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Plastic and Microplastics in Soil Systems: Sources, Environmental Impacts, and Future Perspectives – A Review

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KEYWORDS

Waste Foundry Sand, Waste Plastic, Environment, Plastic Classification

ABSTRACT:

The article examines the increasing vulnerability of soils, groundwater, land resources, agricultural systems, freshwater bodies, and the marine environment to plastic and microplastic contamination. Microplastics are widely distributed in the environment due to the physical and biochemical degradation of plastic products. Although previous studies have primarily investigated plastic from ecological, chemical, agricultural, and public health perspectives, this review emphasizes the importance of integrating civil engineering into the discussion. This analysis synthesizes finding multiple studies to evaluate the occurrence, persistence, and degradation behavior of plastic and microplastic in soils. Particular attention is given to the role of solid waste disposal systems, especially landfills, as a potential source of environmental contamination. From a geotechnical standpoint, the design and management of such facilities are examined to highlight the possibility of microplastic migration from landfills into surrounding soils and the environmental system. Furthermore, the study discusses additional sources related to civil engineering practices, including the use of plastic-derived materials in construction applications such as tire chips, polyethene terephthalates (PET), waste foundry sand (WFS), and dredge sediments used as engineering fills. Overall, the article underscores the dual role of plastic waste in civil engineering as both a potential environmental contaminant and as a material resource and outlines future research directions aimed at mitigating the impact of plastic pollution on geotechnical and civil infrastructure systems.

1. Introduction

Rapid population growth, urbanization, and industrialization have led to a surge in solid waste, with plastic among the most prevalent. The word "plastic" originates from the Greek "plastiko", meaning "moldable", a fitting name for materials created by blending synthetic or semi-synthetic organic monomers

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(primarily from fossil fuels) with inorganic compounds under specific catalytic conditions. While plastic has revolutionised modern life, they have evolved from a technological breakthrough into a significant environmental burden. Despite our scientific progress, we have yet to develop a truly effective solution for permanently closing the loop on the plastic life cycle. Global plastic production has risen exponentially over the last few decades. Roughly 9% of the 6300 Mt of, plastic garbage produced as of 2015 had been recycled, 12% had been burned, and 79% had ended up in landfills (soni et al., 2022).

According to 2021 estimates, Asia has the highest production rates, accounting for 49% of the world's total output, with China being at top producer with 32%followed by North American Free Trade Agreement(NAFTA) 19% and rest of Asia 17%, Europe 15%, whereas the remaining country follows with less significance in terms of global Production(Mustafa et al., 2019). According to the Central Pollution Control Board (CPCB) annual report 2020-21, the Estimated Plastic Waste Generation in India is 34,69,780 tonnes per annum. According to the UNEP Report 2020, the most commonly used plastics around the globe representing 69 % of the global plastic are polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and Polystyrene (PS).These findings underscore the considerable risk of widespread pollution across various ecosystems due to plastics and their remnants, encompassing marine, freshwater, terrestrial, and polar environments. This poses a significant threat to the global environment.

2. Plastic Classifications

Depending on thermal behaviour, plastic can be divided into thermoplastic and thermosetting (soni et al., 2022), which can be seen in **Figure 1**. Global plastic production has risen exponentially over the last few decades. Roughly 9% of the 6300 Mt of plastic garbage produced as of 2015 had been recycled, 12% had been burned, and 79% had ended up in landfills (soni et al., 2022).

