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Review

Repurposing Single-Use Plastic Waste as Artificial Aggregates Partially Replacing the Natural Fine Aggregate in Concrete — A Review

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Abstract: There is a growing increase in the global consumption of plastic in recent times. Reutilization of plastic by recycling is a highly effective solution to manage the increasing plastic waste (PW). Besides, reuse of plastic also helps in improving environmental sustainability. In this context, there is a great demand for the recycled plastics in various applications. This review paper presents an empirical evaluation on the application of single use plastic waste as an artificial aggregate as a replacement to the natural fine aggregate (FA) in concrete mixtures. This review also discusses the influence of mechanical properties on the cementitious composites consisting of plastic waste aggregate (PWA). This paper reviews an overall 135 research papers and illustrates different types of plastics and their application in improving the concrete properties. The review also provides an overview of the works proposed by different researchers and highlights their contribution. In addition, this paper also identifies the research gaps and highlights some of the prominent observations.

***Keywords*:** plastic waste aggregate; concrete materials; mechanical properties; recycled plastic; natural aggregates

1. Introduction

Waste management is one of the biggest crises that the world is facing in recent times and various collective actions have been taken to manage plastic waste effectively to protect the future of the planet [1, 2]. Plastic is one of the extensively used materials and plastic products have become an integral part of daily life. On an average, the global plastic production exceeds 330 Million tonnes per year [3] and according to the United Nations Environment Programme (UNEP), the world generates more than 400 million tons of plastic every year. Plastic is used in various applications such as wrapping, packaging, shopping, manufacturing garbage bags, clothing, industrial applications, toy manufacturing, and household applications [3]. The excessive utilization of plastic materials has become one of the main reasons for the waste management crisis. It is observed that the regulatory standards and consumer requirements have increased substantially [4] and as a result the utilization and management of plastic is controlled effectively. In general, post-utilized plastic is treated using three prominent techniques namely; land filling, recycling, and incineration. These techniques incorporate a hierarchical process for treating the waste [5]. It is anticipated that if the current manufacturing of plastic and waste management continue to increase, then approximately 12,000 Million tons of plastic waste will be dumped in the landfills and in the environment by 2050 [6]. Plastics that are used regularly tend to become obsolete and recycling of such plastics is not plausible. Since plastics are not biodegradable, it is difficult to manage and recycle huge volumes

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of waste plastic which is disposed of on a daily basis. In addition, dumping of large scale plastic requires a larger area for storing the waste [7]. Inappropriate management of plastic waste will have a negative impact on the environment. Hence, various researchers have suggested the recycling of plastic waste which is highly significant from various perspectives [8, 9]. Utilization of plastic waste has various advantages; it improves environmental sustainability, increases industrial production, reduces environmental pollution and maximizes the utilization of natural resources which cannot be replenished [10]. The conversion of raw plastic materials into recycled plastic aggregate is shown in figure 1.

Figure 1. Raw plastic waste turned into recycled plastic aggregate [10]

Among different materials that use recycled waste as aggregate, concrete is the most common material which prominently uses plastic waste as an artificial aggregate [11]. The superior attributes of concrete such as high compressive strength, robustness, cost effectiveness and longer lifetime makes it an ideal material in the construction industry. Major raw materials that constitute concrete as a construction material are cement, aggregate and water which are abundantly used in the construction sector [12]. In general, the volume of aggregate in the concrete mixture is roughly around 65% to 80% and has a profound impact on the attributes of concrete such as volume stability, robustness, durability, potential capability, and permeability [13]. A significant volume of FA and coarse aggregates (CA) is essential to manufacture high quality concrete for large scale applications. The utilization of waste materials in manufacturing processes improves the recycling process which in turn helps in reducing the volume of waste materials that are dumped in landfills, especially plastic waste. In addition, mixing of waste material in concrete also helps in addressing the critical environmental issues related to waste disposal, aggregate mining, and lack of aggregate in the construction sector [14]. Among different recycling processes, the recycling of PW in the manufacturing of concrete is signified as an optimal technique for eliminating the PW. In this process, recycled plastics are reused without degrading the quality and without deteriorating their properties. Most prominently, recycled plastics act as a potential alternative to the natural aggregators. The increased prominence of using recycled plastics in the formation of concrete has gained huge significance in recent times. Various research works have been presented in the existing literary works that used recycled plastics in cementitious composites. One of the most common forms of plastic used in the concrete is plastic aggregates (PA) which is used as an artificial aggregate instead of natural aggregate. The characteristics and attributes of plastic aggregates and their utilization in concrete composite is investigated by various researchers [15–17].

