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Polymeric Wastes as Concrete Aggregate for Acoustic and Thermal Insulation Enhancement

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ABSTRACT

Polymeric wastes, specifically polyethylene terephthalate (PET) and scrap tyre rubber (STR), pose a significant environmental issue. PET, a thermoplastic polymer, is widely used in manufacturing bottles, PET cups, containers, fibres, films, and packaging materials. On the other hand, colossal rubber tyre waste quantities represent other environmental problems. However, PET and STR wastes are often discarded in the immediate vicinity, contributing to water resource pollution and landfill site strain. One solution is to replace aggregates in concrete mixtures with these wastes, a preferable alternative to landfill disposal because of the large volume and slow decomposition rate in landfills. Recycling PET and STR helps mitigate environmental pollution and promotes resource conservation and sustainability. This study aims to review previous research undertaken in the field and validate the findings of concrete's fresh, mechanical, and functional characteristics. Based on the review, most studies confirmed a noticeable decline in the mechanical characteristics of mortar and concrete. However, these studies did not effectively focus on using PET and STR as sound and thermal insulation aggregates. Replacing PET and STR as aggregate in concrete can reduce thermal conductivity and acoustics.

Keywords: polyethylene terephthalate, scrap tyre rubber, sound insulation, thermal insulation.

INTRODUCTION

Polyethylene terephthalate (PET) and scrap tyre rubber (STR) waste constitute a significant proportion of waste widespread in different places and landfills, posing a considerable ecological challenge due to their resistance to degradation for a long time. There are nearly twelve million tons of abandoned plastic waste in the ecosystem, with a substantial portion originating from disposable packaging [Thornton, 2002]. Among consumer plastics, polyethylene terephthalate (PET) stands out as one of the most widely used materials globally, particularly in the production of used in the packaging of liquids (especially water) and other consumer products [Fraternali et al., 2011; Frigione, 2010]. Global PET production has surpassed 6.7 million tons annually, with a remarkable surge in Asia, primarily due to heightened demand in China and India [Kim et al., 2010]. On the other side, used tyres also pose challenges associated with their waste disposal. Many tyres are discarded or buried in landfills worldwide, posing a substantial environmental threat. In Europe, approximately 355 million tyres are manufactured annually by 90 companies, accounting for about 24% of global tyre production [Presti, 2013]. The yearly predictable number of tyres reaching the end of their life worldwide is around 1.2 billion [Pacheco-Torgal et al., 2012a]. Properly managing waste rubber tyres has become a pivotal global environmental concern. Disposed tyres undergo various methods of disposal, including burning [Thomas et al., 2016], disposal as piles in landfills (Park et al., 2015), or repurposing as floor sports facilities and additives in asphalt [Gheni et al., 2019]. The accumulation of tyre stockpiles introduces risks to health, the environment, and the economy, contributing to pollution of the air, water, and soil [Park et al., 2015].

Managing plastic and tyres with diverse waste to significant challenges such as limited landfill space, environmental risk, and management costs have prompted finding alternative solutions like incorporating waste into bricks, tiles, blocks, and concrete mixes. For instance, recent research has been focused on a particular avenue involving the integration of rubber from used tyres into concrete production – a material extensively used in construction and known for its significant resource consumption. A viable strategy to address the challenge of waste tyre disposal is to use aggregates (fine or coarse) and mix (as a percentage by weight or volume) with cement, and this represents a substitute for normal aggregates (sand and gravel). Using crumb tyre rubber instead of aggregates in concrete contributes a sustainable and eco-friendly methodology to resource management. The utilisation and recycling of these wastes in concrete offer the potential to reduce the consumption of raw materials, leading to economic efficiency and sustainable development within the construction industry. Previous studies have not compared the utilisation of produced waste of polymers (used plastic and rubber) to mix with the concrete. Therefore, the main aim of this study is to compare and offer a comprehensive perspective on the possible application of waste materials, specifically plastic and rubber, as sustainable components in the production of mortar and concrete. Therefore, this research aims to compare and offer a comprehensive assessment of the potential use of plastic and rubber waste as environmentally friendly materials for mortar and concrete production. This study assessed the significant progress made in crumb rubber and plastic concrete for the comprehensive review. This study delves into a detailed examination and analysis of its fresh concrete properties, mechanical properties, durability, and other relevant characteristics. Despite possible workability and compressive strength losses, waste materials can be included in secondary construction parts. Some examples of these applications are traffic safety barriers and territories, shock absorbers, noise limitations, noise absorbers (to manage sound effectively), and earthquake shock-wave absorbers in buildings.

Given the anticipated urbanisation and predicted global population growth to around 9.8 billion individuals by 2050, it is unlikely that concrete output will decrease. According to the United Nations, the worldwide urban population is anticipated to increase from 55% in 2018 to 68% by 2050, leading to a higher need for concrete. Therefore, to mitigate the environmental impact of concrete, using PET and STR materials could effectively address this concern. Furthermore, previous studies showed that by replacing different proportions of aggregates with rubber and plastic, they focused on determining compressive and tensile strength and thermal insulation and produced lightweight concrete. It was noted that there are very few studies on sound insulation. Studies have shown that after replacing a portion of coarse and fine aggregate, concrete decreases in varying proportions depending on the proportions of replacement or addition of plastic and tyre rubber waste. The future goal is to study the effect of replacing plastic and tyre rubber waste in concrete for sound insulation and thus getting rid of the large quantities of these wastes generated by considerable quantities worldwide, especially in Iraq, and their significant impact on the environment.

PET AND RUBBER

PET waste

Plastics found in nature originate from diverse sources, such as packaging industries and household materials. Plastic waste is produced annually at over 6 billion tons (Jnr et al., 2018). The build-up of this plastic waste poses an environmental problem because most plastics are non-biodegradable, requiring over 400 years to break down. Consequently, plastic waste is deposited in landfills, requiring substantial space and impacting landfill capacities (Da Costa et al., 2016). Plastic waste's pervasiveness has also significantly threatened marine habitats, ecosystems, and human well-being [Singh & Ruj, 2015]. Research has shown that the breakdown of plastic waste produces nanoparticles that enter the food chain, adversely affecting animal health (Prata et al., 2019). Plastic materials come in a variety of forms and are used for a range of reasons. Nevertheless, some plastics fit into the thermoplastic category, making them acceptable for recycling. Polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polystyrene (PS), polypropylene (PP), and polyvinyl chloride (PVC) are examples of these thermoplastics.

