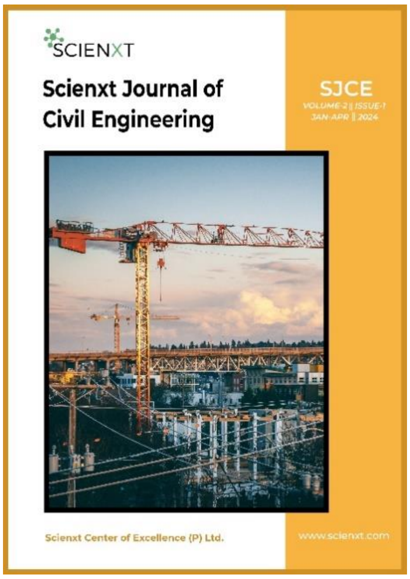

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Utilization of plastic waste in civil engineering construction materials: A comprehensive review

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Abstract:

The accumulation of plastic waste has emerged as a critical environmental concern, with significant impacts on ecosystems and human health. Addressing this challenge requires multifaceted approaches, including the development of sustainable solutions for plastic waste management. One promising avenue is the utilization of plastic waste in civil engineering construction, which not only provides an alternative outlet for waste streams but also has the potential to enhance material properties and promote sustainability in the construction industry. This comprehensive review critically examines recent research efforts focused on incorporating various types of plastic waste into concrete, asphalt, soil stabilization, and other construction applications. The techniques, performance characteristics, economic considerations, and environmental impacts associated with utilizing plastic waste in construction materials are evaluated. Additionally, the review discusses emerging technologies, challenges, and future research directions in this field, providing a holistic perspective on the potential of plastic waste as a valuable resource for the construction industry.

1. Introduction:

Plastics have revolutionized modern society due to their versatility, durability, and cost-effectiveness. However, the widespread use of plastics has led to a significant accumulation of plastic waste, posing severe environmental challenges [1]. According to a report by Geyer et al. [2], only 9% of the global plastic waste generated in 2015 was recycled, while 79% ended up in landfills or the natural environment, contributing to pollution and ecological degradation. The construction industry, known for its substantial material consumption, has emerged as a promising domain for the utilization of plastic waste. By incorporating plastic waste into construction materials, such as concrete, asphalt, and soil stabilization applications, the industry can contribute to mitigating plastic pollution while potentially improving material properties and reducing production costs [3].

This review aims to provide a comprehensive overview of the current state of research on the utilization of plastic waste in civil engineering construction. It critically examines the various techniques, material performance characteristics, economic considerations, and environmental impacts associated with incorporating plastic waste into concrete, asphalt, soil stabilization, and other construction materials. Additionally, the review discusses emerging technologies, challenges, and future research directions in this field, offering insights into the potential of plastic waste as a valuable resource for the construction industry.

2. Plastic waste in concrete:

Concrete is one of the most widely used construction materials globally, with an annual production exceeding 25 billion tons [4]. The incorporation of plastic waste into concrete has been extensively studied as a means of improving concrete properties, reducing production costs, and diverting plastic waste from landfills and the environment.

2.1 Plastic aggregate replacements:

One approach to recycling plastic waste in concrete involves partially replacing conventional aggregates, such as gravel or crushed stone, with plastic waste particles. Various types of plastic waste, including polyethylene terephthalate (PET) bottles, high-density polyethylene (HDPE) containers, and mixed plastic waste, have been investigated as partial aggregate replacements in concrete mixtures.

Siddique et al. [5] studied the effects of incorporating PET bottle waste as a partial replacement for fine aggregates in concrete. They found that incorporating up to 50% PET particles by weight improved the compressive, splitting tensile, and flexural strengths of the concrete compared to the control mix without PET. However, higher PET contents led to reduced strengths due to the weak interfacial bond between the PET particles and the cement matrix.

Choi et al. [6] investigated the use of HDPE plastic waste as a partial replacement for coarse aggregates in concrete. They reported that incorporating up to 50% HDPE particles by volume resulted in a slight decrease in compressive strength compared to the control concrete, but significantly improved the flexural strength and toughness of the concrete. The improved toughness was attributed to the ability of the HDPE particles to bridge cracks and resist pullout from the cement matrix.