As discussed previously, the majority of the plastic types are non-biodegradable and are highly toxic in nature. Since plastics are chemically unreactive, they can sustain in the environment for a longer period of time and can last for centuries. However, it is detrimental for the environment to hold plastic waste for long since it emits toxic elements and disposing them into landfills is not a feasible solution [18]. Though burning or incinerating plastic waste can eliminate plastic materials on a large scale, it can cause significant harm to the environment due to the emission of carbon dioxide and several other noxious chemicals. In this context, recycling is considered as a potential alternative to process PW. Majority of the plastic waste is reused in the construction sector and the composition of this waste along with the concrete is being excessively investigated [19–21]. These works discuss the utilization of different recycled plastic waste in cement mortars and reviews the workability and mechanical properties of the cement mortars. The incorporation of other waste materials such as fly ash [22], geopolymer aggregates made with fly ash [23], waste glass [24] or biochar [25] in concrete are also investigated in existing works. This review paper emphasizes the adaptation of PW as aggregate, and hence more research works related to the same are reviewed.

In general, plastic waste is segregated into different types, cleaned and are shredded into multiple elements of different size and shape before mixing into the concrete mortars. This is one of the most popular methods used while using plastic waste into the concrete. Fundamental analysis reveals that mixing plastic aggregates into concrete can reduce the workability, and strengthen the mechanical characteristics of the concrete mix [26]. An enhancement in the abrasion resistance of the concrete was observed in the past decades while using polyethylene terephthalate (PET) plastic as an aggregator instead of using natural aggregator. This is mainly due to the coarse texture of the plastic materials compared to the texture of natural aggregators [27]. It can be inferred from the existing works that there is an increase in the water absorption capacity of the concrete when mixed with PW as aggregate. This mixture also elevates the volume of air which results in the inappropriate mixing of the natural and artificial aggregates. The density of these two aggregates differ from each other wherein the natural aggregate sinks in the cement mixture while the plastic waste aggregate floats [18]. It is also observed that the inclusion of PA increases the drying shrinkage and increases the resistance to the penetration of chloride ions. This is due to the reduced restraint of the PA compared to natural aggregates. Despite the advantages, the inclusion of plastic waste into concrete has certain limitations. The main challenge associated with the mixing of PWA into the concrete is the chemical incompatibility between plastic and cement mixture. The hydrophobic nature of plastic makes it difficult to chemically mix their aggregates with the cement mixture and as a result the robustness of the binding between the plastic and cement mixture becomes weak [28]. This attribute results in the decrease of key attributes with the increase in the amount of plastic mixed in the concrete [28].

A brief overview of the concrete properties using plastic waste as aggregate is discussed in table 1.

Table 1. Concrete properties with PWA

Reference	Concrete	Type of PW	Replacement of PW	Particle size (mm)	Ratio of water to cement	Properties
[29]	Concrete	Metallic plastic	0.5%, 1%, 1.5%, 2%	5 to 20 mm	0.45	Oxygen permeability, corrosion, sulphate attack, load variations
[30]	Concrete	Electronic PW (E - plastic)	5%, 15%, 25%	2 to 8 mm	-	Compressive strength (CS), flexural strength (FS), splitting strength
[31]	Concrete	PET	20%, 30%, 40%, 50%	5 to 12 mm	0.42, 0.48, 0.57	Density, compressive strength, workability
[32]	Concrete	Electronic PW (E - plastic)	5%, 10%, 15%	10 to 20 mm	0.5	Compressive strength, splitting strength, water absorption, porosity
[33]	Concrete	-	25%, 50%, 75%, 100%	1 to 10 mm	0.5	Density, compressive strength, workability
[34]	Concrete	PET	5%, 10%, 15%	0.15 to 7 mm	0.42, 0.54	Compressive strength, flexural strength, elastic modulus
[35]	Concrete	PET	7.5%, 15%	3 to 10 mm	0.51 to 0.61	Compressive strength, splitting strength, elastic modulus, abrasion resistance
[36]	Concrete	Electronic PW (E - plastic)	4%, 8%, 12%, 16%, 20%, 24%	1.86 to 2.78 mm	-	Compressive strength, absorptivity, permeability