In contrast, artificial fibres and thermosetting polymers comprise the category of plastics that cannot be recycled. Materials consisting of multiple layers and laminations, including plastics like Teflon coating, PUF (polyurethane foam), Bakelite, polycarbonate, melamine, and polyester, represent examples of non-recyclable plastics. Figure 1 illustrates the categorisation of various polymers and their respective applications. One of these plastic categories is PET (Figure 2), a type of polyester created by synthesising ethylene glycol and terephthalic acid. PET is well-known for its outstanding characteristics, including high stability, remarkable pressure resistance, resistance to various substances, and efficient gas containment capabilities, making it a common choice in the packaging industry. These attributes make it a preferred option for sealing carbonated beverages to preserve their gas content (Plastics Europe).Yesilata et al., 2009 replaced the fine aggregate with PET plastic material, which came in strip, square, and irregular shapes, each sizing 1 mm (controlled by a volumetric value of 40 cubic centimetres). In contrast, Tang et al., 2008 opted for irregular PET plastic, ranging in size from 0.1 to 5 mm, constituting 5% by weight, instead of fine aggregate; in contrast, in the study conducted by Frigione, 2010, the fine aggregate was substituted with irregular PET plastic waste in two different proportions: 25.64% and 16.95% by weight, with the plastic particles being smaller than 4mm and embraced PET plastic in Flaky and cylindrical forms with 2–16 mm sizes, utilising 5, 10, and 15 volume percentages to replace the coarse aggregate.

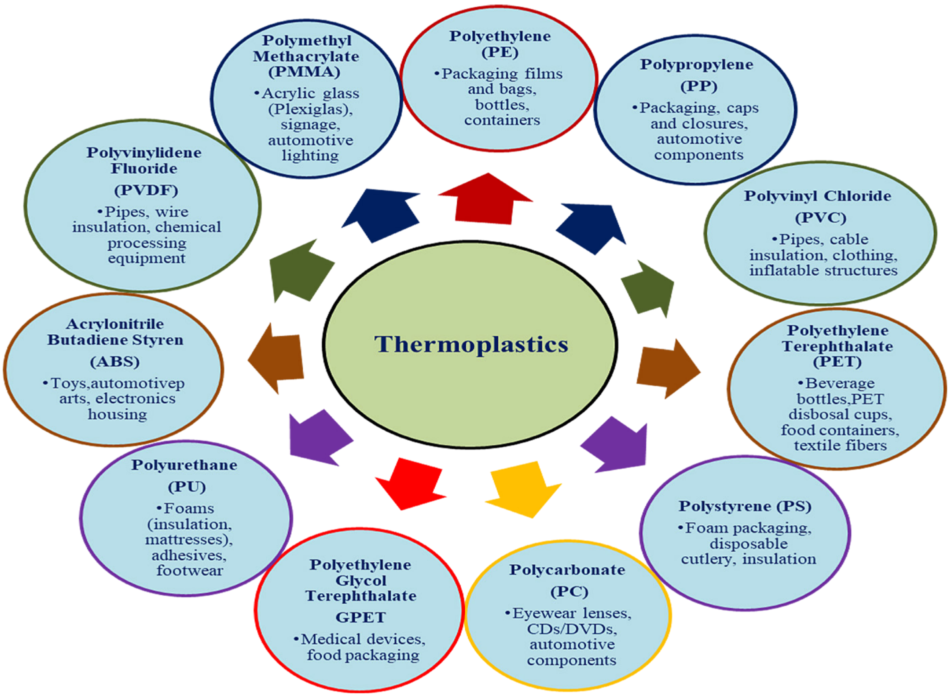

Figure 1. Plastic types and their respective practical uses

Figure 2. Polyethylene terephthalate (PET) is used in drinking water

Numerous scholars have employed variously sized flaky PET plastic waste particles to replace fine or coarse aggregate in their research. Albano et al., 2009 substituted fine aggregate with flaky PET plastic waste particles, choosing sizes of 2.6 mm and 11.4 mm and utilising volume percentages of 10 and 20. Similarly, Sadrmomtazi et al., 2016 and Rahmani et al., 2013a replaced fine aggregate with flaky PET plastic waste particles measuring less than 4.75 mm, employing weight percentages of 5, 10, and 15 and volume percentages, respectively.

As per the findings presented by [Islam et al., 2016], they opted for substituting the coarse aggregate with PET plastic waste particles that were characterised as flaky (with sizes greater than 4.75 mm). This replacement was carried out at varying percentages by volume, specifically 20%, 30%, 40%, and 50%. In contrast, according to the research conducted by (Saikia and de Brito, 2014), they took a different approach by replacing coarse and fine aggregates with PET plastic waste particles. These particles were divided into flaky (2 to 11 mm) and spherical (1 to 4 mm). The substitution was done at different percentages by volume, which included 5%, 10%, and 15%.

In the construction of concrete mixtures, [Correia et al., 2014] and [Silva et al., 2013] chose to incorporate PET plastic waste particles in two different forms: flaky particles with sizes ranging from 2 to 11 mm and regular pellets with sizes ranging from 1 to 4 mm. These substitutions were made in place of both coarse and fine aggregates. They were implemented at varying weight percentages within the 7.5% to 15% range.

On the other hand, [Ferreira et al., 2012] took a unique approach by utilising PET plastic waste particles in three distinct forms: lamellar, irregular, and cylindrical granulates, with particle sizes all under 20 mm. These granulates were employed as replacements for both coarse and fine aggregates in the concrete mixture. In this case, the substitution percentages ranged from 7.5% to 15% and were measured by volume.

Rubber waste

Automobile tyres are a vital component of the rubber industry's output, necessitating the recycling of used tyres to remove their metal, textile, and rubber material components, which may be used as essential components to make various products [Hunag et al., 2016]. Mechanical processes can generally reduce rubber material to powder or tiny pieces. Rubber materials can generally be mechanically processed into powdered form or fine fragments.

Rubber and plastic possess low weight, limited water absorption, strength, rigidity, and hydrophobic properties, which repel water and promote air trapping on their surfaces. To efficiently turn various types of used plastic and rubber into usable material, it can be processed using many methods, such as physical and chemical re-extrusion and energy recovery techniques [Albano et al., 2009]. Depending on the plastic/rubber waste type and the processing method, diverse shapes of aggregates (plastic and rubber) can be derived. These aggregates' form, composition, and size greatly influence the durability of both concrete and mortar. A comparative analysis of previous studies employing different aggregates can be conducted to understand their influences. The following sections will examine the impacts of the used plastic and rubber integration as substitutes for aggregates, explicitly focusing on fresh properties, hardened properties, durability, and functional characteristics.