In addition to single-polymer plastic waste, researchers have also explored the use of mixed plastic waste as aggregate replacements in concrete. Kou and Poon [7] evaluated the properties of concrete containing up to 100% replacement of natural coarse aggregates with mixed plastic waste particles derived from post-consumer plastic containers. They found that incorporating up to 20% plastic waste particles did not significantly affect the compressive strength of the concrete, but higher replacement levels led to reduced strengths due to the poor adhesion between the plastic particles and the cement paste.

2.2 Plastic fiber reinforcements:

Another approach to utilizing plastic waste in concrete involves incorporating plastic fibers as reinforcements. Plastic fibers can improve the tensile strength, ductility, and crack resistance of concrete by bridging and arresting crack propagation.

Alhozaimy et al. [8] investigated the use of recycled polyethylene (RPE) fibers derived from plastic bags and other polyethylene waste as reinforcements in concrete. They found that incorporating up to 1% RPE fibers by volume significantly improved the flexural strength, toughness, and impact resistance of the concrete compared to the control mix without fibers.

Rahmani et al. [9] studied the effects of incorporating recycled PET fibers from plastic bottles into self-compacting concrete (SCC). They reported that adding PET fibers at dosages of up to 1.5% by volume enhanced the mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, of the SCC compared to the control mix without fibers.

In addition to single-polymer plastic fibers, researchers have also explored the use of hybrid fiber reinforcements combining plastic fibers with other types of fibers, such as steel or natural fibers. Yin et al. [10] investigated the performance of concrete reinforced with hybrid fibers consisting of recycled PET fibers and steel fibers. They found that the hybrid fiber reinforcement improved the flexural strength, toughness, and impact resistance of the concrete compared to concrete reinforced with either PET fibers or steel fibers alone.

2.3 Economic and environmental impacts:

The utilization of plastic waste in concrete can provide economic and environmental benefits. From an economic perspective, incorporating plastic waste as aggregate replacements or fiber reinforcements can reduce the demand for conventional raw materials, such as gravel, crushed stone, and steel reinforcements, potentially leading to cost savings in concrete production [11]. Environmental benefits can arise from diverting plastic waste from landfills and the natural environment, reducing greenhouse gas emissions associated with plastic production and disposal, and promoting a circular economy by repurposing waste materials. Life cycle assessment (LCA) studies have been conducted to evaluate the environmental impacts of concrete incorporating plastic waste.

Ro et al. [12] performed an LCA of concrete containing recycled HDPE as a partial replacement for coarse aggregates. They found that incorporating HDPE plastic waste into concrete resulted in lower energy consumption and greenhouse gas emissions compared to conventional concrete production, primarily due to the reduced demand for natural aggregates and the avoidance of HDPE disposal in landfills or by incineration.

Ferreira et al. [13] conducted an LCA study on concrete containing recycled PET fibers as reinforcements. They reported that the incorporation of PET fibers led to reduced environmental impacts in several categories, including global warming potential, acidification potential, and eutrophication potential, compared to conventional steel fiber-reinforced concrete.

However, it is important to note that the environmental benefits of utilizing plastic waste in concrete may be offset by factors such as increased transportation distances for collecting and processing plastic waste, as well as potential leaching of additives or degradation products from the plastic waste into the environment over time [14].

3. Plastic waste modifications of asphalt binders and mixtures:

Asphalt, also known as bitumen, is a widely used binder in the construction of flexible pavements, such as roads and airport runways. The incorporation of plastic waste into asphalt binders and mixtures has been explored as a means of improving the performance and durability of asphalt pavements while providing an outlet for plastic waste recycling.

3.1 Waste plastic modifiers:

Various types of plastic waste have been investigated as modifiers for asphalt binders and mixtures, including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC).

Polypropylene (PP) and polyethylene (PE) are two of the most commonly used plastic waste modifiers for asphalt. Researchers have found that incorporating PP and PE into asphalt binders can improve the rheological properties, such as viscosity and temperature susceptibility, as well as the rutting resistance and fatigue life of the modified asphalt mixtures [15, 16].

PET from plastic bottles has also been explored as a modifier for asphalt binders. Researchers have reported that incorporating PET into asphalt binders can enhance the binder's viscosity, stiffness, and rutting resistance [17, 18].

