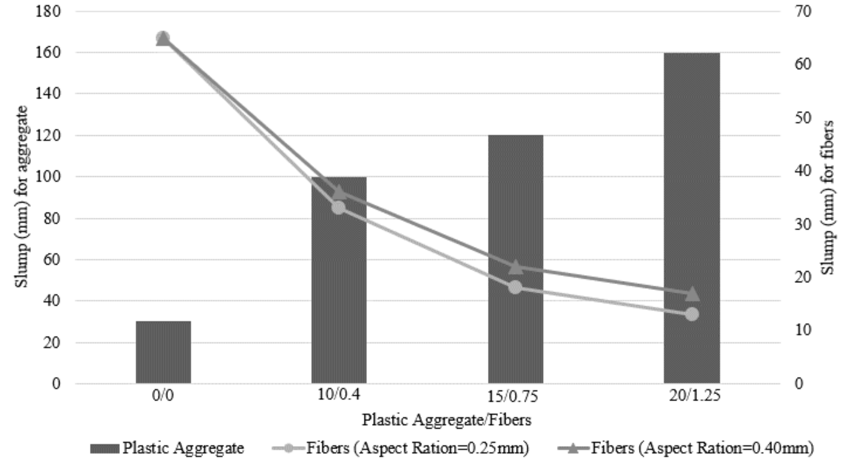

Figure 1: Slumps flows. (Ali, K. et al., 2021; Khatab, H.R. et al., 2019)

In contrast, the use of plastic waste as an aggregate has been found to enhance the flowability of concrete. The plastic waste used as an aggregate had a lower weight and smaller particle size compared to sand. Additionally, the waste aggregate exhibited a smaller specific surface area than sand, facilitating mass gain in the mortars generated from the waste. Moreover, the plastic waste surface requires less water for wetting compared to sand, significantly influencing the fluidity of the mortar (Safi, B. et al., 2013).

4. MECHANICAL PROPERTIES

4.1 Compressive Strength

Compressive strength (CMS) is one of the most important and practical characteristics of concrete. The CMS of concrete with PW fibers or aggregate is displayed in Table 3 and Figure 2 While PW as aggregate decreased the CMS of concrete, PW as fiber raised it.

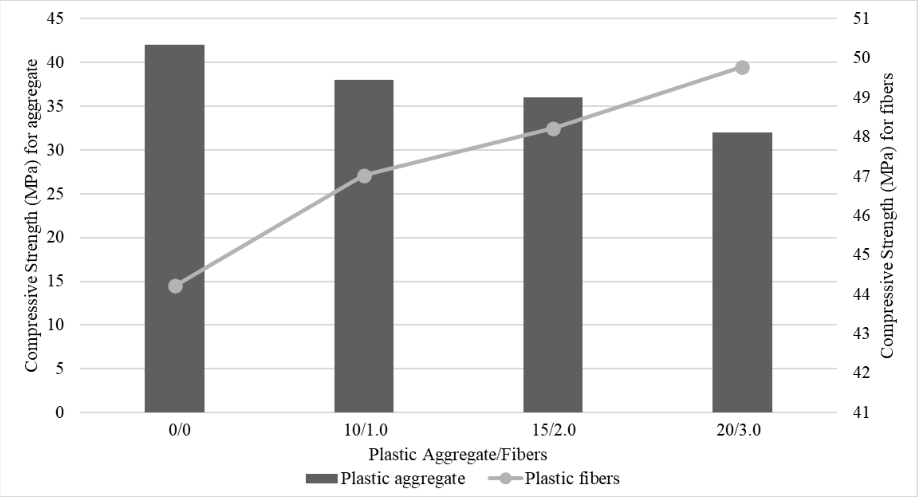

Figure 2: Compressive Strength (Ali et al., 2021; Chen, 2013).

