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Influence of replacing aggregates by recycled waste plastic on the mechanical properties of concrete: A review

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Abstract

The rapid escalation in plastic production and consumption has resulted in a substantial increase in plastic waste, presenting serious environmental issues. In recent years, researchers have explored the possibility of using recycled plastic as an alternative aggregate in high-strength concrete, aiming to mitigate plastic waste and improve sustainability in construction practices. This study reviews the effects of incorporating recycled Plastic Aggregates (PA) on the properties of high-strength concrete. The review examines the effect of PA on concrete's physical, mechanical, and durability characteristics, highlighting both the potential benefits, such as enhanced energy absorption and sulfuric acid resistance, as well as limitations, including reduction in compressive strength. Current research indicates that despite changes in mechanical properties, concrete with recycled PA remains viable for many engineering applications. The findings confirm the need for further investigation into pre-treatment methods to optimize plastic aggregate performance, contributing to sustainable waste management and eco-friendly construction solutions.

1. Introduction

The growing production of waste materials, especially plastics and industrial by-products like slag, ceramics, ash, glass, and recycled concrete aggregate, has resulted in their extensive application in concrete manufacturing. These substances are now being utilized in conventional construction and cutting-edge technologies such as 3D printing [1–3]. Studies have shown that these materials can improve concrete characteristics, but only within certain thresholds, necessitating research to determine the optimal amount that preserves concrete's essential engineering properties. Waste products like glass and plastic, which present environmental risks and are often disposed of in landfills, are being investigated for various concrete uses [4–6].

Plastic production has seen exponential growth since its industrial debut in the 1920s, owing to its numerous benefits over alternative materials, including cost-effectiveness, high strength-to-weight ratio, longevity, user-friendliness, and low density. Global plastic production reached 299 million tons in 2013 [5,6], exceeding 2015 forecasts by approximately 2 million tons [7]. However, the buildup of plastic waste has emerged as a major environmental issue. While ceasing plastic production is not a viable option, recycling presents a potential remedy to this urgent problem.

The recycling of various organic and inorganic waste materials, encompassing those from construction, electronics, and agriculture, has gained traction due to increasing disposal expenses and diminishing landfill capacity [8]. Recycling is both sustainable and beneficial for natural resource conservation. Despite the generation of millions of tons of plastic waste worldwide, often ending up in rivers, oceans, and landfills, only about 25% undergoes recycling [8,9]. To address this, efforts are underway to convert Waste Plastic (WP) into products for use in construction, particularly in concrete [5].

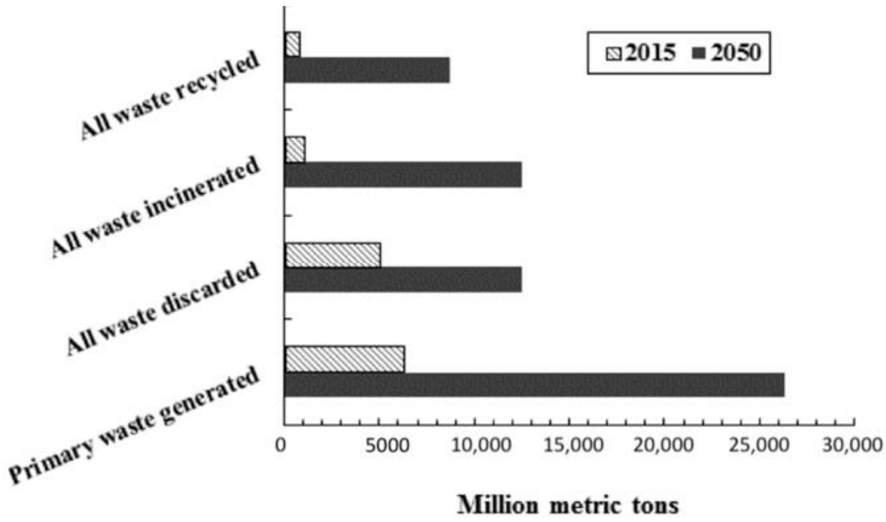

Fig. 1. Predicated cumulative amount of WP and discharge method (2015 till 2050) [7].

Fig. 1 depicts the accumulative generation and disposal of WP from 1950 till 2015, with projections for 2050. By 2015, merely 16% of the total plastic waste had been recycled. Although projections indicate that up to 33% may be recycled by 2050, the quantity of unrecycled waste remains considerable. A significant obstacle in recycling plastic waste is contamination by organic and inorganic materials, which complicates the recycling process [6]. Nevertheless, utilizing recycled plastic as an aggregate in concrete may offer a feasible solution, especially in applications where contamination has minimal impact on concrete properties.

The yearly worldwide output of concrete surpasses 5.3 billion m3 [10], offers a significant opportunity for the incorporation of recycled plastics. This practice not only mitigates environmental impact but also helps reduce plastic waste in landfills. While various types of plastics exist—including PET, PLA, PP, HDPE, PVC, and PS [9] not all are appropriate for use as concrete aggregates. Currently, PET and resin-based plastics are the most frequently utilized types in concrete production [11–13]. In concrete, recycled plastic has been used as both coarse and fine aggregate. Despite its environmental benefits, PAs possess different mechanical and thermal properties compared to natural aggregates (Table 1).