In addition to thermoplastic polymers like PE, PP, and PET, researchers have also studied the use of thermoset plastic waste, such as PVC, as asphalt modifiers. PVC has been found to improve the thermal stability, viscosity, and rutting resistance of modified asphalt binders [19, 20].

3.2 Performance of plastic waste-modified asphalt:

The incorporation of plastic waste into asphalt binders and mixtures has been shown to improve various performance characteristics, including resistance to permanent deformation (rutting), fatigue cracking, and moisture damage.

Rutting resistance is a critical performance parameter for asphalt pavements, as rutting can lead to safety hazards and increased maintenance costs. Several studies have reported that the addition of plastic waste, such as PE, PP, and PET, to asphalt binders and mixtures can significantly improve the rutting resistance compared to conventional asphalt mixtures [15, 17, 18].

Fatigue cracking is another major distress mechanism in asphalt pavements, caused by repeated traffic loading and temperature fluctuations. Plastic waste modifiers have been found to enhance the fatigue life of asphalt mixtures by improving the binder's elasticity and flexibility [16, 19].

Moisture damage, or stripping, is a common issue in asphalt pavements, where water infiltration can lead to the debonding of the asphalt binder from the aggregate, compromising the pavement's structural integrity. Researchers have reported that the incorporation of plastic waste modifiers, such as PE and PET, can improve the moisture resistance of asphalt mixtures by enhancing the adhesion between the binder and aggregates [17, 18].

3.3 Life cycle assessments:

In addition to evaluating the performance characteristics of plastic waste-modified asphalt, researchers have also conducted life cycle assessment (LCA) studies to assess the environmental impacts of these materials compared to conventional asphalt mixtures.

Zhao et al. [21] performed an LCA on asphalt mixtures containing recycled plastic fibers derived from PET bottles. They found that the incorporation of PET fibers resulted in lower energy consumption and greenhouse gas emissions compared to conventional asphalt mixtures, primarily due to the reduced demand for virgin asphalt binder and the diversion of PET waste from landfills or incineration.

Fang et al. [22] conducted an LCA study on asphalt mixtures modified with recycled plastic bags (RPBs). They reported that the use of RPBs as modifiers in asphalt mixtures led to lower environmental impacts in several categories, including global warming potential, acidification potential, and human toxicity potential, compared to conventional asphalt mixtures.

However, it is important to consider factors such as transportation distances for collecting and processing plastic waste, as well as potential leaching of additives or degradation products from the plastic waste into the environment, which may offset some of the environmental benefits [14].

4. Soil stabilization with plastic waste:

Soil stabilization is a critical process in civil engineering projects involving earthworks, foundations, and infrastructure development. Plastic waste has been explored as a potential soil stabilizing agent, offering an alternative to conventional stabilization methods using cement, lime, or chemical additives.

4.1 Mechanisms of soil improvement:

The incorporation of plastic waste into soils can improve soil properties through various mechanisms, depending on the type and form of the plastic waste used.

Plastic fibers or strips can act as reinforcements within the soil matrix, improving the soil's tensile strength, shear resistance, and ductility. The plastic fibers or strips can bridge and arrest crack propagation, enhancing the soil's overall resistance to deformation and failure [23, 24].

Plastic granules or shredded plastic waste can act as frictional and drainage-promoting inclusions within the soil matrix. The rough surfaces of the plastic particles can increase the frictional resistance and interlocking between soil grains, improving the soil's shear strength and compaction characteristics [23, 25].

The hydrophobic nature of plastic waste can also contribute to soil stabilization by reducing the soil's water absorption capacity and improving its resistance to moisture-induced deterioration, such as swelling and loss of strength [25, 26].

4.2 Characteristics of plastic-stabilized soils:

Numerous studies have investigated the effects of incorporating various types of plastic waste on the engineering properties of soils, including strength, compaction characteristics, permeability, and durability.

Consoli et al. [24] studied the use of polyethylene terephthalate (PET) fibers obtained from recycled plastic bottles as soil reinforcements. They found that incorporating PET fibers at dosages of up to 0.5% by weight significantly improved the unconfined compressive strength, tensile strength, and ductility of sand-clay mixtures compared to unreinforced samples.

Chebet and Kalumba [23] investigated the effects of plastic fiber reinforcements on the strength and compaction characteristics of expansive clay soils. They reported that the addition of plastic fibers derived from recycled plastic bags improved the maximum dry density and optimum moisture content of the clay soils, as well as their unconfined compressive strength and California Bearing Ratio (CBR) values.