Many studies employed rubber pieces in a mixture instead of aggregate as follows. Guo et al., 2017 employed crumb rubber particles smaller than 4.75 mm in size to substitute for 15%, 25%, 35%, and 50% of fine aggregates (by volume). Furthermore, Bisht and Ramana (2017) replaced fine aggregates with 0.6 mm-sized crumbed rubber in proportions of 4%, 4.5%, 5%, and 5.5% (by weight). Su et al. [2015] substituted a range of 0–20% fine aggregates with rubber chips, with 2–4 mm particle sizes and 0.8–2 mm. Ganjian et al. [2009] opted for chip rubber with particle dimensions exceeding 4.75 mm instead of coarse aggregates, incorporating weight percentages of 5%, 7.5%, and 10%. In a separate investigation conducted by Reda Taha et al. [2008], they substituted fine or coarse aggregates with chip rubber, sizes ranging from 5 to 20 mm, and crumb rubber, between 1 to 5 mm. These replacements were made at 25, 50, 75, and 100 volume percentages. Khaloo et al. [2008] implemented a replacement strategy using chip rubber, characterised by particle sizes falling between 4.75 to 15 mm, and crumb rubber, with sizes less than 4.75 mm. The substitution percentages were set at 12.5, 25, 37.5, and 50 by volume for fine and coarse aggregates.

Asutkar et al. [2017] employed angular rubber, ranging from 10 to 20 mm, as a substitute for coarse aggregates at volume percentages of 5, 10, 15, and 20. Ghedan and Hamza [2011] utilised angular rubber, smaller than 10 mm, to replace 15% of the coarse aggregates by weight. Raffoul et al. [2016] selected angular rubber categorised into three size ranges, 0–5 mm, 5–10 mm, and 10-20 mm, to replace fine and coarse aggregates. These substitutions were performed at 10, 20, 40, 60, 80, and 100 volume percentages.

In their research, as reported by Paine et al. [2002], rubbers with various shapes, such as angular, flaky, and elongated, were employed. These rubbers came in different sizes, including 0.5–1.5 mm, 2–8 mm, and 5–25 mm. They were substitutes for fine and coarse aggregates, with volume percentages set at 2, 4, and 6.

Al-Akhras and Smadi [2004] substituted 10% of the fine aggregates by weight with irregular rubber, which had a size of less than 0.045 mm. This replacement was done at the following percentage levels: 2.5, 5, 7.5, and 10. Paine et al. [2002] utilised irregular and jagged rubber shapes ranging from 0 to 8 mm to replace fine or coarse aggregates with 10, 20, 30, and 40 substitution percentages by weight. Angelin et al., [2017] used semi-spheroidal rubber (using two ranges of size 0.02–0.06 mm and 1.7–2.1 mm) instead of 30% of fine aggregates (by weight). They also replaced fine aggregates with semi-fiber rubber with two sizes, 0.06–0.1 mm and 2.5–2.9 mm, using 10% (by weight). Grdić et al. [2014] added granulated rubber, ranging in size from 0.5 to 4 mm, into the mixture, replacing fine aggregates at equivalent volume percentages of 10, 20, and 30. Su et al. [2015] substituted 20% of the fine aggregates with granulated rubber, using two sizes of 0.5 mm and 3 mm, by volume. Bravo & De Brito [2012] replaced fine and coarse aggregates with granulated rubber (with size < 11.2 mm) as an equivalent replacement (by volume) for 5%, 10%, and 15%. Additionally, they employed elongated rubber as an equivalent replacement for 10, 20, 30, 40, and 50% of the volume instead of fine or coarse aggregates with a size smaller than 20 mm. Hunag et al. [2016] used powder rubber (with size < 4.75 mm) instead of fine aggregates with percentages of 10, 20, 30, and 40 (by volume). Tyre rubber with different sizes can be seen in Figure 3.

Waste of used rubber is widely used as either fibres or aggregate (fine and coarse) in different applications. Used rubbers replace them instead of everyday materials (sand and gravel) and mix with concrete in fine or coarse forms. Some instances of rubber waste are also used as fibres and binders [Gupta et al., 2016; Nuzaimah et al., 2018]. Investigating the incorporation of reused plastic and rubber proved to be a successful method for improving the characteristics of mortar and concrete in particular uses [Saikia and de Brito, 2012]. For instance, concrete made using the recovered polyolefin (PO) waste after fire exposure showed better mechanical performance [Colangelo et al., 2016; Correia et al., 2014]. Including plastic fibers in concrete has enhanced post-crack flexibility and improved flexural toughness. Concrete with added plastic pieces has shown improved flexibility in the phase after the crack and improved flexural toughness [Yin et al., 2015]. Incorporating rubber particles could result in a reduction in both workability and compressive

Figure 3. STR types with different sizes

strength. It is applied in secondary parts and building walls of structures, earthquake shockwave dampeners in buildings, and used in improving the sound and thermal insulation in sports or meeting halls, airports, buildings, and others [Siddique & Naik, 2004]. Furthermore, plastic, rubber, mortar, and concrete can be made less dense and less fragile. The physical characteristics of both natural aggregate and aggregate made of plastic or rubber are displayed in Table 1. They also display advantages concerning water resistance, reducing noise, and thermal resistance [Ferrándiz-Mas and García-Alcocel, 2013; Rashad, 2016].

TRANSFORMING PLASTIC AND RUBBER WASTE INTO AGGREGATE MATERIAL

Plastic aggregate is primarily produced using virgin polypropylene (PP) and polyethylene terephthalate (PET) [Yang et al., 2015]. Typically, components of PET and PP are subject to three processing steps before being employed as aggregate in concrete [Hopewell et al., 2009]. Initially, impurities like labels and adhesives are eliminated by washing with disinfectants and detergents to ensure the desired quality of the final product. The used plastics are converted to tiny particles by cutting them to form known as flakes in the following stage. After being heated, they are extruded into the form of pellets. Sorting the rubber components as aggregate from other waste, most of its waste originates from automobile tyres. The waste of STR is considered raw materials for producing other products [Thomas et al., 2016]. Mechanical treatment can turn rubber into powder or tiny particles. Typically, there are 3 phases in the reuse and recycling method (Torretta et al., 2015). STR are firstly crushed and shredded before being ground. Grinding or rolling presses are commonly utilised to create rubber particles over 0.475 cm. These coarse rubber particles (with sizes of 7.5 cm to 0.475 cm) undergo additional processing using rolling or rotary crushing mills into granular or crumb particles. Additional crushing is done using a mill known as a rotating colloid to get fine rubber (as powder) with diameters smaller than 7.5 cm.