The majority of existing literary works have focused on adopting plastic waste as an aggregate into the concrete mixture by sorting, processing, and recycling PW. Despite the availability of several studies, there is a lack of a comprehensive analysis which investigates the role of plastic waste as an artificial aggregator in concrete. In this context, this review paper focuses on summarizing the existing literary works related to the application of recycled PW as fine aggregate in concrete from 2014 to 2021. In this review paper, all related research papers and review papers were reviewed and discussed. The prominent contributions of the review paper are summarized as follows:

- The review emphasizes the influence of recycled plastic waste on the physical and mechanical attributes of the concrete such as resistance, compressive strength, flexural strength, tensile strength, elastic modulus and thermal conductivity.
- In addition, this review paper also investigates the impact of PW on the durability of the concrete in terms of water absorption capacity, permeability, carbonation, and shrinkage.
- Furthermore, the review also discusses the state-of-art of plastic waste aggregate, and research gaps observed from existing literary works.

The review paper is further structured as follows: Section 2 describes the types of plastic and plastic waste management. Section 3 provides a comprehensive analysis on different materials and mixtures involved in the analysis. Section 4 presents the review of existing studies that use plastic waste as aggregator. Section 5 discusses the mechanical properties and experimental test required for measuring the strength of the concrete with PW as an artificial aggregate. Section 6 discusses the recent advancements, challenges and research gaps and Section 7 concludes the paper with some value-added information observed from the literature.

2. Plastic Waste Management

This section provides a brief overview of different plastic categories and PW. This section will also discuss the plastic waste problem and plastic waste management techniques.

2.1 Types of Plastic

Plastics are introduced to satisfy the increasing demands of industrial and domestic users. Most commonly, plastics are categorized into two types namely thermosetting polymers and thermoplastics [37].

(i) Thermosetting polymers: These polymers are also known as thermosets which include different forms of plastics such as polyurethane, phenol formaldehyde, epoxy resins, vinyl ester and silicone. These polymers undergo heating to a level where there is a significant change in their chemical properties. Upon heating, the dimension of the polymers change and form a chained network, which is used to manufacture a wide range of materials. However, it is not practically feasible to reform or re-melt these plastics once they are heated and formed [37].

(ii) Thermoplastics: Thermoplastics belong to the category of flexible plastics which can be reheated, reshaped and molded frequently. These attributes make thermoplastics more flexible and reversible. Thermoplastics melt upon heating and become hard after cooling [37]. Some of the examples of thermoplastics are as follows: Polyethylene terephthalate (PET), piolystyrene, polystyrene, polycarbonate, polyarylsulfone, fluoropolymers, polyethylene and polyvinyl chloride (PVC) [38]. The categorization of plastic is done based on the type of polymers and hence the characteristics and properties of plastics vary from one type to another.

2.2 Current Plastic Waste Management Techniques

Aggregation of plastic waste is increasing exponentially on a daily basis and this is mainly due to the non-biodegradable nature of plastic waste and inappropriate disposal techniques [39]. Existing waste management techniques such as landfilling, recycling and incineration do not have a great prominence in minimizing the disposal of PW. In addition, these techniques are not environmentally friendly. Hence, these techniques are considered irrelevant in current times. Several researchers have attempted by different researchers to transform existing plastic waste management techniques. These researchers have suggested that reusing and recycling of PW is highly effective compared to conventional techniques. However, the existing recycling techniques are not effective in mitigating the potential impacts of pollution due to increased PW and this is due to the large-scale disposal of PW in landfills. Hence it is highly challenging to find an appropriate, cost effective and ecofriendly approach for managing plastic waste and there is a scope of research in this context.

2.2.1 *Landfilling of plastic wastes*

Landfilling is one of the oldest approaches used to deal with the management of PW [40]. It was anticipated that an approximate 43% of the PW is disposed of in landfills. Landfilling is mostly used for disposing non-recyclable plastics by concealing them into deep soil. However, this process requires a larger area and can pollute the environment if buried for a long time. As a result, this technique is considered as the last option for handling plastic waste. Furthermore, a significant volume of toxic chemicals is emitted from PW which can have an adverse effect on the quality of groundwater and marine life.