Table 1: Common characteristics of cementitious and plastic materials [14].

Material	Elastic Modulus (GPa)	Tensile Strength (MPa)	Thermal Conductivity (W/m.K)
PE	0.6-1.4	18-30	0.33-0.52
PET	2.1-3.1	55-80	0.15
PP	1.3-1.8	25-40	0.12
PS	3.1-3.3	30-55	0.105
PVC	2.7-3.0	50-60	0.17-0.21
Limestone gravel	70	-	2.29-2.78
CP(w/c =0.5)	15-20	-	1
Quartzite sand	70	-	4.45

The characteristics of recycled plastic concrete are also affected by the pre-treatment of plastic waste, which influences the bond strength between aggregates and cement paste. Additionally, inherent plastic characteristics like shape, low fire resistance, and surface texture can substantially influence concrete performance.

Incorporating Recycled Plastic (RP) as a portion of substitute for aggregate in concrete significantly impacts the material's characteristics. To optimize its use, it is essential to grasp the correlation between the quantity of plastic utilized and the subsequent alterations in concrete's engineering attributes. This analysis seeks to deliver a thorough examination of current studies on recycled plastic integration in concrete, emphasizing high-strength formulations. By meticulously evaluating research on the fresh, mechanical, and longevity properties of concrete containing plastic aggregate, this paper presents crucial information for both academics and professionals in the realm of building sustainably.

2. Mechanical Properties

The mechanical properties of cement-based materials play a crucial role in determining their practical applicability. This segment provides an overview of the mechanical characteristics of concrete that incorporates RP, as documented in various research studies.

2.1 Compressive strength

Fig. 2 illustrates the findings of numerous researchers who examined the Compressive Strength (CS) of concrete containing varying proportions ranging from 5% to 100% by weight of recycled WP as both fine and coarse plastic aggregates. Most studies indicated a progressive decline in CS as the percentage of waste plastic increased [14-19]. In a study by Kou et al. [20], sand was substituted with recycled polyvinyl chloride (PVC) granules in concrete mixtures, up to a maximum of 50%. After 28 days, the CS was approximately 50% lower compared to the reference concrete. When 30% of the sand was replaced in the same mixture, the strength reduction was about 25%. It's worth noting that the PVC granules were produced by crushing PVC scrapers between (1.18 - 4.75) mm, resulting in angular-shaped particles. To maintain slump values within the 160–180 mm range, specific amounts of superplasticizer were utilized.

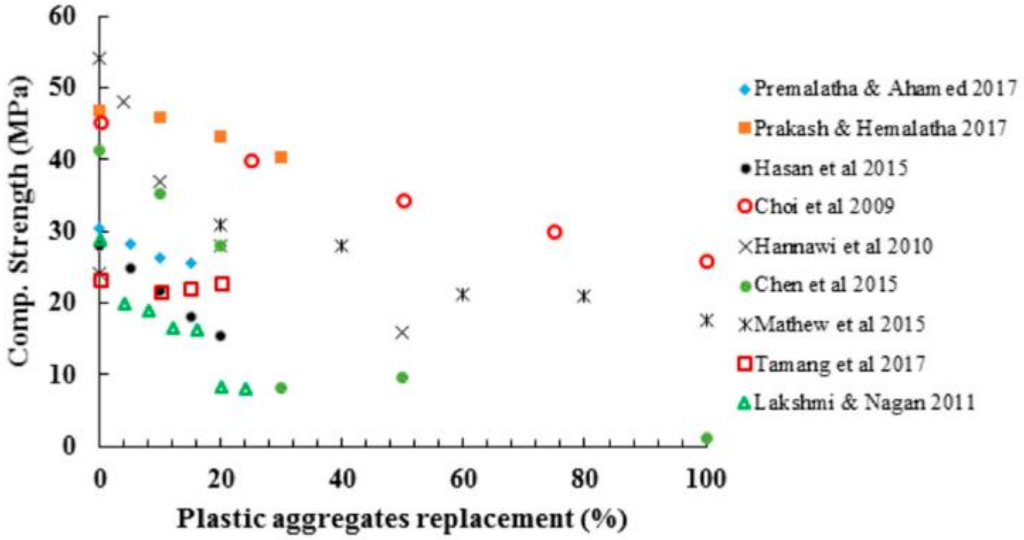

Fig. 2. Concrete with recycled PAs under 28 days test for CS [19,21-28].

The Eurocode 2 provides comprehensive directives for the structural design in the context of fire, indicating a post-fire CS reduction factor of 0.45 for normal-weight concrete that incorporates siliceous aggregates when subjected to temperatures reaching 600 °C [29]. The decrease in CS is attributed to C-S-H degradation above 400 °C [21] and Portlandite breakdown in a range varying from 200 °C to 600 °C [30–32], this is considered to be the limit for retaining concrete's mechanical qualities. The 0.45 factor was only attained by concrete mixtures that included PP fibers (poly propylene fibers) and plastic debris, concrete with 6 kg/m^3 of polymeric addition showed the highest residual CSs.