If plastic aggregate is substituted for virgin sand to the extent of 20% to 100%, the 28-day CMS of concrete can be decreased by as much as 70% (Saxena et al., 2018). Plastic fiber significantly improves CMS. A 3% fiber additive raises the CMS of a typical concrete sample by 12.5% (Chen, 2013). Adding 1.5% plastic fibers raised CMS compared to other components ranging from 0% to 2% (Al-Hadithi & Nahla, 2016). When Hama et al. (Hama & Nahla, 2017) used three different types of plastic waste in place of sand in self-compacting concrete, they discovered that an increase in plastic content had an impact on the CMS of the concrete. As the size of the plastic sand grows, the CMS of concrete decreases. When 12.5% of natural sand is substituted with fine plastic, the CMSs of fine plastic, coarse plastic, and mixed plastic are 47, 37 and 42 MPa, respectively. This results from the inadequate adhesion between the plastic aggregate and mortar (Saxena et al., 2018).

Table 3: Summary of Compressive Strength (CMS).

Reference	Plastic Waste	Compressive Strength (MPa)
(Raghatate, 2012)	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
(Ali et al., 2021)	0%,10%,15% and 20%	28 Days 42, 38, 36 and 32
(Asokan et al., 2010)	0%, 5% and 15%	WC 61.45, 70.25 and 65.21 OC 54.80, 66.17 and 59.77
(Pešić et al., 2016)	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
(Faraj et al., 2020)	2 mm fibers 0%, 5%, 10%, 15%, 20%, 25%, 30%,	28 Days 82, 81, 80, 77, 72, 70, 68, 66

Reference	Plastic Waste	Compressive Strength (MPa)
	35% and 40%	and 65
(Chen, 2013)	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
(Mulyono et al., 2021)	0%, 2%, 4%, 6%, 8% and 10%	28 Days 21.26, 13.29, 14.43, 11.50, 6.60 and 5.70
(da Silva et al., 2014)	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

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

The decrease in CMS may be explained by the hydrophobic properties of plastic aggregate and the inadequate cement-plastic sand interaction. Research has shown that plastic aggregates absorb very little water (Islam et al., 2016), which results in an excess of water in the mix. A film forms around the aggregates as a result of the excess water, which hinders the aggregates' ability to interact with the cement. Pezzi et al. (Pezzi et al., 2006) reported that SEM investigations revealed visible fractures between the flexible aggregates and cement matrix as well as a water film surrounding the aggregates. A prior study (Lee et al., 2019) found that a poor interaction between plastic materials and cement is the primary cause of strength loss. The CMS of PET aggregate decreases when the replacement of plastic aggregate increases, regardless of the type of plastic aggregate employed or the curing duration. Following a 28-day period, the CMS of concrete with plastic pellets (PP) at every replacement level and concrete with 5% plastic fine aggregate (PF) exceeded 75% of the reference concrete. The CMS of concrete deteriorated at a usually moderate rate, but it got worse as the number of plastic fragments increased. It's possible that the addition of plastic components reduced the bonding strength (Raghatate, 2012).

4.2 Flexural Strength

Flexural strength, also known as modulus of rupture, represents the maximum bending stress a material can withstand before yielding. At the point of collapse, the material experiences the highest level of stress. A three- or four-point FLS test approach is used for the most popular test, transverse bending testing.

Results for FLS in concrete with PW aggregate or fibers are shown in Figure 3 and Table 4. Similar to its effect on CMS, PW as fiber improved concrete FLS; however, PW as aggregate decreased FLS. FLS values were 9–15 MPa. When comparing PW concrete with regular concrete, the FLS differences were small. The surface of the fractured samples demonstrated that the plastic waste did not form strong, interlocking contacts with the cement (A.M.M. et al., 2021). The reasoning behind the reduction in modulus of elasticity, loss of CMS and split tensile strength (STS), and modification to concrete's flexural strength (FLS) behavior due to the addition of PET aggregate is identical to that which underlies these outcomes. When the reference specimen failed, it split in half, but the concrete beams made from a combination of PET and plastic fiber did not. The specimen was spared brittle failure during the test because the PET concrete beam and plastic fiber particles bridged the crack (Saikia & De Brito, 2014).