Dutta and Rani [25] studied the use of shredded plastic waste as a soil stabilizing agent for expansive soils. They found that incorporating shredded plastic waste at dosages of up to 0.6% by weight significantly reduced the free swell index, swelling potential, and swelling pressure of the expansive soils, indicating improved resistance to volumetric changes induced by moisture fluctuations.

In addition to strength and swelling characteristics, researchers have also investigated the effects of plastic waste on soil permeability and durability. Rasheed et al. [26] reported that the addition of plastic waste strips to sandy soils improved the soils' resistance to erosion and reduced their permeability, which could be beneficial for applications such as embankment construction and canal lining.

4.3 Field applications:

While the majority of research on plastic waste-stabilized soils has been conducted at the laboratory scale, there have been some field-scale demonstrations and applications of this technology.

In India, researchers from the Indian Institute of Technology Guwahati have applied plastic waste-stabilized soil technology in the construction of rural roads and embankments [27]. They reported that the incorporation of plastic waste strips or fibers into the soil subgrades improved the structural performance and durability of the roads, while also providing a sustainable solution for plastic waste management.

In the United States, researchers from the University of Illinois at Urbana-Champaign have explored the use of plastic waste-stabilized soils for erosion control and slope stabilization applications [28]. They found that the inclusion of plastic waste strips or fibers within soils significantly improved the soils' resistance to surface erosion and shallow slope failures.

While these field demonstrations have shown promising results, further research and pilot projects are necessary to develop standardized design guidelines and construction specifications for the widespread implementation of plastic waste-stabilized soil technology in civil engineering projects.

5. Other recycling applications:

In addition to concrete, asphalt, and soil stabilization, plastic waste has been explored for various other construction applications, including structural insulated panels, plastic lumber, and soil reinforcements.

5.1 Structural insulated panels:

Structural insulated panels (SIPs) are composite building materials consisting of rigid insulating foam cores sandwiched between structural facing materials, such as oriented strand board (OSB) or fiber-cement boards. SIPs have been increasingly used in residential and commercial construction due to their high insulation performance, structural integrity, and ease of installation.

Researchers have explored the use of recycled plastic waste as the insulating foam core material in SIPs. Expanded polystyrene (EPS) foam, which is commonly used in SIPs, can be derived from recycled polystyrene waste, such as food packaging and disposable cups [29].

In addition to EPS, researchers have also investigated the use of other recycled plastic foams, such as polyurethane foam derived from recycled refrigerator insulation, as core materials for SIPs [30]. These recycled plastic foam cores can provide similar insulation performance to conventional SIP cores while diverting plastic waste from landfills and reducing the demand for virgin plastic production.

5.2 Plastic lumber:

Plastic lumber, also known as plastic wood or wood-plastic composites (WPCs), is a building material composed of plastic waste and wood fibers or other fillers. Plastic lumber has gained popularity as an alternative to traditional wood lumber due to its durability, moisture resistance, and low maintenance requirements.

Various types of plastic waste, including polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), have been used in the production of plastic lumber. The plastic waste is typically shredded, melted, and mixed with wood fibers or other fillers before being extruded into lumber-like profiles [31].

Plastic lumber has found applications in outdoor furniture, decking, fencing, and landscaping products, where its resistance to rot, insects, and weathering offers advantages over traditional wood products. Additionally, the use of recycled plastic waste in plastic lumber production here is a continuation of the review paper on plastic waste utilization in civil engineering construction:

Additionally, the use of recycled plastic waste in plastic lumber production helps to divert plastic waste from landfills and reduce the demand for virgin plastic resins [32]. However, concerns have been raised about the potential leaching of additives and degradation products from plastic lumber into the environment during its service life and disposal [33].

5.3 Plastic soil reinforcements:

Plastic waste has also been utilized in soil reinforcement applications, such as geosynthetic reinforcements for retaining walls, embankments, and slope stabilization projects.

Geosynthetic reinforcements, such as geogrids and geotextiles, are commonly used to reinforce and stabilize soil structures by providing tensile strength and confinement to the soil mass. Traditionally, these geosynthetics have been manufactured from virgin polymers like polyester, polypropylene, or high-density polyethylene (HDPE).