Workability of PET and STR aggregate

The primary conclusions of this research showed that resistance of variously formed particulates, especially, is significantly affected by the form and quantities of the plastics, which govern most of the concrete workability that has plastic aggregates—it observed that concrete incorporating PET waste experienced reduced workability due to the flaky shape of the plastic, which hindered the flow of the freshly mixed concrete. The reduction in workability accelerated with the increasing content of plastic. Employing a plastic percentage ranging from zero to 15%, a 42% loss in workability was detected. Rai et al. [2012] found that mixing plastic flakes with irregular shapes produced a similar outcome. Nevertheless, the loss of workability can be reduced by either pre-soaking the aggregates of plastic beforehand and adding them to the concrete mixture or by adding a small amount of superplasticiser [Ferreira et al., 2012]. It determined that as particle sizes and roughness increased, the workability of concrete diminished. This was attributed to the heightened porosity caused by these factors, impeding workability.

Several researches on rubber have demonstrated that adding rubber aggregates to concrete reduces its workability, with the degree of reduction depending on the quantity of rubber and its particle size. Even a modest crumb rubber aggregate percentage of under five per cent with a size particle of 0.06 cm. Bisht & Ramana [2017] showed reduced concrete workability. However, a workable mixture appropriate to the casting and

Table 1. The physical characteristics of natural aggregate and aggregate mixed with plastic or rubber

Category	Type aggregate	Volumetric density (g/cm^3)	% of water absorption after 24 hours.	Relative density	Ref.
Used plastic	Polyethylene terephthalate	0.438	0.10	1.35	[Ferreira et al., 2012]
Used rubber	Ground rubber produced mechanically	0.044	0.80	1.01	[Siddika et al., 2019]
	Rubber made using cryogenics	0.046	1.30	1.07	
Natural aggregate	Gravel	1.624	1.32	2.79	[Senthil Kumar and Baskar, 2015]
	Sand	1.656	1.80	2.65	

vibrating of fresh concrete can still be produced by replacing the sand (30%) with rubber as fine aggregate [Angelin et al., 2017]. The loss in workability caused by the irregular particle grading and rough surface of rubber waste can be reduced, comparable to that with an aggregate of plastic, by adding a superplasticiser [Youssf et al., 2014].

MECHANICAL PROPERTIES

Dry density

Colangelo et al. [2016] adopted recycled polyolefin waste to replace natural aggregates. Concrete containing 35% plastic aggregate showed a density drop of about 23% relative to regular concrete (with a density of 2.156 g/cm^3). When using PET fine aggregate up to 50 per cent in mortar, the density decreased by approximately 37.5 per cent, with a bulk density of around 1.5 g/cm^3 [Safi et al., 2013]. [Batayneh et al., 2007] also found evidence of the same trend of density loss. When the PET (as coarse aggregate) was replaced by natural coarse aggregate (with a range of volumes from 20% to 50%), Islam et al., 2016 found that it led to a reduction in density of 4–10%. The plastic aggregates were around 70 per cent lighter weight than sand, thus explaining why this occurred. In contrast to sand, which has a specific gravity of 2.61 g/cm^3, plastic aggregates have a specific gravity that ranges from 0.9 to 1.34 g/cm^3.In addition to the plastic, Asutkar et al., [2017] employed crumb rubber to replace fine aggregate with a range of 10–30%. This replacement led to a reduction in the unit weight of concrete by up to 28%. Contrary to ordinary concrete's density of 2.13 g/cm^3, 20% of rubber chips mixed with concrete have a 1.9 g/cm^3 [Gesoglu et al., 2017]. Gisbert et al. [2014] discovered a comparable decline when rubber crumbs were used instead of sand at ten, twenty, thirty, and forty per cent. Additionally, this led to density reductions of approximately percentages (respectively) 17, 18, 21, and 28. The leading cause of this drop was the decreased density of rubber particles (510–1200 kg/m^3), which is close to 50% of the aggregate density of sand and rubber [Eiras et al., 2014].

Compressive strength

Compressive strength was significantly affected by the inherent hydrophobic and non-hydrating properties of aggregates made of plastic, as well as by criteria such as shape, size, and quantity. Generally, an escalating decline in the compressive strength of concrete was noted as PET aggregate content increased. By reducing the number of hydration products generated in the interface region, the addition of plastic material also lowered the interaction of bonds and compressive strength [Gesoglu et al., 2017]. According to a study by Coppola et al. [2016], finer plastic aggregates (with sizes 0.18 to 2 mm) showed fewer voids; this helps offset the loss of compression strength. On the other hand, Yang et al. [2015] stated that a slight increase in compressive strength was observed for concrete that self-compacts short columns with lengths of 0.15–0.4 cm and containing recyclable plastics at less than 20% due to the capacity of plastic particles to fill some voids within the concrete. Keeping the recyclable plastic in the concrete or mortar mixture at ≤ 20% is usually recommended to avoid a significant compressive strength drop. In addition, bigger plastic particles reduced compressive strength because smooth surface layer formation decreased the bond at the interface of the aggregate matrix. Lamellar forms of aggregate were more harmful than spherical ones in terms of aggregate shape [Ferreira et al., 2012; Saikia & de Brito, 2014], as they increased surface area and water demand, thereby reducing the interfacial transition zone, also known as the ITZ zone. Regarding the rubber aggregate, most previous investigations have consistently shown that increased CR content generally reduces compressive strength. A weakening ITZ results from high crumb rubber content because of apparent weak adhesion and crumb rubber accumulation on the fracture surface [Li et al., 2016]. Mohammed and Adamu [2018] discovered that substituting 20% and 30% of fine aggregates with crumb rubber reduced compressive strength by 16.3% and 23.2%, respectively, compared to regular aggregate concrete. According to images by Mohammed and Adamu [2018] (Figure 4) obtained using electron microscopy that applies to scan field emission, a thicker ITZ and more significant voids in the hardened concrete relate to higher crumb rubber replacement rates. In another study, Fernández-Ruiz et al. [2018] tested the effect of combining crumb rubber powder with concrete. They compared compressive strength with regular aggregate concrete, using the percentage of 2.5 and 5 crumb powder of rubber in place of cement, which decreased compressive strength (respectively) by 28 and 38.2%. Mishra & Panda [2015]