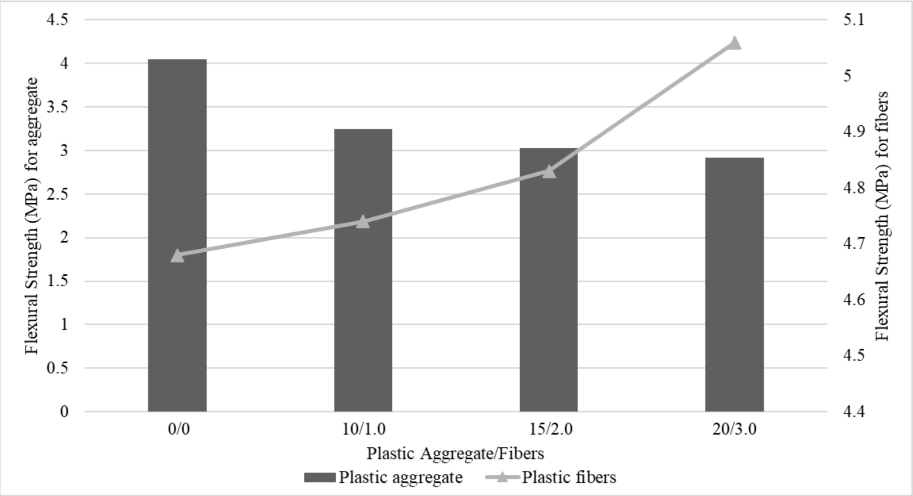

Figure 3: Flexural Strength (FLS) (Chen, 2013; Jaivignesh & Sofi, 2017).

Concrete samples with volume fractions of high-density polyethylene (HDPE) fibers ranging from 0.2 to 1.0 percent were evaluated using polyethylene that was cut from waste plastic containers. The results of the strength tests showed that adding HDPE fibers to concrete at a volume of 0.6 percent might increase its CMS, STS, FLS, and impact strengths by up to 15 percent, 23 percent, 22 percent, and 200 percent, respectively. Increasing the fiber volumes to 0.8 percent and 1.0 percent only resulted in negligible benefits (Bhavi et al., 2012). The results indicated that adding PET fibers to mortars increased mortar toughness and improved FLS (Khatab et al., 2019). According to many studies, fibers increase the FLS of concrete by preventing cracks (Ahmad et al., 2021; Cosgun, 2015; Li et al., 2004; Sharafeddin et al., 2013; Yin et al., 2019). The addition of only 0.75–1.25% of HDPE fibers (by volume) might maintain concrete's post-cracking tensile capability at 30–40% of its maximum FLS capacity (Pešić et al., 2016). Research showed that FLS improved with increases in PF concentration of up to 1.75 percent by volume. Increasing the PF concentration decreased the strength because of the uneven distribution of PFs, but the value was still higher than the control combination (Al-Hadithi & Hilal, 2016). The same types of PF and ingredients showed comparable results in other research (Khairi Mosleh Frhaan & I. Al-Hadithi, 2017).

Table 4: Summary of Flexural Strength (FLS).

Reference	Plastic Waste	Flexure Strength (MPa)
(Jaivignesh & Sofi, 2017)	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
(Faraj et al., 2020)	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
(Ruiz-Herrero et al., 2016)	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
(Chen, 2013)	% 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
(Mulyono et al., 2021)	0%, 2%, 4%, 6%, 8% and 10%	28 Days 3.60, 2.70, 2.90, 2.54, 1.77 and 1.72
(Da Silva et al., 2014)	0%, 5%, 10% and 15%	PP 1.35, 1.25, 1.20 and 1.18

Reference	Plastic Waste	Flexure Strength (MPa)
		PF 13.5, 1.25, 0.8 and 0.75
(Mahmoud Hama, 2021)	0%, 15%, 30%, 45%, 60% and 75%	28 Days 3.63, 4.28, 4.00, 3.45, 3.10 and 2.08

4.3 Split Tensile Strength

As previously said, the CMS of concrete is among its most significant and useful characteristics. Withstanding compressive forces is a capability of concrete as a structural material. Compaction strength is used to determine the necessary characteristic in applications where shear or tensile strength are crucial. Within 10% to 15% of its compressive strength is typically the concrete's STS. Table 5 and Figure 4 illustrate the STS of concrete that uses PW as aggregate, or fibers.