Given that PP fibers and PW generally melt at roughly 200 °C, one would anticipate that CPP (Concrete with Polypropylene fibers) and CPW (Concrete with Plastic Waste) samples would experience a decrease in tensile strength to match that of CREF after being subjected to temperatures of 600 °C [30]. However, the findings presented in Figure 11 reveal that CPW exhibits a higher residual tensile strength compared to both CREF and CPP. According to Neville [33] the tensile strength (TS) of concrete was of essential relevance, as cracking in actual structures occurs due to tensile strains, and structural damage in tension-bearing parts is often caused by the development of microcracks. The TS behavior observed in CPW samples after high-temperature exposure demonstrates the beneficial effects of incorporating plastic waste into high-strength concrete.

While the use of PET aggregates can enhance the sustainability of concrete by recycling waste materials, it is crucial to find an optimal balance. The study suggests that lower percentages of PET (such as 2.5% to 5%) may be more effective in maintaining acceptable compressive strength while still contributing to sustainability efforts. Higher percentages, like 7.5%, significantly reduce strength and may not be suitable for structural applications. [34]

In summary, while incorporating waste plastics like PET into concrete mixes can promote environmental sustainability, careful consideration must be given to the impact on compressive strength. The findings highlight the need for further research to optimize the use of recycled materials in concrete, ensuring that the mechanical properties meet the necessary standards for construction applications.

2.2 Elastic modulus

Researchers showed that the elastic modulus of concrete decreased linearly as the proportion of PAs in the mix increased [21,35]. This reduction is primarily attributed to the low elastic modulus of plastic itself [20]. Such behavior aligns with the composite materials theory, which states that a composite's elastic properties are substantially governed by the elastic characteristics and relative amounts of its components [36]. Remarkably, research has shown that the decrease in CS is more noticeable than the decrease in the modulus of elasticity [36, 37], as shown in Figure 3. Similar empirical findings have been documented regarding alternative categories of soft inclusions, including functional microcapsules [38,39] and expanded polystyrene beads [40]. This phenomena can be explained by the failure being driven by the levels of stress surrounding these inclusions, while elastic characteristics are determined by each component and their corresponding specifications [41,42].

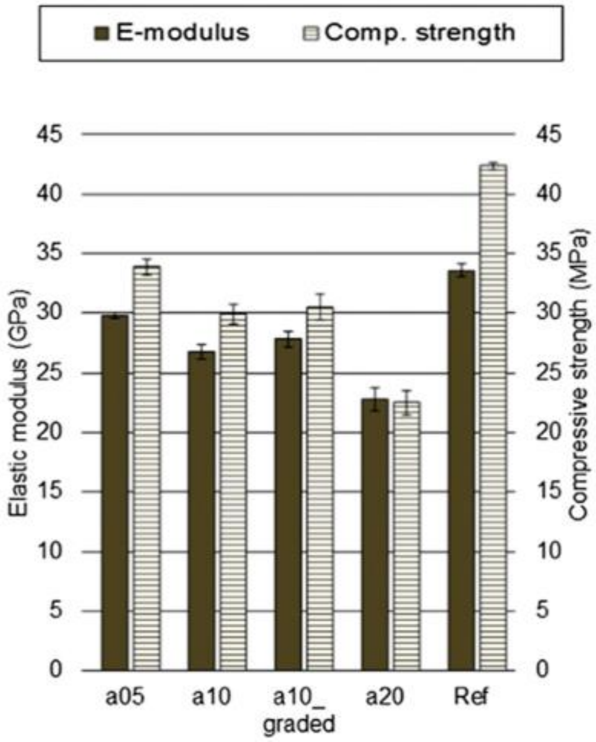

Fig. 3. Measured CS and elastic moduli for various concrete WP aggregate percentages [33].

Research has shown that incorporating waste plastic aggregate not only affects the elastic modulus but also substantially modifies the ratio of Poisson of concrete. Yang et al. [42] demonstrated that when 15% of waste plastic aggregate was added, Poisson's ratio increased markedly from 0.195 (in the control concrete) to 0.25. Further research is necessary to elucidate the underlying mechanisms responsible for this observed change in behavior.

In summary, adding waste plastic aggregates to concrete affects its mechanical properties, mainly because plastic has a lower elastic modulus. As the amount of plastic aggregates increases, the elastic modulus of the concrete decreases steadily. However, the compressive strength reduces more noticeably than the elastic modulus. This happens because stress around the plastic particles causes cracks, while the elastic modulus depends on the properties of all the materials in the mix. More studies are needed to better understand these changes and find ways to improve concrete with plastic aggregates.