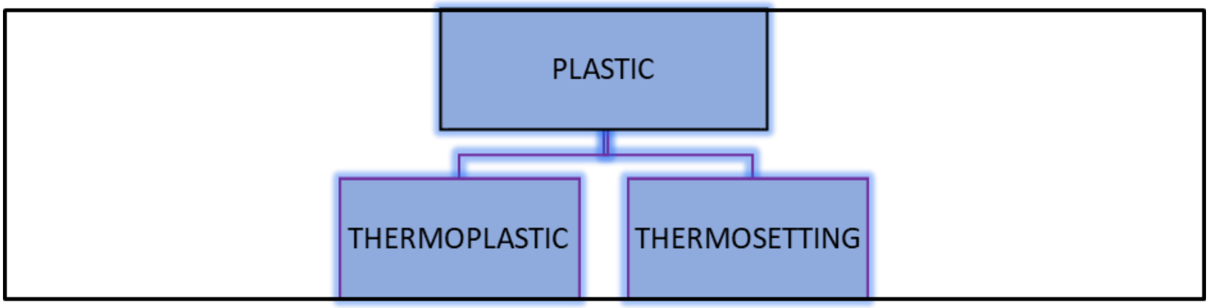

Fig.1: Types of Plastic

Due to its light weight, durability, corrosion resistance, and ease of moulding, it is frequently utilised in many industries such as construction, packaging, automotive, and electronics, to name a few. Though it has wide application, it too has a few constraints, like its non-biodegradability, which raises environmental problems along with health problems, thus making plastic waste management critical. Plastic can be broadly classified into two categories as thermoplastic and thermosetting (Kadhone et al., 2022a), based on their function and properties. Thermoplastics are a type of plastic that softens when heated and hardens when cooled, making them extremely recyclable and reusable in a variety of applications, such as the making of composite bricks (Subhani et al., 2024). The schemes of thermoplastic and thermoset polymeric materials, as shown below in **Figure 2** (left), represent thermoplastics, with weak intermolecular forces between polymer chains, and (right) represent thermosets, with strong covalent bonds(Kazemi et al., 2021).

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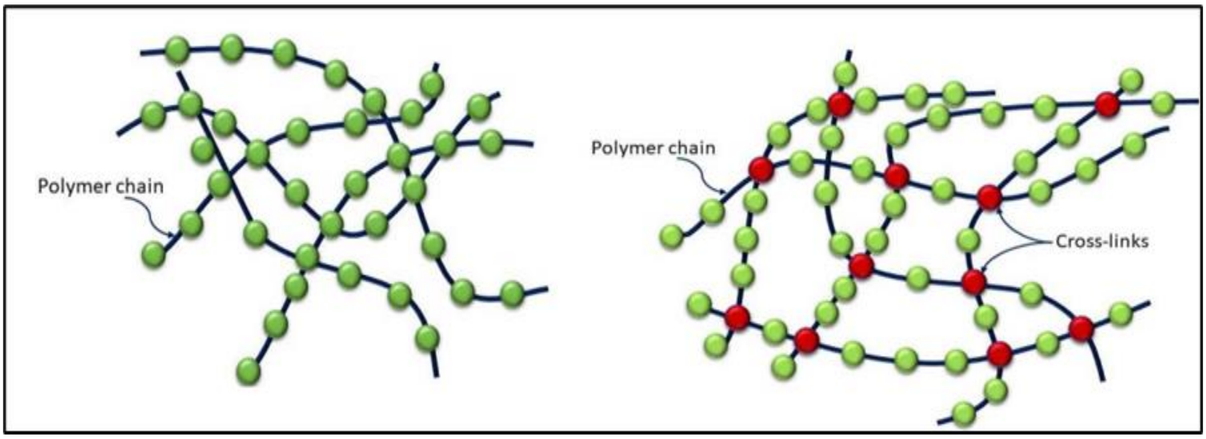

Fig.2: Structure of Thermoplastic (left) and Thermosetting Plastic (Right)

Because of their ubiquitous use in packaging, automotive, and consumer goods, they play a large role in plastic waste generation. This abundance of waste thermoplastics provides an opportunity for utilisation in sustainable construction materials, such as inclusion into composite bricks and paver tiles, to name a few. Each thermoplastic is assigned a specific code called the Resin Identification Code (RIC), which categorises them based on polymer composition, mechanical characteristics, and recyclability. From the plastic waste generation profile in **Figure 7** (Bhattacharya et al., 2018) it is evident that HDPE/LDPE, PP, and PET from the majority fraction are suitable for recycling into construction composites. Hence, the study strategically focuses on PET, HDPE/LDPE, PP and mixed plastic, which comes under multilayered plastic.