2.2.2 *Incineration of PW*

Incineration is a conventional way of managing plastic waste which is adopted to minimize the amount of plastic waste disposal [41]. Incineration has replaced the adoption of the landfilling approach since it can reduce nearly 80 % to 90% of the total waste. In addition, incineration is advantageous compared to landfilling in terms of being more advanced, fast process, and reduction time. However, incineration is termed an undesirable approach since it poses potential threat to human health by increasing the concerns of environmental pollution and threat to economic sustainability [42]. The burning of PW releases high toxic fumes, chemical gas emissions, detrimental elements, metals, acid, volatile organic compounds, gaseous elements such as carbon monoxide, polycyclic aromatic compounds etc.

2.2.3 *Plastic Recycling for Construction Aggregate*

Recycling is considered as the most feasible and advantageous technique for waste management. This process is profoundly used in various parts of the world to reuse plastic waste. Recycling process has the ability to reduce the adverse effect on the environment and regulate the depletion of natural resources [40]. Recycling plastic waste is often combined with other recycling processes such as mechanical, chemical, and thermal recycling. In this process, the PW are granulated, segmented into several elements (particles) and are processed by heating them based on their chemical state. Recycling increases the chances of reusing plastic materials and can improve the cost effectiveness, and maximizes the volume of waste disposal.

In this context, utilization of plastic waste in concrete applications is gaining huge significance in recent times. This process also reduces the plastic pollution problems. In construction applications, the plastic waste replaces the conventional aggregate since it does not require any excessive recycling treatment. Besides, plastic waste can be used directly in concrete mixtures as an alternative to natural fine aggregates. The PWA mixes appropriately within the hardened concrete mixture and thereby avoids reinstating of plastic materials into the environment unlike other conventional recycling processes such as landfilling and incineration [43] [44]. In addition, plastic waste in concrete mixture also improves the physical and mechanical properties of the concrete [45].

3. Overview of Research on the Utilization of Plastic Aggregates

Improper management and recycling of PW are one of the prominent factors responsible for increased plastic pollution. The replacement of natural aggregates with PWA in the construction section is studied by several researchers [46–48]. The adoption of PW in concrete helps in reducing the utilization of natural aggregates, which is one of the primary concerns. Various studies have investigated the feasibility of using different plastic subsidiaries such as PET, HDPE, LDPE, PP and PVC in construction industries [49–51].

The PWA is used in different concrete based applications such as construction of bricks [52], pavement [53] [54] and replacement of natural aggregate in concrete [55, 56]. Different forms of plastics are used in concrete applications and among different forms, plastic as aggregate is considered highly significant. Two types of PWA namely coarse aggregate (CA) and fine aggregate (FA) are used to replace natural aggregates. Several studies in the past have examined the physical and mechanical characteristics of concrete with CA and FA as aggregate replacement [57] [58]. Majority of the PWA discussed in existing works were grinded into small particles which are then sieved to generate a fraction of desired sizes [59–61]. Further, smaller particles were used along with other construction materials such as concrete, pavement, bricks, mortars etc. Few works have also employed plastic pellets which undergo the melting process in order to palletize the plastic before using PWA in concrete mixtures [62]. Furthermore, PWA is modified by heating and by subjecting it to mechanical treatment wherein plastic aggregates are mixed with other additives to enhance the quality of the construction materials [63].

Table 2 illustrates the utilization of PWA in concrete as discussed by existing studies.

Table 2. Existing works on the utilization of PWA in concrete

Reference	Plastic types	Types of replacement	Percentage of replacement (%)
[64]	EPS	Fine	0, 15, 20, 25
[65]	PET	Fine	0, 5, 10, 15
[66]	HDPE	Coarse	0, 0.5, 1, 2, 4, 6
[67]	PET	Coarse	0, 10, 20, 30
[68]	PS	Coarse	0, 5, 10, 15
[69]	E- Plastic	Fine	0, 2, 4, 6, 8, 10
[70]	PET	Coarse	0, 5, 10, 20
[71]	HIPS	Fine	0, 10, 20, 30, 40, 50
[72]	PET	Fine	0, 1, 2, 3
[73]	PS	Coarse	0, 45, 67, 73, 82
[74]	E- Plastic	Coarse	0, 10, 20, 30

The studies discussed in table 1 indicate that the PWA can be used in concrete with different percentages. Majority of the studies reveal that the materials formed with PWA complies with the construction standards and validates the potential capability of PWA as an effective aggregate for concrete. For instance, the authors in [75] investigated that the mortar mixed with 10% and 25% of PWA obtained a comprehensive strength of 35.12 MPa and 22.86 MPa respectively. The obtained values are beyond the desired values which is 17.25 MPa. Despite the availability of various literary works, the commercial production and adoption of PWA in concrete is still in the infant stage. Though there is an increasing demand for PWA as an artificial aggregator, the market for PWA is yet to be established and as a result, the application of PWA is limited [76]. Different works that studied the application of recycled PW as aggregate in concrete and the properties influencing concrete are tabulated in table 3.