2.3 Fracture, tensile, and flexural specifications

The incorporation of waste PAs as a substitute for natural aggregates is anticipated to impact the Fracture Strength (FS), Tensile Strength (TS), and Flexural Strength (LS) characteristics of concrete. Most researches indicated a progressive decline in splitting TS and LS as the proportion of waste PAs increases. For instance, Akçaözoğlu et al. [43] evaluated the LS and TS of mortar having primarily PET in fine aggregate form (particles smaller than 4.75 mm) versus mortar with a mix of sand and PET. The latter exhibited superior strength compared to the former [41]. Another investigation revealed a gradual decrease in the LS of concrete as PVC content rose by about 17.5% [22]. After 120 days, concrete samples with 2.5% to 20% PVC showed approximately 19% and 96% lower flexural strength, respectively, compared to the control mix. Furthermore, concrete samples with 20% PVC displayed poor surface quality, with higher PVC content leading to surface crumbling due to inadequate strength [22]. Additional studies e.g., [23,25,34,26] also noted a reduction in LS and bending strength. As depicted in Fig. 4, the level of LS and the subsequent segregation of concrete experienced a notable reduction as the proportion of PVC powder increased. This phenomenon can predominantly be attributed to factors analogous to those responsible for the diminished CS when incorporating plastic aggregates, particularly the inadequate adhesion between the aggregates and the cement matrix. Upon attaining peak strength, the majority of plastic particles within the concrete matrix do not undergo failure; rather, they disassociate from the cement paste, thereby providing further evidence of the suboptimal bond.(see Fig 5)

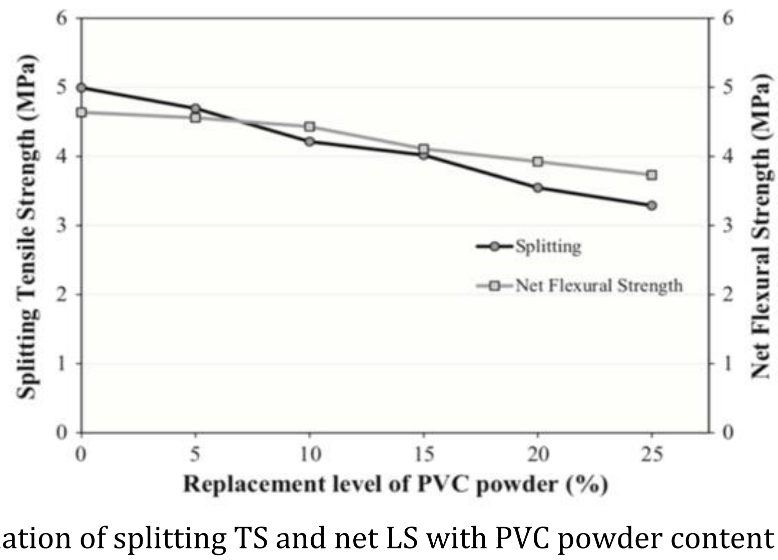

Fig. 4. Variation of splitting TS and net LS with PVC powder content (net LS refers to ultimate LS) [34].

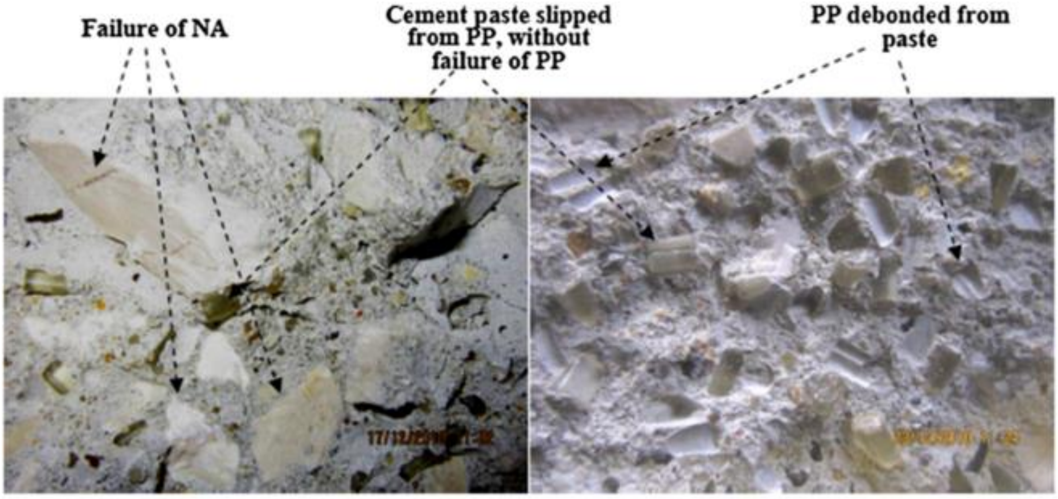

Fig. 5. Samples of concrete with PP following failure in the TS splitting test [42].

Several studies have indicated that incorporating a moderate amount of WP aggregate can enhance the LS and splitting TS of concrete. Hosseini et al. [43] explored the effects of different percentages of MPW (Mixed Plastic Waste) fibers (0.25%, 0.5%, 0.75%, 1.0%, and 1.25%) on concrete, focusing on its flexural and direct tensile strength. The results showed that mixes containing 0.5% fibers achieved the highest flexural and tensile strengths, while no significant improvement was observed at 1.25% fiber content compared to the control mix without fibers. Similarly, Yang et al. [42] found that replacing natural aggregates with moderate amounts of recycled plastic improved flexural and splitting tensile strengths, with optimal results observed at 15% replacement for splitting tensile strength and 20% for flexural strength. However, exceeding 20% replacement typically leads to a decline in these properties.