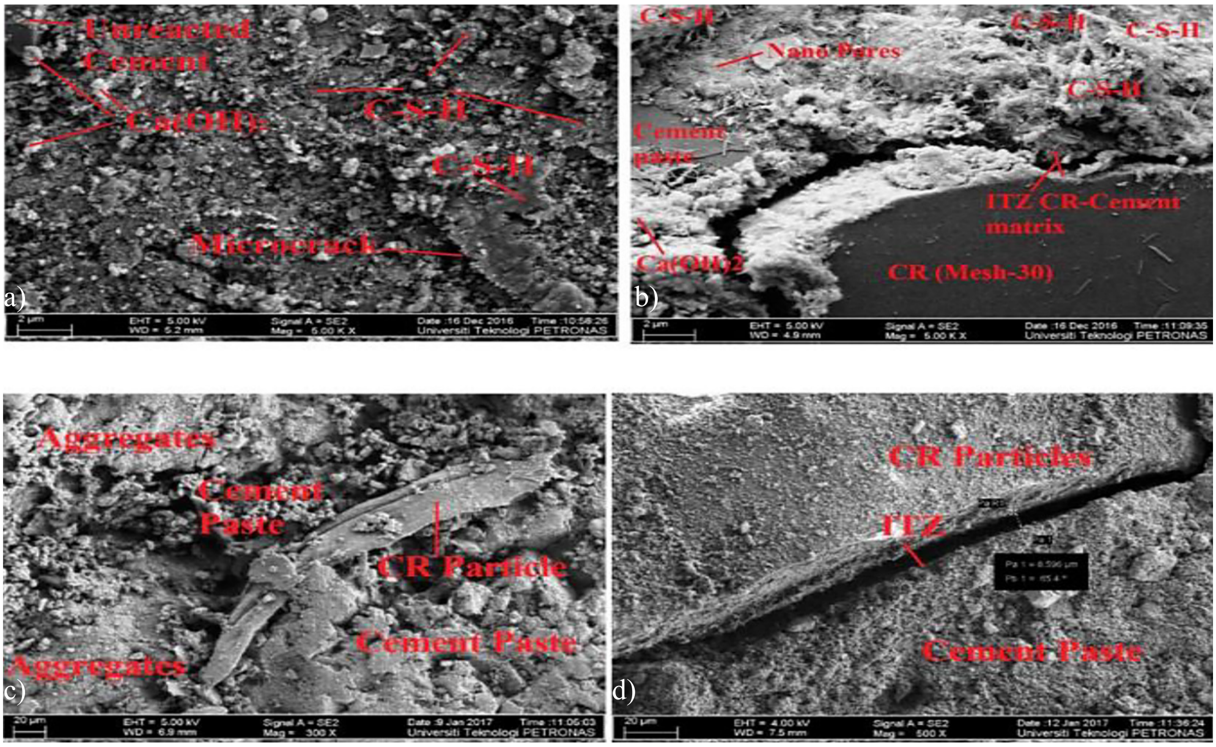

Figure 4. FESEM images for CRC mixtures [Mohammed & Adamu, 2018], (a) concrete with 0% CR, (b) concrete with 10% CR, (c) concrete with 20% CR, (d) concrete with 30% CR

found that compressive strength decreased when coarse aggregate replacement and self-compacting rubber concrete increased.

Though certain research studies have shown negligible changes or gains in strength, it is crucial to remember that concrete containing crumb rubber particles does not consistently negatively impact compressive strength [Bisht and Ramana, 2017; Gonen, 2018; Ismail et al., 2018]. Two potential reasons for these variations are as follows. Firstly, the size of the crumb rubber has a crucial impact on compressive strength. Fine crumb rubber aggregates tend to have fewer voids than coarse aggregates [Gonen, 2018; Ismail et al., 2018]. Further, the size of the poor interface between the particles and the matrix may be minimised, and the adverse effects of different strains in the paste of rubber cement may be offset by using fine-crumb rubber particles [Ismail et al., 2018]. For example, Gonen [2018] substituted 0.5% of the weight of sand and gravel with crumb rubber. Their findings showed that when using two mm-sized crumb rubber, the compressive strength decreased by 8.3%, while with one mm-sized crumb rubber, the reduction was only 3.6%. Furthermore, once the optimal level of crumb rubber replacement was achieved, the distribution of crumb rubber aggregates in the concrete became more uniform, resulting in an enhanced compressive strength [Da Silva et al., 2015]. This effect may also be attributed to improved aggregate gradation within the concrete [Sofi, 2018]. Da Silva et al. [2015] compared to their counterparts without crumb rubber, concrete tactile paving blocks with 10% crumb rubber showed a substantial about 9% improvement in compressive strength after seven days and a 2.2% increase after 28 days.

Tensile and flexural strengths

Adding plastic as aggregates led to a reduction in the concrete's tensile strength in addition to compressive strength. However, the tensile strength seemed more reliant on the bonding properties than the compressive strength, which was more affected by the size of the particles. These bonding characteristics were primarily related to the composition and number of plastic aggregates employed for replacement [Ferreira et al., 2012; Saikia and Brito, 2013]. Furthermore, the plastic aggregate's smooth surface texture, along with the increased area of surface, led to a weaker interfacial bonding, which was principally brought through the accumulation of too much water that was free. Tensile strength was further significantly negatively impacted by this component [Sharma and Bansal, 2016]. The mixtures showed more flexibility and plasticity as the percentages of aggregates made of plastic substitution rose. Consequently, this enhanced flexibility, stemming from the nature of plastic materials, reduced the likelihood of brittle failures [Sadrmomtazi et al., 2016]. Notably, Colangelo et al. [2016] observed a gain in tensile strength despite maintaining the plastic material's 10% substitution fraction. They explained how this minimal quantity of plastic grains could act like fibres, producing a bridging effect between cracked surfaces. However, when the aggregate amount of plastic in the mixture grew, the link between the aggregate and the matrix decreased, which dominated the decline in flexural strength.

A persistent reduction in tensile strength was consistently noted in rubber-containing samples. Tensile strength reductions of 40.1%, 44.1%, 48.9%, and 58.5% were documented in samples with corresponding rubber proportions of 20%, 30%, 40%, and 50% [Youssf et al., 2017]. This decrease in strength was ascribed to the dimensions of the rubber particles (1.18 mm and 2.36 mm) employed, as they possessed a restricted ability to span the tensile cracks. Moreover, the lack of an adequate interfacial transition zone (ITZ) created cracking channels that accelerated collapse. It may be inferred that the rubber aggregate acted as voids and weak points, which helped to cause the strength of the tensile force to decrease [Pacheco-Torgal et al., 2012b; Saikia and Brito, 2013]. Nevertheless, preparing the rubber aggregate with a solution of sodium hydroxide, or NaOH, proved to be a successful strategy for reducing the tensile strength after treatment. Compared to samples without the preliminary treatment, the rubber particles underwent a 30-minute pre-treatment in a ten per cent sodium hydroxide solution, and the following tensile strength showed an increase of about fifteen per cent [Youssf et al., 2017]. A study by Benazzouk et al. [2007] discovered that whenever the rubber aggregate substitution proportion ranged from twenty per cent to thirty per cent (sized 0.1 cm), the flexural strength rose by approximately 18 per cent. The enhancement has been attributed to the rubber's elastic and no brittle characteristics under loading, which prevented cracks from spreading throughout the structure's matrix and postponed the fracture stage. Al-Akhras and Smadi [2004] performed studies with rubber replacement ratios of sand at values of 2.5, 5, 7.5, and 10 (sized < 0.15 mm), and they noted a corresponding tendency of results obtained by Benazzouk et al. [2007]. This improved flexural strength across all the mixtures, potentially due to the rubber aggregate's filler properties, creating a more dense, uniform, and narrow transition zone. On the other hand, Uygunoğlu & Topcu [2010] found that flexural strength decreased when the percentage of rubber aggregate rose from 10 to 50 per cent (sized ranges from 0.1 cm to 0.4 cm). Pedro et al. [2013] connected the weakening to microstructural abnormalities in fresh cement, aggregates, and concrete mixtures, particularly at the interfacial transition zone.