Table 3. Papers highlighting the properties that influence concrete

Reference	Type of Plastic	Properties of PWA Influencing Concrete
[77]	PET/ PC	Mechanical properties
[78]	PET	Different curing properties
[79]	PET	Mechanical properties
[80]	PET	Mechanical properties
[14]	PET	Abrasion behavior and mechanical properties
[34]	PET	Mechanical properties
[81]	PP	Mechanical properties
[82]	PET	Erosion resistance against acidic effects
[83]	PET	Mechanical properties using CA
[84]	PET	Inclusion of light expanded clay

[85]	HDPE	Mechanical properties and thermal properties
[86]	PET	Mechanical properties
[87]	PVC	Mechanical properties
[88]	PET	Mechanical properties and physical properties

Correspondingly, table 4 highlights the research works that studied plastic aggregates as replacement.

Table 4. Overview of research works that studied plastic as aggregates

Reference	Observations
[89]	The study analyzed the utilization of PET aggregates in concrete. The PET aggregates improved the splitting, tensile and flexural strength while negatively affecting the compressive strength.
[90]	The recycled PVC aggregates were used to replace the natural aggregates in concrete to produce a light and abrasive resistant material. Experimental analysis showed that the inclusion of PVC aggregates diminished the compressive strength, splitting, and tensile strength along with the decrease in the workability and elasticity modulus.
[91]	In this study, the PET aggregates and sand were treated thermally to obtain a lightweight aggregate which can be used to replace natural aggregates. Though the compressive strength of the material was reduced significantly, PET aggregates are still considered as protective materials and can act as effective replacement to natural aggregates.
[92]	Different types of plastics such as PP, PVC, PE, and PS were examined to replace the fine natural aggregates. These plastic types improved the porosity of the material while other factors such as thermal conductivity, density, absorption capacity, and compressive strength were heavily affected when the percentage of plastic increased.
[93]	In this work, recycled PP plastic was used to replace natural coarse aggregates to improve the workability of the concrete. The percentage of plastic content in concrete was 10 % and 20% and it can be noted that the mechanical strength of the concrete was affected along with its durability.
[94]	Plastic aggregates (nearly 50%) replaced the coarse aggregate. There was a reduction in the compressive strength and hence it was suggested to restrict the percentage of plastic aggregate to 20%.
[95]	The plastic aggregates in concrete strengthened the resistance of the concrete against abrasion but the compressive strength was compromised.
[96]	This study used foamed mixed PE and PP plastics for replacing sand. For higher percentages of PE and PP, the macro porosity was improved. However, the thermal conductivity and density was diminished.

4. Experimental Analysis

This section discusses the experimental test required for measuring the strength of the concrete with PW as an artificial aggregate.

4.1 Mechanical properties of concrete composites with PWA

Different mechanical properties that describe the performance of the concrete composites with PWA are compressive strength, flexural strength (modulus of rupture), splitting tensile strength, elastic modulus and (Young's modulus), which are discussed in the sub sections below:

4.1.1 *Compressive strength (CS)*

Among different parameters used to determine the performance of the concrete, compressive strength plays an important role since it helps in assessing the quality of the concrete. Compressive strength is defined as the ratio of the strength is equal to the force (F) at the point of failure divided by the cross sectional area. The properties of concrete have a direct influence on the compressive strength and hence it can provide valuable information of different concrete parameters [97]. Several parameters such as types of plastic waste, ratio of water to cement have a profound effect on the compressive strength of plastic concrete. The work mentioned in [28] examined the influence of PWA shapes on the CS of concrete. It was observed that the concrete composites with non-uniform PWA particles experienced a sharp reduction in the CS compared to concrete mixtures with uniform PWA. Meanwhile, elastic modulus is another prominent factor which majorly affects concrete properties. The utilization of PWA (PET aggregates) with high elastic modulus reduces the CS. Consequently, PWA (EPA aggregates) with lower elastic modulus significantly reduces the compressive strength compared to PWA aggregate with high elastic modulus.