While higher plastic aggregate content often reduces the splitting tensile strength, the magnitude of this drop can be minimized by reducing the ratio of water/cement of concrete mix [28]. This strength reduction is commonly attributed to weak bonding between the Cement Paste (CP) and PAs. To address this issue, surface treatment of PAs has been suggested as a potential method to enhance the bond strength at the interface between the cement matrix and PPs, thereby improving the overall performance of concrete.

The inclusion of PAs in concrete is known to enhance its ductility. However, the degree of improvement is directly proportional to what type of plastic utilized. Therefore, selecting the appropriate type of plastic based on design requirements is crucial for achieving optimal performance. At low replacement levels, Hannawi et al. [21] found a small increase in bending capability, which grew more noticeable as the plastic aggregate content approached 5%. Notably, ductility showed a significant increase even at low replacement levels.

The enhanced ductility was attributed to the behavior of the interface for plastic/matrix, this prevents the spread of microcracks. This weak interface creates a void that impedes the growth of cracks, while the PAs themselves further resist the propagation and coalescence of microcracks. Additionally, other studies have noted that some waste plastics, resembling short fibers, can bridge cracks to some extent, contributing to post-peak toughening of the material [25]. On the other hand, concrete containing 50% PET content exhibited a lower elastic load ratio, this was described by the lower availability of cement pastes for covering the increased surface area offered by the high proportion of PET particles. This indicates the importance of optimizing mix design when incorporating high levels of plastic aggregates.

The addition of waste PAs significantly affects the fracture parameters of concrete. Fracture Energy (FG), which is a significant measure for describing the post-peak behavior of concrete, tends decrease with the introduction of PVC powder, as observed by Gesoglu et al. [37] (Fig. 6). This reduction in FG is attributed to the presence of weak PVC particles and an increase in air void content within the concrete matrix. In contrast, the characteristic length (L_{ch}), an indicator of concrete brittleness, was found to increase with higher percentages of PVC powder replacement (Fig. 6). This implies a reduction in brittleness, resulting in more ductile behavior. The increased characteristic length was linked to the weak interface between the CP and plastic aggregates, as well as the non-homogeneous microstructure caused by the plastic addition.

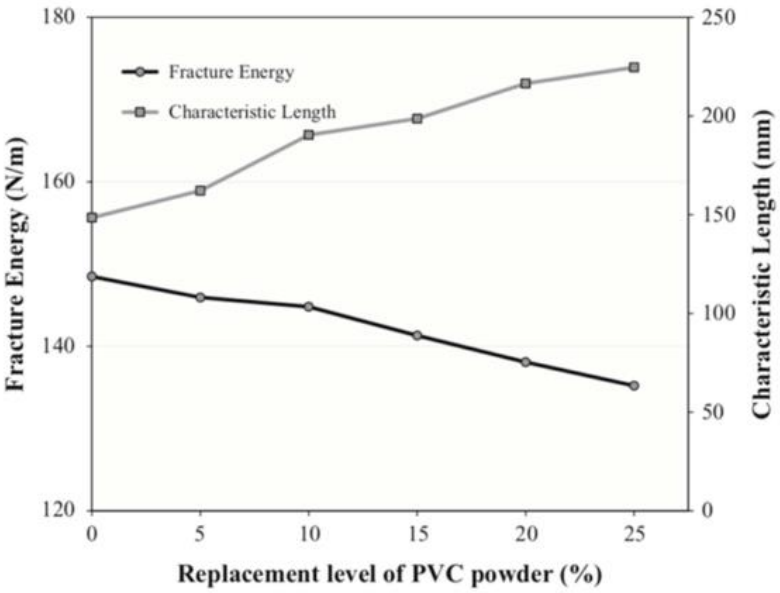

Fig. 6. FG and L_{ch} variations based on PVC powder content [34].

It is important to note that the hardened properties of concrete containing PAs are not solely dependent on the percentage of plastic content in the mix. Factors such as the shape and size of the plastic aggregates, as well as the overall mix composition, play a significant role. Further research is needed to explore these factors in greater depth and to optimize the use of WP in concrete to achieve desired performance characteristics.

In summary, using waste plastic aggregates (PAs) in concrete affects its strength, ductility, and fracture properties. As the amount of plastic increases, the tensile strength, flexural strength, and fracture energy typically decrease due to weak bonding between the plastic and cement paste. However, adding moderate amounts of plastic (e.g., 0.5% fibers or 15-20% replacement) can improve flexural and tensile strength. PAs enhance ductility by preventing crack growth and increasing characteristic length, reducing brittleness. Factors like the type, size, and shape of plastic, along with mix design, are crucial for optimizing performance. Further studies are needed to improve bonding and achieve the best results.

