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PLASTICS AS AGGREGATE PARTIAL REPLACEMENT IN CONCRETE: WASTE MANAGEMENT VS. PERFORMANCE

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Abstract: Using plastic waste as aggregate in concrete contributes to reduced plastic pollution, conservation of natural resources, and enhanced sustainability of construction materials. Using plastic waste as aggregate in concrete helps minimize plastic pollution, natural resource depletion, landfill use, and environmental contamination, while also offering benefits such as improved insulation and reduced resource consumption. The potential use of waste plastic improves the efficiency of construction materials. In that sense, the utilization of plastic in building concrete decreases the dead load, which will help in reducing the costs associated. Also, the utilization of crushed waste plastic material as conventional and other materials in the building construction can helps in reducing the cost of concrete manufacturing. Using plastic wastes in concrete provides strong ecological benefits by reducing plastic pollution, while also offering promising improvements in concrete performance and sustainability. These advantages support the growing research and practical application of plastic–modified concretes in construction. Strong arguments for using plastic wastes in concrete include several environmental, structural, and economic benefits. But, first of all, incorporating plastic waste into concrete offers a practical method to reuse large amounts of problematic plastic waste.

Keywords: cement concrete, plastic waste as aggregate, waste management vs. performance, optimal balance

INTRODUCTION

One of the most common building materials utilized worldwide is concrete. Along with cement and water, aggregate is one of the main basic materials of concrete, accounting for between 55% and 80% of its volume. Coarse aggregates (particles larger than 4.75 mm) or fine aggregates (particles smaller than 4.75 mm) are the two types of aggregates that are utilized. The aggregates needed for concrete come from either natural sources or crushed big rocks.

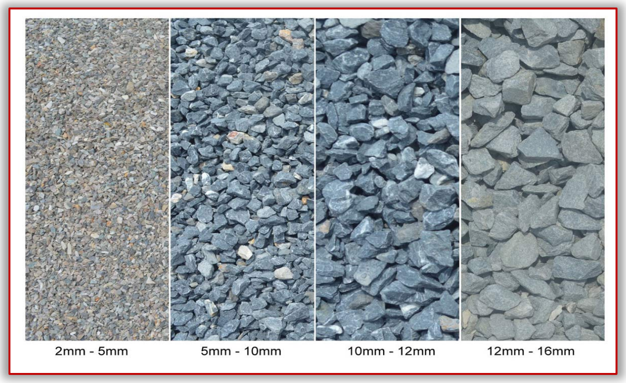
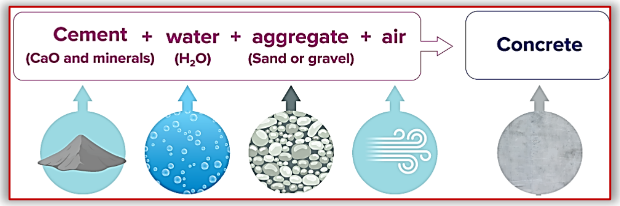


Figure 1. Aggregates for concrete

In cement concrete, fine aggregates are used to fill in the spaces between the coarse aggregate particles, while coarse aggregates are bonded with cement paste during the hydration process. The worldwide building sector accelerates the depletion of aggregate reserves, increasing the demand for natural aggregate consumption annually.



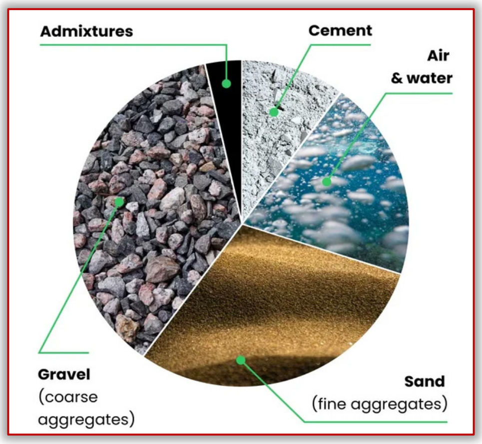


Figure 2. Typical concrete ingredients

The extensive use of natural aggregates will devastate the environment. Therefore, in order to find substitutes for natural aggregates, it is essential to look into the potential of using waste materials and industrial by–products in the manufacturing of concrete. This will lead to sustainable concrete design and a greener environment.