4.1.2 *Flexural Strength (FS)*

The FS defines the capacity of the concrete to resist the effect of deformation under flexural load and is calculated in terms of stress. Several tests have been conducted to determine the flexural strength and in most of the tests the specimen can either be a circular or rectangular cross section. In general, the flexural strength is determined using a transverse bending test wherein the sample concrete material is bent until the sample experiences complete failure. The stress is measured by conducting a 3 or 4-point flexural test. The results of these tests reveal the maximum stress experienced within the concrete under failure load condition [98]. The variation in the FS in concrete materials is used while conducting tensile strength and the strength values are applied on an unreinforced concrete slab to determine the resistance of the concrete towards failure [97]. The work mentioned in [14] observed that the flexural strength reduces with the inclusion of different types of PWA in concrete. It must be noted that the type of PWA also has a profound impact in determining the flexural strength. It is worth noticing that plastic aggregates with uniform shape improves the flexural strength compared to the aggregates with random shape. As mentioned in [14], the flexural strength is reduced by 16% for 15% RPA. [99] investigated the changes in the FS of concrete with the percentage of PWA. The PVC aggregate replaces the sand aggregates and this resulted in the increase of flexural strength by 8%. It was also observed that there was no change in the flexural strength for a replacement ratio of 15% and the values were stable until the ratio was kept below 30%. Similar results were observed when the natural aggregate was replaced by PVC aggregate. It was noted that, for 30% aggregate the FS was increased by 23.5% and a decrease in the FS was observed with 65% and 85% of PVA aggregates respectively [90].

4.1.3 *Splitting tensile strength (TS)*

The TS defines the quality of concrete which replaces natural aggregate with PWA. Concrete materials are characterized by their low tensile strength because of its brittle nature and due to this concrete develops cracks upon experiencing tensile forces. Splitting TS is similar to the functionalities of the tensile strength and the variation patterns are similar to that of flexural strength [97]. It is highly challenging and complicated to measure the tensile strength due to the complexities associated with the application of axial loads in direct tension. Hence, the tension patterns of concrete are evaluated via indirect testing [7]. The main causes for the reduction in the TS is evaluated in several research works and it was observed that the reasons for the reduction of TS is similar to the decrease in the CS. The authors in [28] indicated the effect of uniformly shaped and non-uniformly shaped PWA on the splitting TS. The evenly shaped PWA improves the splitting TS compared to non-uniform PWA. In addition, the TS of concrete with PWA deteriorates with the reduction in the elastic modulus of PWA. The authors in [100] observed that the increase in the PWA content in the concrete mixture can diminish the splitting tensile strength. Experimental analysis shows that the decrease in this strength is attributed to the interfacial transition zone (ITZ) and the water particles aggregated at the surface of PWA can reduce the bonding strength between the concrete and the PWA particles. This validates the linear relationship between the CS and the TS. The inclusion of PWA in concrete also increases the porosity which in turn reduces the splitting tensile strength.

4.1.4 *Modulus of Elasticity/Young's modulus*

The elastic modulus denoted as E_c is measured as the slope of the straight portion of the curve defining the stress and strain. However, the curve is perturbed by the decrease in the CS of the concrete with PWA. In terms of CS, the modulus of elasticity of PWA decreases with the increase in the value of S_{PA}. The elastic modulus of PWA included in the concrete depends on various factors such as type of PWA and type of aggregate and curve characteristics [101]. The value of E_c reduces for three types of PWA namely fine, coarse, and pellet shaped particles and the type of plastic aggregate and porosity also affects the value of E_c. Since the elastic modulus is high in natural aggregates compared to PWA, the increasing PWA aggregate ratio reduces the E_c value of concrete materials. In addition, the increase in the water to cement ratio and porosity reduces the E_c of the concrete. It was observed in [35] that the decrease in the value of E_c results in the difference in the stiffness value between PWA and natural aggregates. Besides, the curing conditions and the relative humidity also have a significant effect on the value of E_c. The experimental analysis shows that the wet chamber curing of concrete with PWA reduces the values of E_c compared to the curing in an outdoor environment. This shows that a high relative humidity results in the higher value of elastic modulus. The expression relating E_c, compressive strength are tabulated in table 5.