3. Durability

Concrete durability is intrinsically linked to its permeability to fluids, which are pivotal in facilitating steel corrosion embedded within concrete structures. Consequently, the careful choice of appropriate concrete constituents is paramount for the enhancement of durability. There exist apprehensions regarding the incorporation of recycled WPs into concrete due to the potential presence of harmful contaminants. Empirical studies have indicated that recycled PAs do not exhibit durability comparable to that of natural aggregates. Nevertheless, certain investigations have demonstrated that durability may be augmented through the incorporation of specialized additives within the concrete matrix or by modifying the characteristics of the plastic materials utilized.

3.1 Shrinkage (SH)

Restricted SH can cause concrete to break even before external loads are applied. The impact of waste-recycled PAs on concrete SH has been a subject of debate in existing research. The amount of drying and free SH increases when the mix contains more recycled WPs. This aligns with expectations, as shrinkage is influenced by two factors: aggregate content, CPSH, and stiffness. Aggregates serve as internal constraints on SH because they do not shrink on their own. As a result, less SH occurs with more stiff aggregates. Incorporating recovered waste plastic is anticipated to increase shrinkage because it is often less rigid than natural aggregates. Akçaözoğlu et al. [43] noted a 56% increase in drying shrinkage when PET aggregates fully replaced fine aggregate, compared to concrete with 50% PET aggregates. Higher free SH was reported by Hannawi et al. [21] when PET aggregate content rose.

Frigione [44] studied a long-period SH reaction of concrete with PET particles in fine aggregate form and found a slightly higher shrinkage value (less than 3%) in specimens containing 5% PET aggregates. The increased SH in plastic aggregate concrete can be attributed to the lower modulus of elasticity of PAs compared to conventional ones. Similar behavior has been observed with additional conforming additions, such as expandable and enhanced polystyrene aggregate [45]. Conversely, researchers have discovered lower drying SH with the use of recycled WP aggregates. Silva et al. [46] ascribed this decline to the permeability character of WP aggregates, which restricts water absorption and allows more water for cement hydration. As drying SH results from capillary tensile forces induced by water loss in concrete, this phenomenon can lead to reduced drying shrinkage. Interestingly, while an increase in free SH is commonly discovered with the addition of recycled WP, it appears to simultaneously decrease restrained SH cracking. Hannawi et al. [21] noted that incorporating PAs reduces mortar sensitivity to shrinkage cracking by delaying crack appearance and reducing crack width. Soroushian et al. [47] discovered the same results. The reason for this impact was that PAs increased deformation ability prior to fracture localization, but PET flake-shaped particles functioned as fibers and prevented crack opening once cracking had already taken place.

In summary, the use of waste plastic aggregates (PAs) in concrete affects shrinkage behavior. While drying and free shrinkage generally increase due to the lower stiffness of PAs compared to natural aggregates, drying shrinkage can sometimes decrease because of the reduced water absorption of plastic aggregates, which helps retain water for cement hydration. Additionally, incorporating PAs can reduce restrained shrinkage cracking by delaying crack formation, reducing crack width, and enhancing deformation before cracks localize. These effects highlight the complex role of PAs in influencing concrete shrinkage and cracking behaviour.

3.2 Porosity and absorption of water (WA)

The extent of a material's porosity can be determined by measuring WA, which is expressed as a percentage of water absorbed under specific conditions [48]. This procedure correlates to the square root of time. The porosity of hardened CP can be measured through water saturation, allowing water molecules to permeate the microstructure [49]. Various researchers have conducted WA and PA tests on concrete samples containing PAs to evaluate their resistance to corrosion of steel [29,31,35,50]. As illustrated in Fig. 7, the WA rate rises in proportion to PAs percentage. An exponential rise in WA was observed in concrete as the content of recycled electronic waste plastic (e-plastic) increased [38]. Concrete containing 15% coarse e-plastic exhibited nearly double the WA in contrast to the concrete reference. In a study by Coppola et al. [50], sand was substituted with recycled PAs at 0.1, 0.25, and 0.5 ratios in lightweight foam concrete production. Their findings showed similar water absorption levels when 10% of sand was replaced with plastic aggregates. However, this trend did not hold true for higher plastic concentrations in concrete. A 1.17 increase in WA was noted when 50% of sand was replaced with plastic aggregates. This significant change in water absorption was attributed to the increased porosity induced by the plastic aggregates, a phenomenon discovered by Ruiz-Herrero et al. [29], also. Their study revealed that concrete samples containing 0.2 polyethylene (PE) and PVC, PAs exhibited 2 and 1.4 higher porosity ratio, respectively, after 28 days [29].