Similar to compressive strength, PW as fiber increased STS in concrete, whereas PW as aggregate decreased STS. Recycled plastic fibers in the concrete mix are useful for reducing fractures, especially those caused by shrinkage, and increasing the ductility of the material, even if they do not significantly increase CMS and STS. The areas where the cracks occur are stitched by the fibers. Put another way, they stop the brittle and quick fracture of a material that, depending on the kind and number of fibers used, may exhibit continuous post-peak deformation (Hafiz Kamarudin et al., 2016). According to studies, STS significantly improved (Khatab et al., 2019). The reason for the increase in STS is because plastic fibers work similarly to reinforcing to promote the bonding of concrete components by serving as a conveyor medium for stresses in the cracking zone (Khatab et al., 2019). The ability of plastic fibers to prevent fractures from spreading quickly is linked to the rise in STS (Ghernouti et al., 2015). The pore water sensitivity (STS) of the control mix was 4.47 MPa, whereas concrete with 10, 15 and 20% plastic sand instead of natural sand showed STS values of 3.96, 3.5 and 3.19 MPa, respectively. The STS was lowered by 29% at maximum replacement when only fine plastic was utilized.

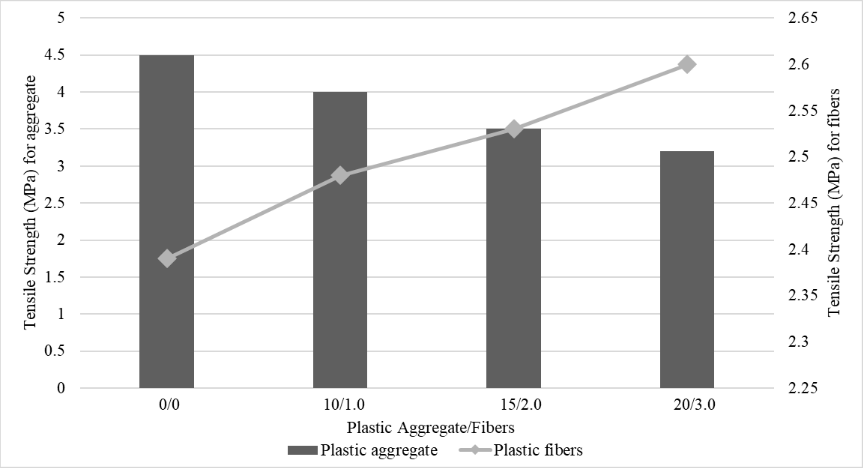

Figure 4: Tensile Strength (STS) (Ali et al., 2021; Chen, 2013).

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

Reference	Plastic Waste	Split Tensile Strength (MPa)
(Jaivignesh & Sofi, 2017)	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
(Ali et al., 2021)	0%, 10%, 15% and 20%	28 Days 4.5, 4.0, 3.5 and 3.2
(Asokan et al., 2010)	0%, 5% and 15%	WC 3.85, 4.12 and 4.22 OC

Reference	Plastic Waste	Split Tensile Strength (MPa)
		3.23, 3.44 and 4.19
(Khatab et al., 2019)	Plastic fibers (0.25 mm) 0%, 0.40%, 0.75% and 1.25%	2.79, 3.03, 3.93 and 2.88
	Plastic fibers (0.40 mm) 0%, 0.40%, 0.75% and 1.25%	2.79, 3.08, 2.95 and 2.96
(Faraj et al., 2020)	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
(Chen, 2013)	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
(Mulyono et al., 2021)	0%, 2%, 4%, 6%, 8% and 10%	28 Days 2.85, 1.98, 2.21, 1.86, 1.15 and 1.17
(Mahmoud Hama, 2021)	0%, 15%, 30%, 45%, 60% and 75%	28 Days 3.29, 3.85, 3.69, 3.08, 2.62 and 1.80