Table 5. Expressions used to evaluate the mechanical properties of PWA-based concretes

Reference	Type of PWA	Splitting TS	FS	Modulus of Elasticity
[102]	PVC	$f_c = 15.356\, f_t + 6.963$	-	$E_c = 0.627\, f_c - 4.9099$
[103]	PET and PC	-	-	$E_c = 0.6534\, f_c - 4.6886$
[104]	PET	$f_t = 0.634\, (f_c)^{0.50}$	$f_c = 0.466\, (f_c)^{0.703}$	-
[67]	PET	$f_c = 11.618\, f_t + 0.9101$	$f_c = 10.888\, f_r - 9.9961$	$E_c = 1.55\, (f_c)^{0.83}$
[105]	PVC	$f_t = 0.16\, (f_c)^{0.87}$	-	$E_c = 0.9078\, f_c - 0.8023$
[90]	PVC	$f_t = 0.0838\, f_c + 0.0106$	$f_c = 0.0804\, f_c + 1.859$	$E_c = 0.9078\, f_c - 0.8023$

4.2 *Test for Durability Properties Containing PWA*

The durability performance of the concrete consisting of plastic aggregates can be analyzed using different factors such as water absorption, permeability, carbonation and shrinkage.

4.2.1 *Water Absorption*

This property of PWA is attributed to different parameters such as permeable pore volume and connectivity defines the porosity. Several existing works have stated that the water absorption capacity increases with the increase in the replacement ratio of sand and PWA. This attributes that natural aggregates and PWA do not mix effectively in the cementitious composites matrix and hence concrete becomes more porous [67] [106]. The work presented in [107] stated that the absorption percentage of concrete mix with PWA (PET aggregate) is higher than fundamental concrete. Besides, the water absorption capacity of concrete varies due to various factors such as volume of PWA, size of PWA particles, and water to cement ratio. The significance of curing and shape of PWA on the water absorbing capacity of concrete with PWA as a replacement of sand is discussed in [78]. It can be inferred from the study that the increase in the volume of PWA increases the absorption capacity.

4.2.2 *Permeability*

Water absorption capacity and porosity are the two prominent factors that influence the permeability of concrete composites containing PWA. [103] determined the gas permeability of mortar and concrete consisting of polycarbonate and PVA as a partial replacement of sand. Apparent permeability (Ka) is calculated using the Hagen-Poiseuille formula wherein the Ka is determined under steady state conditions as shown in equation 1.

$$k_a = \frac{2 * Q * P_{atm} * L * \mu}{A * (P_i^2 - P_{atm}^2)} \qquad (1)$$

where Ka is defined as the apparent permeability, Q is the measured gas flow (m^3/s), P_{atm} is the atmospheric pressure, m is the viscosity coefficient, P_i is the absolute pressure (P_a), l is the sample length (m), and A is the cross sectional area (m^2).

It can be inferred from the experimental analysis reported in [103] that the permeability increases with the increased content of PWA in concrete which in turn increases the porosity with the addition of plastic aggregates. The work in [108] analyzed the permeability of water vapor of cementitious composite containing PWA (recycled high impact polystyrene, HIPS) as an alternative to sand. The volume of water vapor is determined as follows;

$$Wvt = \left(\frac{G}{t}\right)A \tag{2}$$

where W_{VT} is defined as the rate of water vapor transmission measured in g/h m^2, A is the cross sectional area (m^2), G is the change in the weight, t is the time, G/t is the slope of the straight line. Correspondingly, the expression for calculating permeance is given as follows:

$$Permeance = \frac{Wvt}{\Delta p} = \frac{WVT}{S(R_1 - R_2)} \tag{3}$$

where D_p represents the difference in the vapor pressure, R_1 and R_2 are the relative humidity measured at the source and the vapor sink respectively. It can be inferred from the study that the permeability and permeance of the cementitious composites containing HIPS was similar to that of fundamental mortar and no significant difference in the permeability was observed.

4.2.3 *Carbonation*

Similar to permeability, carbonation of PWA based concrete also varies with respect to water absorption and porosity. The authors [109] evaluated the carbonation penetration depth of concrete with fine aggregates and it was observed that the carbonation depth in cementitious composites consisting of 100% PET and fine aggregates was lower compared to the composite consisting of PET and sand. This validates the fact that PET and sand aggregates do not make a homogenous mixture and hence the concrete becomes more porous and allows a higher concentration of CO_2 to penetrate. The authors in [78] stated the concrete with fine aggregates and PET experienced a higher carbonation depth compared to fundamental concrete. The experimental studies have also shown that the carbonation depth varies depending on the method of curing. The depth is lower in concrete samples that are cured in the wet chamber and higher in the samples that are cured in the external environment. This is because of the decrease in the number of open pores for CO_2 penetration in wet chambers.