In the same time, plastic wastes have a global impact on the environment due to pollution. This urges researchers to exploit plastic waste to reduce its spread. Specifically, researchers in civil engineering can focus on using plastic waste in concrete manufacturing. Plastic waste is non–biodegradable, reusing such structures provides us with a possible answer to improve the enhancement of the concrete. In that sense, recycled plastic squanders, such as low and high–density polyethene (LDPE and HDPE, respectively), polyethene terephthalate (PET) and polypropylene (PP), are being utilized as an additional constituent to improve the properties of solid concrete. Finding ways to lessen the health hazards and disposal problems related to these wastes is the main goal of governments and environmental protection groups.

Figure 3. Plastic waste (collected)

The two main ways to use plastic waste in concrete are:

(1) using recycled plastic waste as fibers to reinforce concrete, and

(2) utilizing recycled plastic waste as aggregate concrete substitutive.

— Using plastic fibers as concrete reinforcement may lead to both higher sustainability and structural performance and durability. In that sense, the optimization of the concrete mixture's composition and the dispersed reinforcement dosage is a very important role in the perspective of structural reliability and economics.

Since waste plastic presents lower mechanical performance than high density polymers, which are usually used to produce microfibers, they could be used for this latter application. Plastic fibers are mixed into concrete in small percentages (typically up to 2%) and act like micro–reinforcement throughout the mix. Their primary function is to enhance the tensile strength, ductility, crack resistance, and impact resistance of concrete. The fibers arrest microcracking and help bridge cracks as they form.

Figure 4. Plastic as microfibers (used for reinforcement)

— Plastic is also utilized as a coarse or fine aggregate in many cases, which is very advantageous from an environmental perspective. This approach diminishes the self–weight of concrete in structures and can be used for non–structural elements that do not require high compressive strength due to the properties of such plastic, which are primarily different from other aggregates.

Hence, sustainability in the concrete industry may be enhanced by using such plastic waste along with concrete to meet the requirements of sustainable building and improving thermal properties, reducing the use of natural resources, avoiding pollution, ingestion of waste, and saving energy. Plastic fibers or small plastic fragments are used as a substitute for part of the natural fine or coarse aggregate in concrete (replacement rates typically range from 5% to 20%, sometimes higher). Main aim is waste management—recycling plastic waste by embedding it in concrete, and possibly reducing material costs. This approach is distinct from micro–reinforcement and is expected to directly influence the concrete matrix structure.

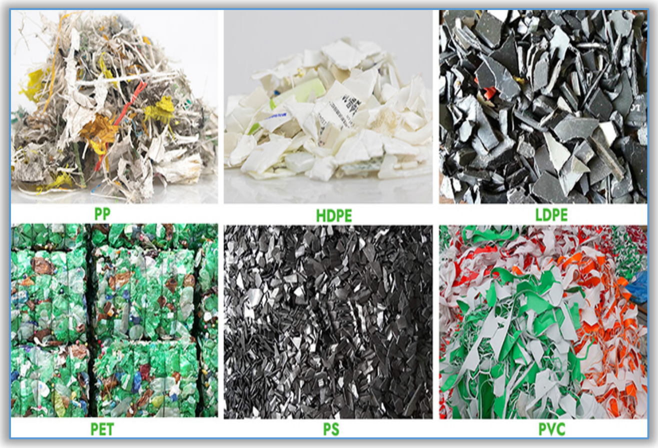


Figure 5. Plastic as aggregate (used for coarse or fine aggregate replacement)

Plastic fibers as reinforcement primarily increase tensile and flexural properties, crack resistance, and ductility by bridging microcracks. As replacement aggregate, plastic fibers reduce density and recycling utility is high, but mechanical performance (especially compressive strength) typically declines at higher replacement ratios—best for non–structural purposes. Structural applications should be cautious or avoid high percentages of aggregate replacement with plastic due to the loss in strength and stiffness.

These differences guide the suitable use of plastic waste in concrete according to desired structural requirements and sustainability goals.

USE OF PLASTIC WASTE AS AGGREGATE: METHODS

Waste plastics have been used in different ways as fibers and aggregate (including fillers) for preparing concrete mixing. However, the application of plastic aggregates is more economical and simpler, as it generally involves fewer processing steps compared with that of fibers. The rising concern of the environmental damage caused by the utilization of natural aggregate has led to an interest in more conservative and cost–effective concrete materials. It has many benefits, including simplicity, cost, and energy savings, and clean recycling, because it is not harming the environment. On the other hand, the potential benefits of using plastic waste as aggregate in concrete mixing are providing new, cost–effective building materials and ensuring the environmental sustainability of the new products.