In conclusion, pre-treatment and using sizes smaller than 1 mm are ideal for using rubber aggregate to prevent any decreases in tensile or flexural strength when incorporating these aggregates. Numerous earlier investigations have concentrated on rubber's mechanical characteristics, including its manageability, compressive strength, flexural strength, and splitting tensile strength.

In terms of workability, Alsaif et al. [2018] opted for granular rubber pieces (sized from zero to 6 mm) and chip rubber pieces (sized 5–0 mm) instead of 30 to 60% (by volume) of fine and coarse aggregates in the mix. Their findings indicated reduced workability within the 13% to 56% range. In a separate investigation by Koutas et al., 2018], the workability decreased by approximately 17% to 38% when granular rubber pieces sized between zero and 4 mm and chip rubber pieces sized between 4 and 20 mm were used in place of 20 to 60% by volume of fine and coarse aggregates. Bharathi Murugan and Natarajan [2015] investigated the workability characteristics by substituting fine aggregate with powdered and granular rubber fragments, ranging from 0.075 mm to 4.75 mm, in amounts of 5% to 25% (by volume). Their findings indicated an improvement in workability within a range of approximately 4% to 44%.

In terms of compressive strength, Ismail & Hassan [2017b] observed a reduction in compressive strength (at the 28-day) within the range of approximately 12% to 58% when they substituted fine aggregate (ranging from 5% to 30% by volume) with powdered and granular rubber pieces, sized between 0.075 mm and 4.75 mm.

Conversely, in a study by Da Silva et al. [2015], after 28 days, compressive strength exhibited a modest increase of 2.2%. This change occurred as they replaced 10% (by volume) of fine aggregate with granular rubber pieces ranging from 1.2 mm to 2.4 mm.

Regarding flexural strength (measured at 28 days), Da Silva et al. [2015] found in the same study a decline in flexural strength within the range of 18% to 32% when employing the same characteristics mentioned earlier. In a separate study, Jokar et al. [2019] pointed out a decrease in flexural strength within the 9% to 19% range. They achieved this by replacing 10% to 15% coarse aggregate (by weight) with granular rubber pieces between 1 mm and 6 mm.

Moreover, Ismail & Hassan [2017a] conducted investigations into the splitting tensile strength (tested at the 28-day) by substituting 5% to 15% (by volume) of fine aggregate with rubber powder, which had sizes of 150 µm and 0.075 mm (respectively). Then, they replaced the fine aggregate with granular rubber pieces sized 4.75 mm. Their findings indicated a reduction in splitting tensile strength by approximately 17% to 31%. Table 2 shows the change in Compressive strength values that resulted from replacing Aggregate with various PET contents.

Sound insulation

Noise pollution has emerged as a significant global environmental concern, leading to various disturbances and significantly impacting work productivity and human living standards [Cao et al., 2018]. According to Oyedepo et al. [2019], fluctuations and contrasts in equivalent noise levels within commercial zones surpass the World Health Organization (WHO) benchmarks. The WHO designates 70 dBA as the acceptable threshold for A-weighted sound pressure levels in commercial areas. The World Health Organization (WHO) defines noise pollution as intrusive or overly loud sounds that can negatively impact human well-being and the environment [Belmokaddem et al., 2020]. Addressing exterior noise from surrounding areas can be achieved by employing sound obstruction techniques. Numerous acoustic components are integrated into construction to enhance sound insulation within buildings. Selecting a suitable material is significant in ensuring optimal acoustic comfort within residential structures [Mustafa et al., 2019].

The most elevated and the most reduced equivalent noise levels were observed in business districts (96 dB (A)) and residential zones (52 dB (A)), respectively. Regarding background

Table 2. PET plastic mechanical properties used in previous studies

Application of plastic waste	Normal compressive strength (MPa)	Compressive strength (MPa)	PET plastic content	Refs.
Coarse aggregate	16.06 (w/c = 0.35), 15.17 (w/c = 0.5), 15.04 (w/c = 0.4).	20.72, 17.12, 17.91, 17.58, 16.64	1%, 3%, 5%, 7%, and 10%	[Hameed & Fatah Ahmed, 2019].
After 7-day Fine aggregate 10% Fine aggregate 15% Fine aggregate 20% After 28-day Fine aggregate 10% Fine aggregate 15% Fine aggregate 20%	21.5 30.5	18.96, 18.43, 17.36 18.60, 18.16, 16.60 18.33, 17.10, 16.10 27.60, 26.80, 26.70 27.50, 26.30, 26.00 27.30, 25.70, 25.20	Coarse aggregate 15%, 20%, 25%	[Jaivignesh & Sofi, 2017]
Added into the mix (7-day) Added into the mix (28-day)	33.6 48.2	35.5, 34.0, 30.7, 28.8 50.9, 49.8, 47.9, 46.6	0.5%, 1.0%, 1.5%, 2.0% (w/c = 0.45)	[Kai Loong et al., 2020]
Fine aggregate (3-day) Fine aggregate (7-day) Fine aggregate (28-day)	19 21 35	21, 17, 14, 13, 12, 9 32, 31, 27, 23, 18, 11 51, 38, 31, 29, 22, 19	5%, 10%, 15%, 20%, 25%, 30%	[Azhdarpour et al., 2016]
Fine aggregate (3-day) Fine aggregate (7-day) Fine aggregate (28-day)	20 32 39.56	25.33, 28.89, 23.11 31.11, 34.22, 32.89 40.00, 42.22, 40.00	0.5%, 1.0%, 1.5%	[Somwanshi et al., 2022]
Fine aggregate	37.53 (w/c = 0.45) 32.72 (w/c = 0.55)	38.2, 39.7, 40.23, 39.23, 36.77, 35.98 36.45, 37.96, 38.29, 39.67, 37.82, 31.44	0.25%, 0.5%, 0.75%, 1%, 1.25% and 1.5%	[Ahmad et al., 2018]
Fine aggregate	19.32 (w/c = 0.681).	12.72, 9.23, 8.40	5%, 10%, 15%	[Zakaria & Al Jauhari, 2023]

noise levels (L90), the highest and lowest were documented in commercial areas (77 dB (A)). Residential regions (44 dB (A)), respectively, while the maximum peak value (L10) occurred in commercial districts (96 dB (A)) and the minimum in residential neighbourhoods (56 dB (A)) [Cao et al., 2018].