4.2.4 *Shrinkage*

Drying shrinkage is one of the most prominent properties of PWA based concrete composites. Several studies have suggested the inclusion of PWA as a replacement of FA results in high drying shrinkage compared to concrete without PWA. This is mainly due to the low stiffness of the PWA which is not resistant to the shrinkage stress in concrete mixtures [110] [111]. These studies have observed that the shrinkage of cementitious composites containing PWA as a replacement of sand is higher under completely saturated conditions. It can also be inferred from these studies that even a small increase in the shrinkage illustrates the increased content of plastic aggregates and this behavior can be attributed to the decrease in the elastic modulus.

Table 6 illustrates the existing works done on the analysis of mechanical properties and durability tests.

Table 6. Existing studies on the analysis of mechanical and durability properties for concrete with PWA

Properties	Tests Conducted	References
Mechanical Properties	Compressive Strength	[112] [113] [114] [115]
	Splitting Tensile Strength	[116] [117] [118] [119]
	Flexural Strength	[120] [121] [122] [123]
	Modulus of Elasticity	[123] [124] [125]

Durability Properties	Water Absorption	[122] [126]
	Permeability	[127] [128] [129]
	Carbonation	[130] [131] [132]
	Shrinkage	[133] [134]

5. Challenges and Research Gaps

Though plastic waste aggregates are included for strengthening the mechanical and physical properties of concrete composites, there are certain environmental issues that restrict the adaptability of PWA in construction materials. PWA can have a negative impact on the human health and sustainability of the environment by releasing lethal pollutants [135]. Various toxic contaminants are also released during the production of construction materials through leaching which poses potential threat to the safety of construction materials. Hence, it is highly important to evaluate the impact of these environmental factors by conducting leaching analysis. In addition, it is essential to analyze the properties and characteristics of the concrete composites and other cementitious mixtures containing PWA. There is a need for an empirical analysis on the adoption of plastic waste as a replacement of natural and fine aggregate in concrete manufacturing. Such studies must focus on minimizing the construction cost along with other factors such as workability of PWA based concrete composites. Enhancing the workability of concrete to improve the mechanical and thermal properties needs significant attention. Furthermore, the analysis of admixtures such as superplasticizers must also be analyzed along with their impact on the mechanical properties of concrete.

6. Conclusion

This review provides a comprehensive analysis on the utilization of PWA in concrete. Several research works have been discussed in this paper with an aim to examine the strength and other attributes of concrete that use recycled PW as a replacement to the natural aggregate. It can be inferred from existing works that the results of each experimental analysis differs in terms of results and it often varies with respect to the variation in the type, size and proportion of plastic used. With the inclusion of PWA, the attributes of concrete composites are decreased. However, this helps in obtaining a lightweight concrete and hence, plastic aggregates can be used in different proportions in concrete and this paper emphasizes this aspect. In this context, this paper also discusses different aspects of plastics such as different types of plastics and its mechanical properties and their effect on the performance of the concrete mixtures.

Some of the prominent conclusions inferred from the existing literary works are as follows:

- With the increase in the percentage of plastics in the concrete mixture, there is a reduction in the CS, FS and TS of the concrete. This is due to the reduction in the binding quality between the cement mixture and the surface of the plastic aggregate.
- The replacement of PET aggregates has a negative impact on the concrete resistance to fire and the rise in the replacement percentage of PET can reduce the mechanical properties of concrete. However, PWA can be accompanied with other subsidiaries to manufacture eco-friendly concrete which can be used in several applications such as construction of highways, pavements and other structures which require high strength.
- Replacing fine aggregates with PWA can enhance the attributes of concrete such as permeability, and water absorption capacity.

Despite the availability of several research works on the utilization of PWA as an alternative to the natural aggregate, there are certain issues which remain defiant. These issues can be considered as a direction for future research. The main issues related to the analysis of thermal insulation properties of PWA based concrete, durability of concrete with respect to its resistance against acids and alkali, resistance to sulphate, and long term sustainability of mechanical attributes of PWA-based concrete will be discussed in the future research.

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