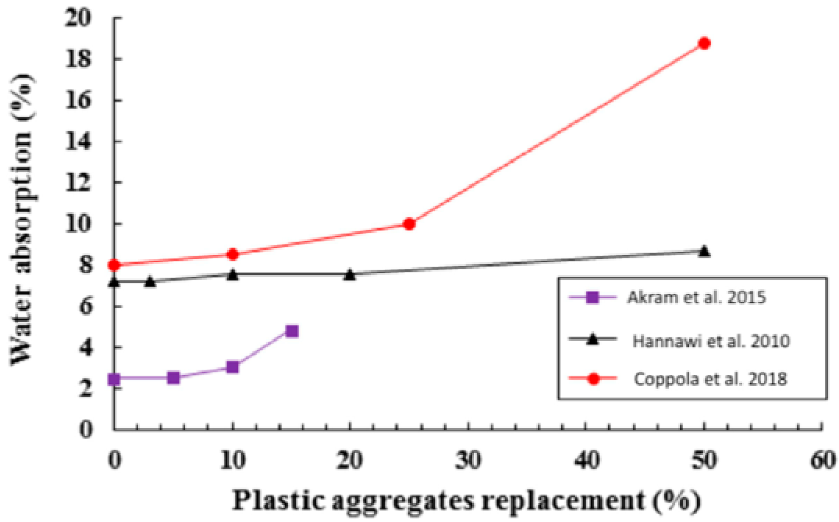

Fig 7. Concrete's WA capacity when combined with plastic aggregate.

Therefore, there is a clear relationship between the inclusion of plastic aggregates in concrete and an increase in water absorption and porosity. Water absorption increases exponentially with higher percentages of recycled plastic in concrete, indicating the significant impact of plastic aggregates on the microstructure. While moderate substitutions (e.g., up to 10% sand replacement with plastic aggregates) may result in similar water absorption levels compared to conventional concrete, higher concentrations lead to a notable rise in porosity. Studies consistently show that the incorporation of plastic aggregates, such as polyethylene (PE) and PVC, results in substantial changes in the concrete's properties, particularly after 28 days of curing. These changes are attributed to the increased void spaces created by the plastic materials, which affect both the durability and resistance to environmental factors.

3.3 Chloride ingress resistance

The protective layer of steel reinforcement may break down and corrosion may start if chloride seeps into concrete, ultimately shortening a structure's lifespan [51,52]. As corrosion products occupy more space than the original steel, this process can cause the concrete cover to crack, further diminishing its ability to shield the steel [52,53]. Consequently, a concrete's resistance to chloride penetration is a crucial factor in evaluating its durability. However, research on concrete containing recycled plastic waste has yielded inconsistent results regarding its resistance to chloride infiltration.

Research conducted by Alqahtani et al. [35] demonstrated that incorporating PAs enhances concrete's resistance to chloride penetration. When using 100% coarse plastic particles in lightweight concrete, chloride ion permeability was reduced by 0.15 and 0.12 compared to the control concrete at water-cement ratios of 0.5 and 0.6, respectively [35]. Kou et al. [20] reported similar outcomes, attributing this improvement to the impermeable nature of WP aggregates, which act as physical barriers to chloride ingress (Fig. 8). Notably, ASTM C1202 states that concrete is deemed to have low resistance to chloride ingress if the charge passed in a swift chloride permeability test (RCPT) is greater than 4000 coulombs. The percentages (0, 0.05 to 0.45), of recycled plastic particle substitution in concrete, are indicated by P0, P5 to P45 in Fig. 8.

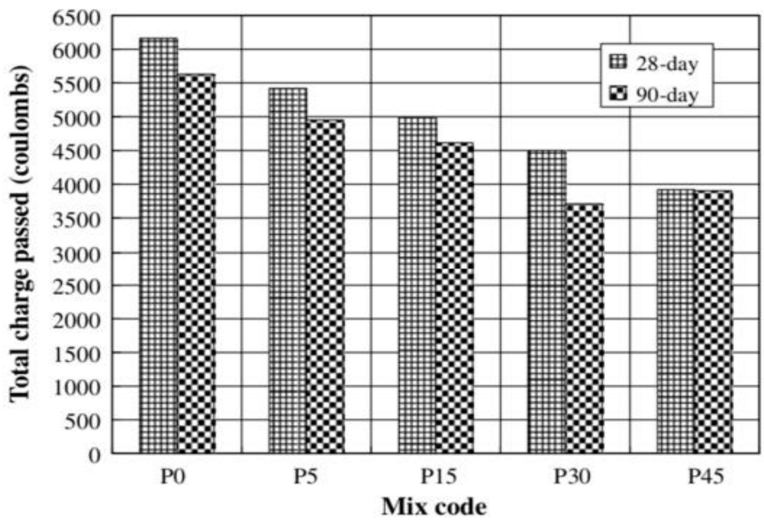

Fig 8. Resistance of mixes with a higher percentage of recycled plastic to chloride intrusion [20].

Conversely, alternative findings have been reported by some researchers. Soroushian et al. [47] observed only a minor reduction in chloride penetration resistance when waste recycled plastic aggregate was incorporated, albeit in small quantities of up to 5%. In contrast, Silva et al. [46] noted an increase in the coefficient of chloride migration as the amount of recycled WP aggregate increased. This trend was particularly evident under suboptimal curing conditions (Fig. 9), though no explanation was provided for this phenomenon. Increased void content, which was not evaluated in their study, could be the cause of the observed behavior. The penetration of chlorides into concrete influenced by curing processes, a well-understood relationship. The microstructure density of concrete, which is dependent on curing conditions, likely plays a significant role in chloride penetration.