- Polyethylene (PE) is a thermoplastic, and elastic polymer. It is used in plastic containers, bottles, bags, and plastic toys. In addition, it can be used for the production of plastic cement.
- Polypropylene (PP) is a thermoplastic polymer used in products such as food containers, packaging, toys, furniture, and textiles. Based on its density it can be named as low-density polyethylene (LDPE), or high-density polyethylene (HDPE).
- Polyvinyl chloride (PVC) is one of the most commonly used thermoplastic polymers in the world. It is used in construction, and packaging for food, textile, and medical materials.
- Polystyrene (PS) is used for lining refrigerators, packaging, construction, and in the medical industry as trays.
- Polyethylene terephthalate (PET) is a clear, strong, and lightweight plastic, commonly found in products such as beverage bottles, perishable food containers, mouthwash, jars, and plastic bottles. It hardly weighs anything, and it is impact-resistant.

Aryan, et al. (Aryan et al., 2019) mentioned various plastic compositions, such as polyethylene terephthalate composition is about 9 %, polyvinyl chloride is about 4%,high-density polyethene/low-density polyethene is about 66 %, polypropylene is about 10%, polystyrene is about 5%, and others are about 6%. In **Figure 3** (Bhattacharya et al., 2018) it is evident that HDPE/LDPE, PP, and PET from the majority fraction are suitable for recycling into construction composites. Hence, the study strategically focuses on PET, HDPE/LDPE, PP and mixed plastic, which comes under multilayered plastic.