However, since plastic wastes have a lower density than the natural aggregates (fine and coarse), the overall weight of concrete is diminishing, creating lighter concrete and lower structural performance. Hence, the priority of the construction industry is sustainability and the analysis on how to design new non–structural building components with an efficient use of plastic waste. To sum up, the use of plastic in concrete is an optimal solution for achieving environmental sustainability. Moreover, plastic wastes are ideal, economical, and safe materials to be utilized within the manufacturing of concrete.

Many studies have explored the idea of replacing natural aggregate (i.e., fine or coarse) with plastic aggregates. Most work has reported reductions in the densities of mixtures incorporating plastic aggregates, with this effect primarily attributed to replacement of higher–density sand or coarse aggregate particles with lower–density plastic materials. The simplest way to utilize shredded plastics as aggregate in the mixture is to mix the concrete simply adding plastic inside.

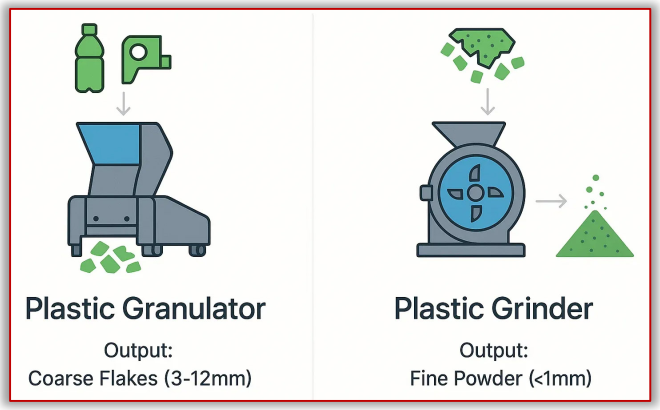


Figure 6. Shredding the plastic

Figure 7. Coarse plastic flakes

Many studies have investigated the idea of incorporating plastic waste in cementitious composites. The majority investigated polyethylene terephthalate (PET), with limited research performed on other types of plastics such as high–density polyethylene (HDPE), polyvinyl chloride (PVC), low–density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). Most previous research treated plastic as an inert material.

USE OF PLASTIC WASTE AS AGGREGATE: KEY ADVANTAGES

Using plastics as a substitute for natural aggregates in concrete is primarily motivated by environmental concerns and waste management, rather than by a desire to enhance concrete performance. The use of plastic waste in cement concrete presents a promising avenue for sustainable construction, offering environmental, economic, and technical benefits while addressing the global plastic waste crisis. Key advantages of replacing natural aggregates (gravel) with plastic waste in concrete include:

— Reduction in concrete density: Plastic aggregates are significantly lighter than natural gravel, leading to a decrease in concrete density by up to 9% or more depending on replacement level. This results in lightweight concrete beneficial for reducing structural loads and improving thermal insulation.

- Environmental benefits: Using plastic waste reduces landfill accumulation and environmental pollution, while conserving natural aggregates and minimizing quarrying impacts. It supports sustainable waste management and circular economy goals.
- Improved toughness and impact resistance: Concrete with plastic aggregates shows increased toughness and better energy absorption, making it more resistant to dynamic and impact loads compared to conventional concrete.
- Enhanced workability: Incorporation of plastic aggregates often improves concrete workability due to smoother particle surfaces, facilitating easier placement and compaction.
- Good durability characteristics: Plastic aggregate concrete can exhibit lower water absorption and better resistance to chemical attacks (acid, alkaline), although permeability may increase slightly due to weak bonding at the plastic–cement interface.
- Acceptable mechanical performance at moderate replacement levels: Partial replacement of natural aggregates with plastic waste (commonly up to 10–15%) can maintain sufficient compressive strength for structural or lightweight concrete applications. For example, 15% replacement showed no significant strength loss in concrete.
- Thermal benefits: Reduced thermal conductivity of plastic aggregate concrete improves insulation performance, contributing to energy–efficient buildings.

Therefore, replacing natural gravel with plastic waste in concrete offers environmental sustainability, lightweight concrete production, improved toughness, and acceptable strength and durability when used at controlled replacement levels, making it a promising approach for eco–friendly construction.