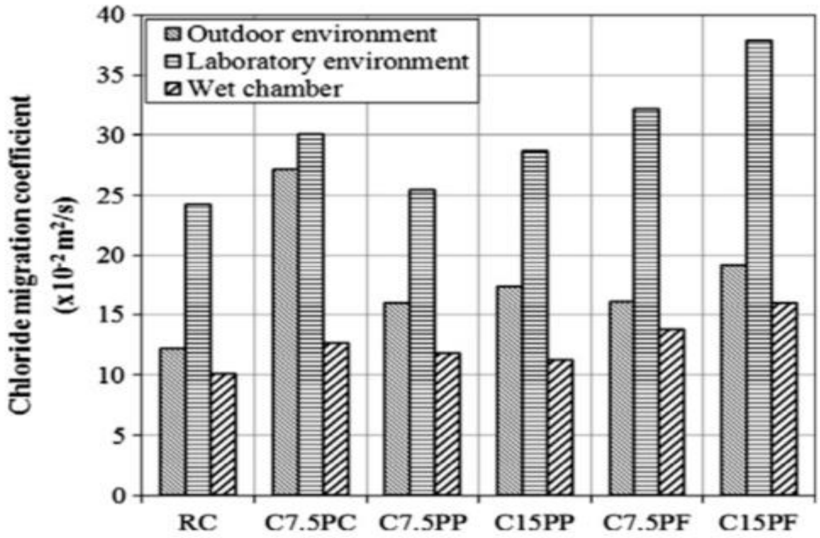

Fig 9. Concrete mixtures cured under various curing conditions at 91 days had a chloride migration coefficient [44] (RC refers to reference concrete). Various percentages of recycled waste plastics are shown by numbers. PC stands for coarse-particle plastic, PF stands for aggregate of fine plastic, and PP stands for plastic aggregate in the form of pellets.

In summary, the resistance of concrete containing recycled plastic aggregates to chloride penetration presents varying outcomes depending on the type and proportion of plastic used and the curing conditions. Studies by Alqahtani et al. and Kou et al. demonstrate that PAs can act as physical barriers, reducing chloride ion permeability, especially in lightweight concrete with higher plastic aggregate content. These findings suggest that the impermeable nature of plastic contributes positively to chloride resistance. However, conflicting results from researchers like Soroushian et al. [47] and Silva et al. [46] highlight that, under certain conditions, incorporating plastic aggregates may lead to increased chloride migration. This inconsistency is possibly influenced by increased void content or poor curing, both of which impact the microstructure density of concrete. Proper curing and optimal aggregate proportions are essential to ensure chloride resistance in concrete with recycled plastics.

4. Discussions and Conclusions

The integration of recycled plastic aggregates (PAs) in concrete represents a sustainable approach to addressing environmental challenges associated with plastic waste while reducing dependence on natural aggregates. However, its effects on mechanical and durability properties require careful consideration to ensure practical applicability in structural and non-structural applications.

Mechanical properties, including Compressive Strength (CS), Tensile Strength (TS), elastic modulus, and Flexural Strength (LS), generally decrease as PA content increases. These reductions are largely attributed to the weak bond between plastic aggregates and the cement matrix, lower stiffness of plastic materials, and increased void content. Despite these challenges, moderate PA incorporation has shown promising improvements in ductility, crack resistance, and post-peak toughness, which are essential for structural resilience under tensile and flexural loads.

In terms of durability, the use of PAs can increase porosity, water absorption, and shrinkage, potentially impacting long-term performance. Nonetheless, innovative approaches, such as surface treatment of plastic aggregates, optimized mix designs, and the inclusion of additives, have demonstrated potential to mitigate these effects. Notably, recycled plastics can enhance resistance to chloride penetration and reduce shrinkage-induced cracking, offering potential for use in marine and harsh environmental conditions.

Key findings also highlight the role of plastic aggregate type, size, and treatment in influencing concrete performance. For example, small and angular particles, as well as treated plastics, tend to improve bonding and mechanical behavior. Furthermore, the beneficial effects of moderate plastic replacement (e.g., 15–20%) suggest that careful proportioning can balance sustainability goals with performance requirements.

Future research should focus on:

1. **Optimizing Mix Designs:** Investigate the combined effects of water-cement ratio, superplasticizers, and curing conditions on performance.
2. **Material Innovation:** Develop advanced treatments for PAs to enhance bonding with the cement matrix.
3. **Performance Under Extreme Conditions:** Study the behavior of plastic aggregate concrete under high-temperature exposure, freeze-thaw cycles, fire resistance, and long-term durability scenarios.

4. **Scaling Up Applications:** Assess the economic viability and environmental impact of large-scale implementation in construction projects, including the influence on multiple cycles of concrete recycling and microplastic pollution.

Nomenclature

CS	Compressive Strength
CP	Cement Paste
FG	Fracture Energy
FS	Fracture Strength
LS	Flexural Strength
WP	Waste Plastic
WA	Absorption of Water
MPW	Mixed Plastic Waste
CPW	Concrete with Plastic Waste
RP	Recycled Plastic
PVC	Polyvinyl Chloride
SH	Shrinkage
TSS	Tensile Strength
PA	Plastic Aggregates
PP	Poly propylene
CPP	Concrete wit Polypropylene

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