The capacity of concrete to soak up sound energy depends on its sound absorption coefficient, which is linked to a metric known as the noise reduction value (NRC). Recent studies indicate that when plastic is incorporated as a filler material in concrete, the sound absorption capability increases compared to standard concrete. This is supported by evidence suggesting that the NRC value for plastic-infused or lightweight concrete surpasses regular concrete by 57%, as demonstrated by Tschiersch & Hoppe [2022] and Poonyakan et al. [2018].

Preliminary investigations have revealed that plastic aggregate offers potential as an efficient material for absorbing sound due to its porous structure, despite the lack of studies on the absorption of sound abilities of concrete and mortar, including used plastic material [Rahman et al., 2012; Rahmani et al., 2013b]. These studies have shown that plastic aggregates, such as EPS (expanded polystyrene), can display favourable sound absorption properties across different frequency ranges compared to standard polyethylene. This is attributed to the microvoids present within EPS [Murugan et al., 2006]. A study by Asdrubali et al. [2008] compared EPS with various naturally occurring sound-absorbing materials. Their investigation demonstrated that EPS achieved a sound absorption coefficient of 0.5 at 500 Hz, leading to a significant reduction in impact noise of 30 dB. This level of performance was found to be comparable to that of natural sound-absorbing materials. Furthermore, it was shown that mortar (lightweight) integrating plastic granules (polystyrene type) performed better absorption of sound than compared to traditional sound-absorbing materials in the study done by Branco and Godinho [2013].

The literature has provided evidence of the improved absorption capacity of the sound when incorporating rubber aggregates into concrete. Issa & Salem [2013] examined wave travel time measurements to evaluate the sound absorption properties, where longer travel times were associated with enhanced sound absorption. The research demonstrated that increased rubber content improved the concrete's ability to isolate sound. Grdić et al. [2014] performed experiments that demonstrated a decrease in wave velocity of approximately 14% for concrete with 20% rubber aggregate and approximately 21% for concrete with 30% rubber aggregate. Khaloo et al. [2008] found the same findings. According to Guo et al, [2017], the rubber's unique bulky methyl side chains may attenuate acoustic waves and increase sound absorption in the mixture with rubber material as aggregate. Yousefzadeh et al. [2008] indicated numerous valuable techniques for determining sound loss in various materials. Compared to other methods, their results show that using an impedance tube for the transfer process is a more accurate way to estimate the loss of sound transmission.

Numerous investigators have explored the sound transmission loss rate by assessing rooms containing concrete with highly porous materials [Asdrubali et al., 2008; Sukontasukkul, 2009; Uthaichotirat et al., 2020]. In this approach, within a rectangular chamber housing a smaller dimension of the specimen, an acoustic source and a microphone are positioned inside the chamber. In contrast, a microphone is positioned outside the chamber. Following the noise emission from the sound source, the microphone positioned inside and outside the room measures the degree of sound loss and sound absorption. The findings indicate that augmenting the presence of porous materials in the concrete can lead to a potential decrease in sound transmission [Sariisik & Sariisik, 2012].

Thermal insulation

Overall, adding plastic granules as aggregate to concrete improved thermal conductivity, mainly because the thermal conductivity of plastic is poor by nature [Iucolano et al., 2013]. When waste plastic fragments were added to concrete, Yesilata et al. [2009] found that thermal conductivity significantly decreased, improving the material's capacity for thermal insulation. This effect was strongly correlated with the shapes of the incorporated plastic aggregate fragments. The enhancement in insulation within the concrete was measured at 10.27% for square fragments, 17.11% for strip-shaped fragments, and 17.16% for irregularly shaped fragments. It became apparent that strip-shaped plastic fragments displayed superior insulation properties to square-shaped pieces. The irregular pieces exhibited the best efficiency for insulation. The explanation is due to the closer proximity and formation of a more effective heat barrier caused by the enhanced adhesion in the irregular structure configuration between plastic and concrete. Considering that plastic possesses lower thermal conductivity than regular sand, Iucolano et al. [2013] emphasised that mixes containing plastic particles exhibited a thermal conductivity roughly five times lower than conventional sand-based concrete. Wang & Meyer [2012] observed a similar pattern whereby an increase in the quantity of plastic led to a decrease in heat conductivity, which was impacted by the hydrophobic properties of plastic, leading to the creation of voids in the mixes.

Rubber exhibits a thermal conductivity value as low as 0.26 W/mK, which is comparable to the use of plastic aggregates in that it significantly reduces thermal conductivity [Eiras et al., 2014]. Because pores have a substantially lower thermal conductivity than the rest of either mortar or concrete, it can be assumed that the adjustment in porosity caused by the addition of rubber particles caused the decrease in thermal conductivity. Greater amounts of rubber material particles resulted in a significant reduction in the thermal conductivity of concrete, according to Guo et al. [2017]. Specifically, the thermal conductivity exhibited percentage reductions about 16, 26, 33, and 41 when the rubber content was set at (respectively) 15%, 25%, 35%, and 50%. These results were consistent with findings from other researchers who also observed a decrease in concrete thermal conductivity upon including rubber aggregates [Corinaldesi et al., 2011; Fadiel et al., 2014; Senthil et al., 2015]. The key factor contributing to this decrease was the greater porosity that emerged because of higher levels of rubber aggregate. Even without using air-entraining chemicals, the study by Benazzouk et al. [2007] demonstrated that the air content increased from two per cent to seventeen per cent when the rubber content went from zero to fifty per cent. Furthermore, findings by Fadiel et al. [2014] illustrated those blends incorporating rubber particles of larger dimensions (with a range size from zero to 0.06cm) displayed decreased thermal conductivity compared to mixtures with smaller-sized particles (with a range size from 0.084–0.2 cm) across all levels of substitution. This phenomenon was attributed to the ability of larger-sized rubber particles to entrap a greater volume of air within the concrete.