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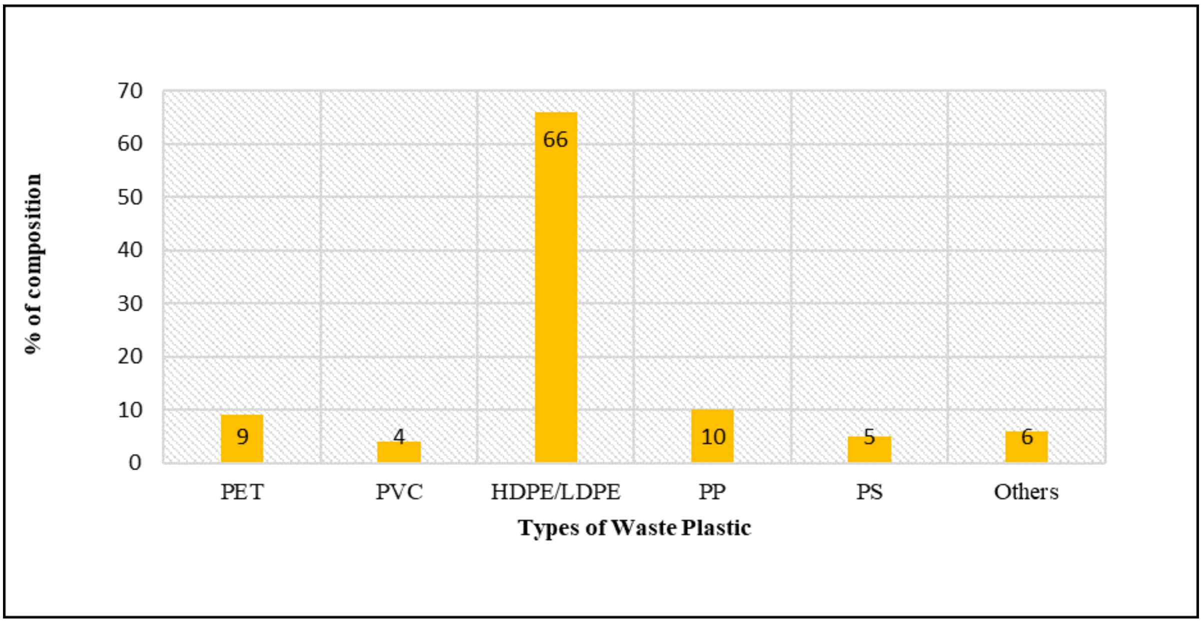
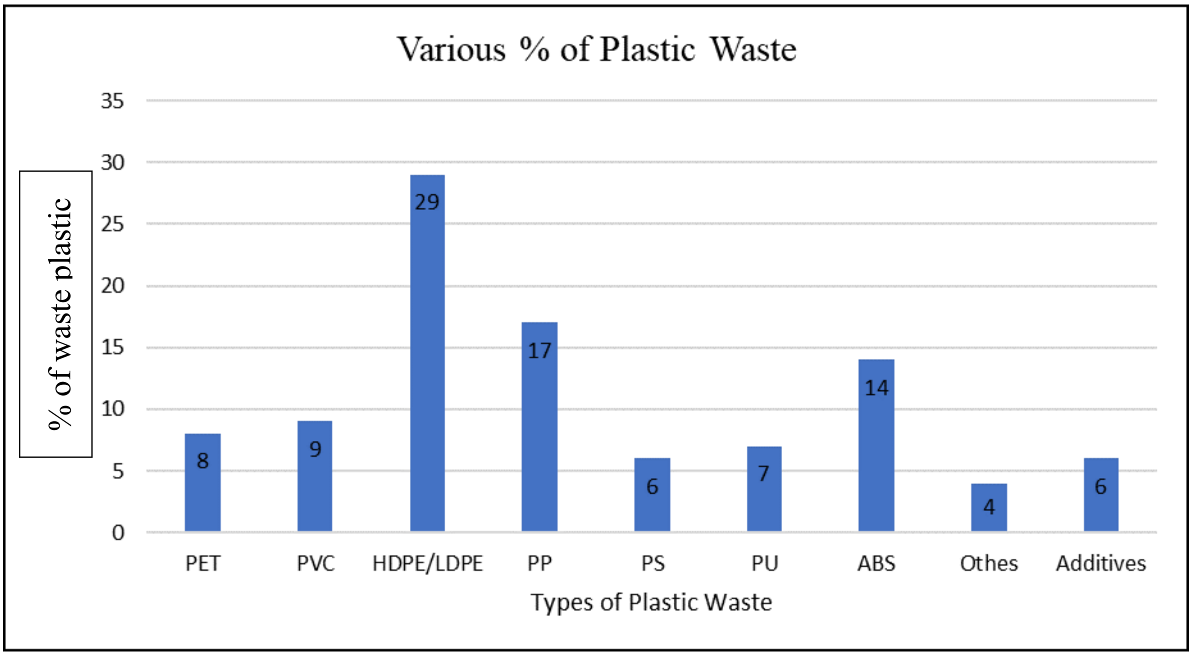


Fig.3: Percentage Composition of Plastic Waste in India

The various percentage breakdown of plastic wastes is low-density and linear low-density polyethylene (LDPE & LLDPE)-16%, high-density polyethylene (HDPE)-13%, polypropylene (PP)-17%, polystyrene (PS)-6%, polyvinylchloride (PVC)-9%, polyethylene terephthalate (PET)-8%, polyurethane (PU) -7%, & acrylonitrile butadiene styrene (ABS)-14%, others- 4%, and additives-6% (Bhatnagar et al., 2019).



These plastic waste materials can now be added with other materials as resource materials to form a new composite material with improved characteristics. They could be admixtures in manufacturing various bricks, which were considered to be building blocks. Similarly, these materials can also be added with asphalt and bitumen for laying flexible pavements, they can also be used in slope stabilization, soil stabilization, and many more applications that have to be researched. When plastic waste materials are substituted or replaced within proportions in the concrete mix, it has environmental and economic benefits.