As previously mentioned, declines in STS may be attributed to plastic's hydrophobicity, its larger surface area, and the way that plastic sand and cement matrix are not well connected (Ali et al., 2021). When 10%, 20%, 30%, and 40% HIPS granules were added at 28 days of curing age, STS decreased by 5.7%, 8.3%, 11.5 percent, and 16.6%, respectively (Şahmaran et al., 2006). The STS dropped as a result of the plastic and cement paste's diminished binding (Yang et al., 2015). One study found that the STS of concrete dropped as the proportion of sand replaced with PET particles rose because the fine plastic's surface area increased. The substitution of fine plastic with coarse aggregate was shown to be negatively correlated with concrete STS by the researchers (Rahmani et al., 2013). The specific gravity of concrete that had 10, 15, and 20% substitutions of plastic sand for natural sand and silica fume for cement were 4.13, 4.3, and 4.42 MPa, respectively. The same factor that contributed to the rise in compressive strength was also responsible for the rise in STS in concrete mixtures containing silica fume (Choi et al., 2009). Previous investigations have shown that silica fume increases the STS of concrete (Abdelgader et al., 2019; Althoey & Farnam, 2019; Ding & Li, 2002; Güneyisi et al., 2012; Jalal et al., 2015; Khan et al., 2020; Rajesh et al., 2020).

5. DURABILITY

5.1 Water Absorption and Porosity.

Figure 5 illustrates the evolution of porosity and water absorption in all mortar formulations during the 28-day period. The results indicate a consistent reduction in porosity across all combinations as the proportion of sand replaced by plastic waste increased.

An investigator (Chidiac, S. et al., 2011) examined the performance of dry-cast concrete blocks incorporating low- and high-density polyethylene. Results from water absorption testing indicated that all formulations, inclusive of polymer aggregates, exhibited higher levels of water absorption. A study (Choi et al., 2011) investigating the physical and mechanical properties of concrete mixes with varying volume fractions of sand replaced by equivalent volumes of plastic (3 percent, 10%, 20%, and 50%) found an increase in water absorption corresponding to the augmentation of PET aggregates. Enhanced sorptivity coefficient values were observed when PET fine aggregates replaced natural aggregates in mortar compositions (Choi, Y., et al., 2005). Another study (Albano, C. et al., 2009) explored the influence of different sizes and replacement rates of PET aggregates derived from shredded bottles. Examination of water penetration depth revealed that progressively incorporating larger sizes and quantities of polymer aggregate fibers resulted in a significant reduction in the water permeability of concrete by a notable magnitude of 17–42 percent. This underscored the greater durability of high-density polyethylene fiber-reinforced concrete (HDPE FRC) compared to standard concrete. Concrete reinforced with HDPE fibers exhibited reduced water permeability and plastic shrinkage cracking, indicating its potential for extended longevity compared to plain concrete (Pešić, N. et al., 2016).

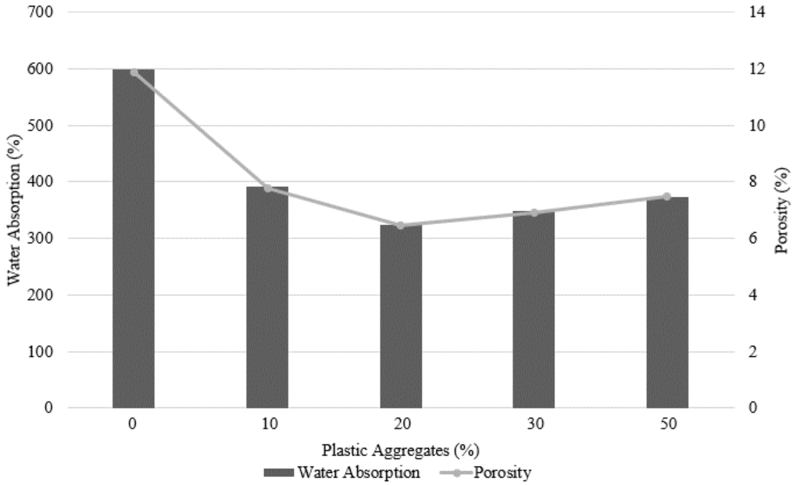

Figure 5: Water absorption and Porosity (Safi, B. et al., 2013)