Plastics can be used as a partial replacement for natural aggregates in concrete to address waste management issues and reduce environmental pollution. However, this comes with a trade–off between improved sustainability and changes in concrete performance.

USE OF PLASTIC WASTE AS AGGREGATE: WASTE MANAGEMENT

Using waste plastics as aggregate replacements helps divert plastic waste from landfills and reduces environmental pollution. Plastics such as PET and polypropylene (PP) can be recycled into aggregates, offering a sustainable alternative to conventional sand and gravel in concrete. This reduces the demand for natural aggregates and the environmental impact of their extraction.

The main purpose is obviously the waste management, defined by:

- Environmental impact: Incorporating waste plastics into concrete helps address the global issue of plastic pollution by diverting non–biodegradable materials from landfills and reducing environmental hazards
- Resource conservation: Using plastics reduces the extraction and depletion of natural aggregates, supporting more sustainable construction practices

Therefore, the environmental benefit of using plastics as a substitute for natural aggregates in concrete can be characterized by significant waste reduction and resource savings. Replacing natural aggregate in concrete with plastic waste generally has mixed effects on the long–term environmental impact. Additionally, diverting plastic waste from landfills or incineration mitigates pollution and conserves non–renewable natural aggregate resources. Using plastic waste in concrete promotes circular economy principles by turning plastic pollutants into construction materials, thus reducing environmental pollution and landfill volume over the long term.

Using plastic waste in concrete supports sustainable waste management by:

- Diverting plastic waste from landfills and oceans: Incorporating plastic waste into concrete prevents large volumes of plastic from polluting terrestrial and marine ecosystems, addressing a critical environmental challenge.
- Reducing consumption of natural aggregates: Plastic aggregates can replace up to about 10% of natural sand or gravel in concrete, saving millions of tons of natural resources annually and reducing environmental degradation from quarrying.
- Lowering carbon footprint and energy use: Recycling plastic waste into concrete aggregates consumes less energy compared to producing natural aggregates, thereby reducing greenhouse gas emissions

associated with mining, processing, and transportation.

- Promoting circular economy: Using plastic waste in construction materials creates value from otherwise non–recyclable plastics, closing the loop in material use and fostering sustainable industrial practices.
- Enhancing sustainability of construction industry: Plastic–modified concrete offers environmental benefits without significantly compromising mechanical properties when used at appropriate replacement levels (typically up to 10–15%), supporting greener building practices.
- Therefore, integrating plastic waste into concrete transforms a major pollution problem into a resource, reduces reliance on finite natural materials, lowers environmental impacts, and advances sustainable waste management and construction

Replacing natural aggregates with plastic waste in concrete is considered a circular economy strategy because it aligns with the core principles of the circular economy, which focus on reducing waste, reusing materials, and recycling resources to minimize environmental impact and resource depletion. Specifically:

- Waste as a resource: Instead of following the traditional linear model of "take–make–waste," using plastic waste in concrete keeps plastic materials in circulation for longer, transforming what would be environmental pollutants into valuable construction inputs.
- Reduction of natural resource extraction: By substituting plastic waste for natural aggregates like gravel and sand, the demand for finite natural resources is lowered, helping to preserve ecosystems and reduce environmental degradation caused by quarrying and mining.
- Minimization of landfill and pollution: Incorporating plastic waste into concrete diverts large volumes of plastic from landfills, oceans, and natural environments, thereby reducing pollution and greenhouse gas emissions associated with plastic disposal.
- Resource efficiency and economic resilience: This approach promotes efficient use of materials and energy, reduces raw material costs, and fosters innovation in sustainable construction, contributing to economic benefits and supply chain resilience.
- Regenerative design: The circular economy aims to design out waste and pollution, and using plastic waste in concrete supports this by recovering and regenerating materials at the end of their life cycle, thus closing the material loop.

Replacing natural aggregates with plastic waste in concrete embodies circular economy principles by turning waste into a resource, conserving natural materials, reducing environmental harm, and promoting sustainable construction practices.