2.1. Plastic Waste as a Resource Material in Pavement

The bituminous binder used in pavement construction work includes both bitumen and tar. Both of these binders have a similar appearance but have different characteristics but both of these binders can be used in pavement work. Bitumen is a complex organic material obtained by distillation of petroleum crude, whereas even "plastics," are derived from various fractions of crude oil through processes like cracking and polymerization. Since both of the materials are produced in the petrochemical industry they have good bonding. For bitumen, typical application temperatures range from around 150°C to 180°C (302°F to 356°F). At these temperatures, bitumen becomes sufficiently viscous for mixing and application, whereas thermoplastic materials like polyethylene and polypropylene typically soften at temperatures ranging from 100°C to 150°C (212°F to 302°F) Bhatnagar et al. (Bhatnagar et al., 2019) studied various properties of Bitumen with various percentages of PET addition and he affirmed that an important use of PET waste materials is the recycling of waste plastic into asphalt for pavement. Bitumen asphalt mix properties such as strength, fatigue life, and other desirable features of bituminous concrete mixes have significantly improved by the addition of processed waste plastic (PET). By addition of 5–10% by weight of bitumen there is increases in pavement performance and lifespan while reduction in bitumen consumption. The procedure is not harmful to the environment and a significant amount of waste plastic is also used. When plastic is melted and mixed with aggregate, it acts as a thin plastic film coating onto the aggregate, thus repelling water and increasing the life span of pavement. So these procedures provide improved pavement infrastructure and are therefore very relevant to society in utilising the waste plastic and thus saving the environment.

To withstand the tire pressure and weather the surface of the flexible pavement should have characteristics that exhibit strength, ability to drain off surface water, and friction, soundness (wearing action of aggregates). So during the laying of flexible pavement when hot stone aggregate (170ºc)is mixed with the hot molten bitumen(160ºc)and then mixed well before laying (Ahmad et al., 2018). The bitumen is chosen based on certain properties like binding, and viscosity. When the waste plastic is mixed with aggregate (160ºc) waste plastics get melted as the melting point of PET is 245ºc to 260ºc(Akinyele et al., 2020), and it improves the properties like voids, and moisture absorption. The addition of Pet in the mix helps to improve the property of porosity and to improve the quality of aggregate and its performance in the flexible pavement.

2.2. Plastic Waste as a Resource Material In Paving Blocks

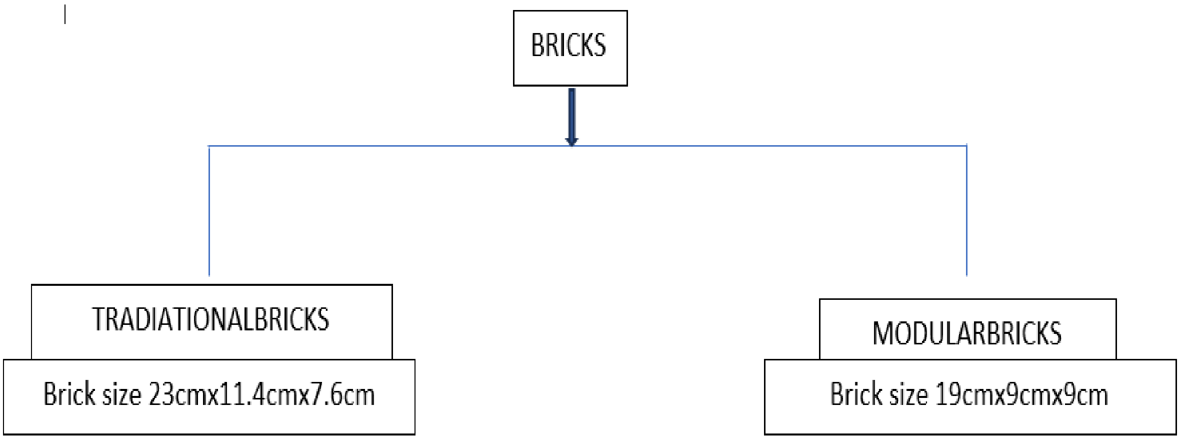
Ahmad et al. (Ahmad et al., 2018). Studied waste plastic utilization [PET] as an addition to cement-based concrete paving blocks. Standard concrete blocks without the replacement of PET have a compressive strength of 21.4 MPa, while 5%, 10%, and 15% of PET have 20.9 MPa, 12.2 MPa, and 10.9 MPa, respectively. The strength performance for PET concrete after 7 days fluctuated with the increase of PET content; 5% PET content has increased the strength up to 49.2% as for 10% and 15% of PET content have deteriorated the performance by 21.2% and 7.8%, respectively. Therefore, if more than 5% is added the PET would fail to improve the strength of the concrete pavement block, but still these can be used for nonstructural applications. The reduction in the compressive strength with the addition of plastic content could be due to low adhesive strength between the plastic surface and the cement paste, coupled with poor morphology also since plastic is an inert material, it does not react with the cement properly.