5.2 Density

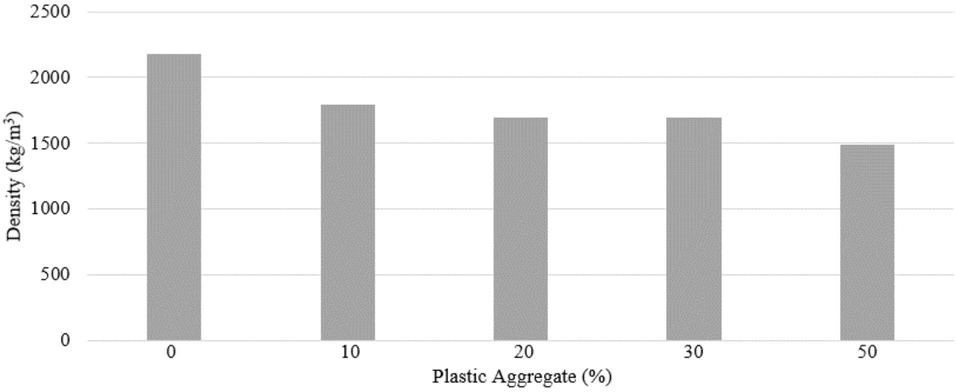

Figure 6: Density (Safi, B. et al., 2013)

Figure 6 shows the density of concrete incorporating plastic waste. It is evident that the density of the concrete decreases with the substitution of plastic waste. The water absorption exhibits a notable increase as the quantity of recycled e-plastic components in the concrete rises (Akram, A., et al., 2015). Compared to the reference concrete, the concrete containing 15% coarse e-plastic experienced approximately a 100 percent increase in water absorption. In a separate investigation (Albano, C. et al., 2009), it was found that recycled plastic aggregates could replace natural sand in lightweight foam concrete at rates of 10%, 25%, and 50%, respectively. Substituting 10% of the sand with plastic aggregates resulted in a water absorption level comparable to that of the reference concrete. However, this pattern did not persist as the proportion of plastic in the concrete increased. When plastic aggregates replaced 50 percent of the sand, water absorption surged by 117 percent. The heightened porosity induced by the presence of plastic particles played a significant role in the substantial change in water absorption in concrete (Coppola, B. et al., 2018). The reduced density of plastic particles, coupled with an increase in porosity, is likely responsible for the decline in concrete density (Yaakob, M. et al., 2016). After 28 days, concrete incorporating 20% polyethylene (PE) and PVC plastic aggregates exhibited an increase in porosity of approximately 200 percent and 140 percent, respectively (Coppola, B. et al., 2018).

6. CONCLUSIONS

The effective and beneficial management of increasing plastic waste in our environment can be strategically addressed through recycling and reuse. This review provides a concentrated overview of ongoing research endeavors aimed at incorporating plastic waste into construction materials. The influence of recycled waste plastics in the form of aggregate (fine or coarse) and fiber on the fresh, mechanical, and durability characteristics of concrete has been examined. The detailed conclusions are stated below:

- The flowability of concrete experiences a decline when incorporating plastic fibers, attributed to their increased surface area. Conversely, the use of plastic waste as aggregates enhances flowability by reducing water absorption. The flowability of concrete may vary depending on factors such as particle shape, size, roughness, water-cement ratio, and volume of cement paste, potentially increasing with the growth of fine recycled waste plastic aggregate.
- The mechanical strength, encompassing compressive, flexural, and tensile strength, diminishes when using plastic aggregates. This decline in strength is attributed to an insufficient bond between the plastic and the cement paste. Conversely, the inclusion of plastic fibers improves mechanical strength by effectively preventing cracks, similar to the positive impact observed with other fiber types.
- The durability of concrete diminished when using plastic aggregate, whereas the inclusion of plastic fibers contributed to improved concrete durability. However, there is limited information regarding the durability of concrete incorporating plastic waste.

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