Researchers have explored the use of recycled plastic waste, including HDPE, PET, and mixed plastic waste, as raw materials for the production of geosynthetic reinforcements [34, 35]. These recycled plastic reinforcements can offer similar tensile strengths and durability to conventional geosynthetics while providing an outlet for plastic waste recycling.

The use of recycled plastic soil reinforcements can be particularly beneficial in erosion control and slope stabilization applications, where the reinforcements help to improve the soil's resistance to erosion and shallow slope failures [28].

6. Challenges and future outlook:

6.1 Logistics and pretreatment:

One of the major challenges in utilizing plastic waste for construction applications is the logistics and pretreatment required for collecting, sorting, and processing the waste materials. Plastic waste streams are often heterogeneous, containing various types of plastics with different compositions and properties.

Effective sorting and separation techniques are necessary to obtain consistent plastic waste feedstocks for specific construction applications. This can involve manual sorting, density-based separation, or advanced techniques like near-infrared spectroscopy (NIR) and flotation processes [36].

Additionally, plastic waste may require pretreatment steps such as washing, shredding, or pelletizing before it can be effectively incorporated into construction materials. These pretreatment processes can add to the overall cost and energy consumption associated with plastic waste recycling for construction applications [37].

6.2 Long-term performance:

While numerous studies have investigated the short-term and laboratory-scale performance of construction materials incorporating plastic waste, there is a need for more extensive research on the long-term durability and performance of these materials under real-world conditions.

Factors such as UV exposure, temperature fluctuations, and potential leaching of additives or degradation products from the plastic waste can influence the long-term performance and environmental impact of plastic waste-incorporated construction materials [14, 33].

Accelerated aging tests and field monitoring of pilot projects can provide valuable insights into the durability and service life of these materials, informing the development of appropriate design guidelines and maintenance strategies [38].

6.3 Standards and specifications:

The widespread adoption of plastic waste-incorporated construction materials requires the development of comprehensive standards and specifications to ensure consistent material quality, performance, and safety.

Currently, there is a lack of widely accepted standards and guidelines specific to the use of plastic waste in construction materials. This can create uncertainties and barriers for engineers, contractors, and regulatory agencies in implementing these innovative materials [39].

Collaborative efforts among researchers, industry stakeholders, and regulatory bodies are needed to establish appropriate standards and specifications covering material composition, testing methods, design criteria, and construction practices for plastic waste-incorporated construction materials [40].

6.4 Public perception:

Public perception and acceptance can be a potential barrier to the widespread adoption of plastic waste-incorporated construction materials. Concerns may arise regarding the perceived safety, durability, and environmental impact of using recycled plastic waste in construction projects [41].

Effective communication and education campaigns are necessary to address public concerns and highlight the potential benefits of plastic waste recycling in construction, such as reducing plastic pollution, conserving natural resources, and promoting a circular economy.

Demonstration projects and pilot studies can also play a crucial role in building public confidence by showcasing the successful implementation and performance of plastic waste-incorporated construction materials in real-world applications [42].

6.5 Resource competition:

As the adoption of plastic waste-incorporated construction materials increases, there is a potential risk of resource competition between different recycling industries vying for the same plastic waste feedstocks. Sectors such as the packaging industry, textile manufacturing, and automotive components also utilize recycled plastics as raw materials [43].

If the demand for plastic waste exceeds the available supply, it could lead to shortages and price fluctuations, potentially affecting the economic viability of using plastic waste in construction applications. Efficient waste management practices, along with increased plastic recycling rates, will be crucial to ensuring a stable supply of plastic waste for various end-use applications [44].

6.6 Life cycle impacts:

While numerous studies have examined the environmental benefits of plastic waste utilization in construction materials, it is essential to consider the potential life cycle impacts of these materials holistically. Life cycle assessment (LCA) studies should consider not only the diversion of plastic waste from landfills and the reduction in virgin material consumption but also factors such as energy and resource demands during material production, transportation emissions, and end-of-life scenarios [45].

For instance, the energy-intensive processes involved in sorting, cleaning, and processing plastic waste may offset some of the environmental benefits gained from recycling. Additionally, the potential leaching of additives or degradation products from plastic waste-incorporated construction materials during their service life or disposal could have adverse environmental impacts [14, 33].