Case studies worldwide

In 2011, a project in Michigan, USA, introduced an inventive method for constructing bike paths using recycled rubber. This innovative approach involves the integration of shredded plastic waste into the asphalt mixture for road development to enhance road longevity and sustainability while addressing plastic waste concerns. The findings underscore the potential advantages of incorporating recycled plastic, such as improved road quality and a reduced environmental footprint. Furthermore, the study discusses the challenges and considerations of this approach, encompassing aspects like material sourcing, durability assessments, and long-term performance evaluations. The project uses recycled plastic to establish a more resilient and environmentally friendly road infrastructure in Michigan (Roads Using Recycled Plastic Built in Michigan). In a different geographical region, specifically in India, an inventive project led by Rhino Machines, an Indian company, involved the creation of a novel brick variety composed of a mixture of recycled plastic and sand (India-Based Rhino Machines Introduces Brick Made from Recycled Plastic and Sand). This innovative method seeks to tackle two prominent problems: the disposal of plastic waste and the need for eco-friendly construction materials. Rhino Machines has developed an exclusive production process for these bricks, which includes melting plastic waste, often in the form of disposable plastics, and blending it with sand to produce a compound. Subsequently, this mixture undergoes compression and controlled heating to shape it into sturdy bricks. This manufacturing process repurposes plastic waste that might otherwise be discarded in landfills or oceans and lessens the environmental consequences of conventional brick manufacturing techniques. The resulting bricks possess several noteworthy attributes:

- sustainability – by incorporating recycled plastic, these bricks play a role in mitigating the ecological consequences of plastic waste while providing a substitute for conventional clay or concrete bricks;
- durability – due to the amalgamation of plastic and sand, these bricks are renowned for their robustness and resilience. This durability can translate into structures and buildings with extended lifespans;
- lightweight – these bricks weigh less than their traditional counterparts, potentially

streamlining transportation and construction procedures;
- insulation – the combination of plastic and sand in these bricks inherently provides insulation qualities, which could enhance energy efficiency in building structures;
- cost-effectiveness – the manufacturing procedure is intended to be economically efficient, presenting an economically feasible option for construction materials;
- versatility – these bricks, made from recycled plastic and sand, have the potential to serve a wide range of construction purposes, spanning from residential structures to infrastructure projects;
- reduced carbon footprint – the production method for these bricks is likely to result in a reduced carbon footprint compared to traditional brick manufacturing, owing to decreased energy and resource demands.

Additionally, this study emphasises the favourable influence of this advancement on India's construction sector and its capacity to serve as a source of inspiration for comparable undertakings on a global scale. It underscores the significance of inventive approaches in confronting urgent environmental and construction-related dilemmas. Furthermore, it underscores the role of these solutions in advancing the circular economy by recycling and reutilising materials that would otherwise be wasted. Another endeavour focuses on using discarded plastics in road construction within the United Kingdom. This project probably outlines a research study, offers guidelines, or presents policies for integrating waste plastic materials into road infrastructure. This inventive strategy entails the fusion of waste plastics with asphalt to enhance road quality and sustainability. It likely delves into the advantages of incorporating waste plastics into road construction, including improved road longevity, reduced maintenance requirements, and a diminished volume of plastic waste in landfills. The work probably examines technical aspects of the process, such as the suitable plastic types, mixing ratios, and their effects on road performance. Additionally, it addresses the challenges, regulatory aspects, and potential environmental considerations associated with this methodology. Overall, it likely furnishes insights into how discarded plastics can be repurposed to create more resilient and environmentally friendly road networks.

CONCLUSIONS

Overall, adding rubber and plastic particles has a similar impact on decreasing the workability of both concrete and mortar. Furthermore, more significant percentages of these aggregates typically cause workability to decline significantly. The configuration and size of plastic aggregates influence the workability of the concrete. The information suggests that rubber aggregates may improve workability compared to plastic aggregates when both are used at the same replacement levels. This advantage mainly stems from the ability to efficiently pre-treat and appropriately grade rubber aggregates. Considering that the specified limits for the specific gravity of aggregates for both rubber and plastic are (respectively) 900–1340 kg/m^3 and 510–1200 kg/m^3, the density values of concrete or mortar produced using these aggregates are close to one another. The amount of replacement, either rubber or plastic aggregate, typically exhibits a significantly decreased density compared to aggregates made from nature, like river sand (with a specific weight of 2610 kg/m^3), significantly impacting the density of either concrete or mortar. Because of this, the density of the concrete decreases linearly as the quantity of rubber, plastic, or both particles increases. Typically, using such aggregates results in a 30% reduction in mortar or concrete density, regarded as the most significant decline possible. Concerning compressive strength, adding the particles of rubber or plastic as aggregates to a mixture of cement and concrete decreased their compressive strength. This decline in strength can be ascribed to various factors, including the limited adhesion between the smooth-surfaced aggregate and the cement matrix, the inherently lower strength of the aggregates, and the presence of voids within the mixtures. However, the reduction in compressive strength can be partially reversed by reducing the particle sizes of plastic and rubber when added as aggregates.

In this context, the potential of rubber aggregate appears more favourable, particularly when subjected to chemical pre-treatment, as it can enhance surface bonding and, as a result, elevate compressive strength. Nevertheless, it is advisable to restrict the inclusion of these aggregates in mortar or concrete to a maximum replacement level of 20% to prevent excessive reductions in strength. Conversely, under specific circumstances, there may be beneficial impacts on the tensile strength of mortar or concrete when employing these aggregates, especially when they are smaller and used at lower replacement levels. In addition to their role as fillers, the flexibility of these aggregates contributes to reduced susceptibility to brittle failure under tensile loads, occasionally leading to enhanced tensile strengths.

The notable benefit of integrating plastic and rubber aggregates becomes apparent in their favourable influence on the environmental attributes of mortar or concrete. These aggregates effectively lower thermal conductivity and significantly improve sound absorption capabilities by introducing gaps and enhancing porosity within the mixture. Using recycled plastic and rubber pieces in concrete or mortar made from cement presents a promising solution for managing non-biodegradable waste materials. Using these aggregates, concrete gains distinctive qualities involving decreased weight, greater flexibility, and improved functional qualities like minimal heat and acoustic conductivities. Conversely, it is essential to consider that adding these kinds of recycled materials as aggregates may reduce the workability and strength of the resulting concrete and mortar mixtures. On the other hand, applying chemical pre-treatment to rubber aggregate can help mitigate the loss of strength of concrete by strengthening the bond between the rubber pieces (as aggregate) and the cement (as paste). Investigating the use of substances that are not biodegradable, like plastic and rubber waste in concrete and mixing with cement as mortar, enables us to address environmental issues associated with the disposal of these substances and develop new solutions that address the shortage of natural aggregates.

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