USE OF PLASTIC WASTE AS AGGREGATE: PERFORMANCE

From point of view of the obtained mechanical properties of concrete, using plastics as a substitute for natural aggregates, the effects on concrete performance can be synthetized as follow:

- Compressive strength: Most studies show that replacing natural aggregates with plastics generally leads to a reduction in compressive strength, especially at higher replacement levels. Some research indicates that up to 10–15% replacement can be achieved without significant loss, but beyond this, strength typically drops notably. Generally, the compressive strength decreases with higher plastic content
- Toughness and flexibility: Concrete with plastic aggregates may exhibit increased toughness and impact resistance, making it less brittle compared to conventional concrete
- Workability: The workability of concrete often improves with the addition of plastics, due to the smoother surface and lower density of plastic particles. Therefore, the workability often increases

From point of view of the durability and other properties, we can obtain:

- Density: Plastic aggregates lower the density of concrete, resulting in lightweight concrete suitable for non–structural or specific lightweight applications
- Thermal properties: Thermal conductivity is reduced, which can be beneficial for insulation purposes
- Water absorption and durability: Durability characteristics such as water absorption and resistance to acid/alkali exposure can be maintained at low replacement levels, but may decline as plastic content increases. Therefore the durability is acceptable at low levels, but declines at high levels

Using plastics as a substitute for natural aggregates in concrete have the following limitations:

- Structural use: High levels of plastic aggregate replacement are not suitable for structural concrete due to compromised mechanical strength. Due to reduced mechanical properties, concrete with plastic aggregate is often recommended for non–structural applications such as pavements, facades, and insulation, which still contribute to environmental benefits but limit use in load–bearing structures.
- Performance trade–offs: While some properties (like toughness and workability) may improve, the overall mechanical performance (especially compressive and tensile strength) is generally reduced compared to conventional concrete.

The performance impacts on concrete can be summarized as:

- The compressive strength of concrete generally decreases as the percentage of plastic aggregate replacement increases, due to weaker bonding and the lower strength of plastic compared to natural aggregates.
- Workability of the concrete mix is sometimes improved with low plastic replacement levels since plastics are less water absorbent, but this can decline with higher plastic content or coarser irregular plastic shapes.
- The density of the concrete is also reduced by using plastic aggregates, which can benefit lightweight concrete applications but may affect structural capacity.

Potential durability and material performance considerations remain concerns in using plastics as a substitute for natural aggregates in concrete. Plastic aggregates are generally less dense and have weaker bonding to cement matrix than mineral aggregates, which can increase porosity and fragility in the concrete. This can lead to reduced compressive and flexural strength and potentially reduce the lifespan or increase maintenance requirements of concrete structures if not properly optimized. Weak bonding may cause micro–cracking and increased permeability, which affect durability under environmental stressors (e.g., water ingress, freeze–thaw cycles). Also, preparing plastic waste for use as aggregate (e.g., shredding, sieving) requires energy, which may somewhat offset environmental benefits from material substitution, although this is usually less than the impact of quarrying natural aggregate.

OPTIMAL BALANCE BETWEEN MECHANICAL PERFORMANCE AND ENVIRONMENTAL BENEFITS

The key factors ensuring an optimal balance between mechanical performance and environmental benefits in materials like concrete with waste aggregate replacements (e.g., plastic) include:

- Proper material selection and proportioning: Choosing the right type and amount of waste material (e.g., plastic type and particle size) to partially replace natural aggregates ensures mechanical strength is maintained while maximizing waste utilization.
- Particle size and shape control: Smaller and well–graded waste particles improve bonding with cement paste, reducing voids and maintaining strength, while larger particles tend to weaken the matrix.
- Mix design optimization: Adjusting water–cement ratio, use of supplementary cementitious materials, and admixtures can compensate for weaker interfaces caused by waste aggregates, improving durability and strength.
- Processing and treatment of waste materials: Surface treatments or grinding of plastic waste can enhance adhesion with cement, improving mechanical properties without sacrificing environmental gains.
- Replacement level management: Limiting waste aggregate replacement to an optimal percentage (often 10–15%) balances strength retention with environmental benefits like reduced natural resource extraction and landfill diversion.
- Durability considerations: Ensuring the modified concrete meets durability requirements (e.g., resistance to chemical attack, freeze–thaw cycles) is essential for long–term sustainability and performance.
- Lifecycle and energy analysis: Evaluating the full environmental impact, including energy savings from reduced quarrying and waste disposal, helps identify the best trade–offs between eco–benefits and mechanical performance.
- Design approach: Integrating mechanical performance goals with sustainability objectives during design and production phases leads to cost–effective, energy–efficient, and environmentally friendly materials.