Comprehensive LCA studies that account for these factors across the entire material life cycle are necessary to guide the development of sustainable and environmentally responsible practices for plastic waste utilization in construction [46].

7. Emerging technologies and future directions:

7.1 Chemical recycling:

While the majority of current plastic waste recycling techniques for construction materials involve mechanical processing (shredding, melting, and remolding), chemical recycling technologies are emerging as promising alternatives. Chemical recycling involves breaking down plastic waste into its molecular building blocks through processes such as pyrolysis, gasification, or depolymerization [47].

The resulting monomers or hydrocarbon compounds can then be used as feedstocks for the production of new plastics, fuels, or other valuable chemicals, potentially creating higher-value products from plastic waste compared to mechanical recycling [48].

In the context of construction materials, chemical recycling could enable the production of high-performance polymers or polymer precursors from plastic waste, which could be used as binders, coatings, or additives in concrete, asphalt, or other construction materials [49].

While still in the early stages of development, chemical recycling technologies offer an exciting avenue for valorizing plastic waste and enabling its integration into advanced construction materials.

7.2 Additive manufacturing:

Additive manufacturing, also known as 3D printing, has emerged as a transformative technology in various industries, including construction. The ability to create complex shapes and geometries through layer-by-layer material deposition offers opportunities for innovative design and construction methods.

Researchers have explored the use of recycled plastic waste as feedstock materials for additive manufacturing processes, such as fused deposition modeling (FDM) and pellet-based 3D printing [50, 51].

In the construction industry, additive manufacturing with recycled plastic waste could enable the production of customized concrete formworks, architectural elements, or even entire building components. This approach could reduce material waste, enable design flexibility, and promote the circular economy by repurposing plastic waste into functional construction components [52].

However, challenges related to material properties, print resolution, and scalability need to be addressed before widespread adoption of plastic waste-based additive manufacturing in construction can be achieved [53].

7.3 Bio-based and biodegradable plastics:

As concerns over the environmental impact of traditional plastics grow, the development of bio-based and biodegradable plastics has gained increasing attention. Bio-based plastics are derived from renewable resources, such as plant-based materials or microbial fermentation, while biodegradable plastics can be broken down by microorganisms into natural substances like carbon dioxide and water [54].

The utilization of bio-based and biodegradable plastics in construction materials could potentially mitigate some of the environmental concerns associated with conventional plastic waste, such as persistence in the environment and leaching of harmful additives [55].

Research efforts are underway to explore the use of bio-based and biodegradable plastics as reinforcements, binders, or additives in construction materials like concrete, asphalt, and soil stabilization [56, 57].

However, challenges related to material performance, durability, and cost-effectiveness need to be addressed before widespread adoption in construction applications can occur. Additionally, the development of appropriate infrastructure and regulatory frameworks for the end-of-life management of biodegradable construction materials will be crucial [58].

8. Conclusion:

The utilization of plastic waste in civil engineering construction has emerged as a promising approach to address the global plastic waste crisis while potentially improving material performance and promoting sustainability in the construction industry. This comprehensive review has highlighted the various techniques and applications for incorporating plastic waste into concrete, asphalt, soil stabilization, and other construction materials.

While significant research progress has been made, several challenges remain, including logistics and pretreatment of plastic waste streams, long-term performance evaluation, development of industry standards and specifications, addressing public perception concerns, and ensuring a stable supply of plastic waste feedstocks.

Emerging technologies such as chemical recycling, additive manufacturing, and the development of bio-based and biodegradable plastics offer exciting avenues for valorizing plastic waste and enabling its integration into advanced construction materials.

Interdisciplinary collaboration among civil engineers, material scientists, environmental researchers, and policymakers is crucial to overcoming these challenges and realizing the full potential of plastic waste utilization in the construction industry, contributing to a more sustainable and circular economy.

Comprehensive life cycle assessment studies and pilot projects are necessary to holistically evaluate the environmental, economic, and social impacts of plastic waste-incorporated construction materials, informing the development of sustainable practices and regulatory frameworks.

As the global emphasis on circular economy principles and waste valorization continues to grow, the construction industry has a vital role to play in providing innovative solutions for repurposing plastic waste streams, promoting resource efficiency, and mitigating the environmental burdens associated with plastic waste accumulation.

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