These factors collectively enable the development of sustainable concrete mixes that maintain structural integrity while significantly reducing environmental footprints through waste reuse and resource conservation.

Balancing the waste management and performance of the concrete, we can conclude the followings:

- Partial replacement (typically less than 20%) of fine or coarse aggregates with plastic can yield workable concrete with acceptable strength for certain non–structural applications while providing meaningful waste reduction.
- Additives and treatments can improve the bonding and mechanical performance of plastic aggregate concrete, potentially offsetting some strength losses.
- Full replacement of natural aggregates with plastic is usually not feasible due to severe strength reduction, but blends and optimized replacement levels allow sustainability goals to be met with manageable performance trade–offs.

Proper balancing of these factors is essential to maximize sustainability over the service life of concrete structures. The optimal replacement percentages for plastics as aggregate substitution in concrete lie mostly within the 5–20% range, where waste reduction benefits are significant, and the compressive strength and workability remain largely acceptable for many construction applications. Therefore, the best trade–offs between strength loss and waste reduction when using plastics as aggregate replacement in concrete generally occur at low replacement percentages, usually between 5% and 20%:

- Around 5% replacement of fine aggregate with plastics often shows little to no strength loss. This level also improves the cement–plastic bond, maintaining structural properties.
- For polyethylene terephthalate (PET), replacement up to about 10–15% can produce acceptable compressive strength without severe degradation, while higher percentages (above 20–25%) tend to significantly reduce strength and workability, limiting applications to non–structural uses.
- Polypropylene (PP) plastic aggregates can perform better than PET, with optimum replacement around 5–10% showing better compressive strength and density characteristics compared to higher levels where strength declines.
- Studies suggest replacing up to 20% of fine aggregate with optimized plastic waste can effectively balance sustainability goals with structural performance, allowing the production of structural concrete with preserved workability and mechanical properties.
- At 5–10% replacement levels, the strength trade–offs of PET, PP, and PP fibres in concrete show distinct behaviours. The combination of plastic fibres (particularly PP) with PET aggregate replacement is often recommended to optimize both strength and ductility performance while achieving waste reduction.

So, the plastic waste used as aggregate replacement in concrete offers a promising approach for plastic waste management and environmental sustainability. However, careful consideration of replacement levels and concrete mix design is necessary to maintain adequate performance, balancing ecological benefits with structural requirements.

CONCLUSIONS

The primary benefit of using plastics as aggregates in concrete is environmental, not performance–related. While certain properties like workability and toughness can improve, overall mechanical strength tends to decrease, limiting the use of plastic aggregate concrete to non–structural or specialized applications. The practice is best viewed as a sustainable waste management solution rather than a means to enhance concrete performance. Replacing conventional aggregate in concrete with plastic waste offers significant ecological and economic advantages, principally via plastic waste mitigation, resource conservation, and cost savings. However, trade–offs in mechanical properties mean that optimization and careful application selection are essential to maximize both sustainability and performance.

Replacing conventional aggregates with plastic waste in concrete can significantly reduce long–term environmental impact by lowering carbon emissions, conserving natural resources, and reducing pollution. However, these benefits depend heavily on managing possible reductions in concrete durability and performance through mix design optimization and appropriate application choices.

Using plastics as aggregates in concrete is fundamentally an environmental strategy rather than a performance–driven one. While plastic aggregates generally reduce some mechanical properties of concrete, their primary value lies in significant environmental benefits. Incorporating plastic waste as a partial aggregate replacement helps divert large volumes of plastic waste from landfills and ecosystems, mitigating pollution and waste management challenges. Also, the construction industry consumes vast amounts of natural aggregates like sand and gravel, whose extraction results in resource depletion, habitat destruction, and CO_2 emissions. Replacing a portion of these with recycled plastic aggregates preserves natural resources and reduces environmental degradation linked to quarrying and mining.

Performance–wise, plastic aggregates typically reduce compressive, flexural, and tensile strengths compared to natural aggregates due to poor bonding and different material properties. This limits their use, especially in structural concrete, indicating their role is not to enhance technical performance but to provide an eco–friendly solution.

In essence, plastics as aggregates are a sustainability and waste management innovation. The trade–off is that concrete performance may decline somewhat, but this is acceptable especially in non–structural applications where environmental impact reduction takes precedence over maximal strength. This underscores plastics' use in concrete primarily as an environmental solution rather than a performance upgrade.

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