2.3. Plastic Waste as a Resource in Other Construction Materials

Finding materials that can lower construction costs while strengthening engineering infrastructure is a topic of great interest for researchers. The use of plastic waste for construction applications in the engineering industry holds a high capability of decreasing worldwide ecological contamination and environmental pollution.

Plastic aggregates, cementitious materials, soil stabilisation additives, and other construction resources obtained from plastic waste were examined by Ogundairo et al.(Ogundairo et al., 2021) and he affirmed that the behavior of plastic waste in construction materials is innately unique concerning synthetically manufactured materials. Nevertheless, construction materials made from plastic waste can provide comparable or better outcomes than traditional construction materials. The use of plastic waste will gradually empower the reduction in the utilization of conventional construction materials, subsequently diminishing the carbon footprint associated with the production of such materials.

Classification of Bricks



Good burnt bricks, sometimes referred to as fired bricks, have several advantageous qualities that make them appropriate for use in a variety of construction applications. Burnt bricks should have sufficient compressive strength to withstand the loads experienced in construction. Typically, the compressive strength of burnt bricks according to IS 1077:1992 ranges from 3.5 N/mm² to 35 N/mm², depending on factors such as composition, manufacturing process, and firing temperature. When polyethene terephthalate was added as a partial replacement of soil to 5%, then the compressive strength of the burnt brick was found to be 3.5 N/mm^{2,} which does not fall under any category of IS 1077:1992(BIS, 1992) to the same, it was 5.15N/mm^2 when no polyethene terephthalate was added. so only based on compressive strength, we can say that the brick is not suitable for construction various other characteristics should be studied. While samples containing over 10% PET collapsed during the firing process, samples containing less than 10% PET did not collapse but instead underwent shape deformation. When compared to the control sample, the bricks with PET content had a lower compressive strength, however, the sample with 5% exhibited some decent results in terms of structural efficiency. This suggests that bricks with 5% or less PET might function effectively, although more research is needed on this. If binder-like bitumen of 2% is added along with waste plastic then the compressive strength of the brick is enhanced. It is evident from **Figure 4** that the brick's compressive strength increases with varying percentages of plastic material when 2% bitumen is added as a binder, by IS code 1077:1992.

2.4. Plastic Waste as a Resource in Composite Brick Production

The topsoil is often used for brickmaking. It is well known that the topsoil is a rich source of nutrients for vegetation, this nutrient base is depleted by large-scale brick manufacturing since they are extensively used for brick making. so there should be an alternative for partial or full replacement of topsoil .potential partial replacements are polyethylene terephthalate reinforced in clayey soil(Louzada et al., 2019), recycled waste of blacksmith, waste plastic(Kadhone et al., 2022b), foundry sand(Hossiney et al., 2018).

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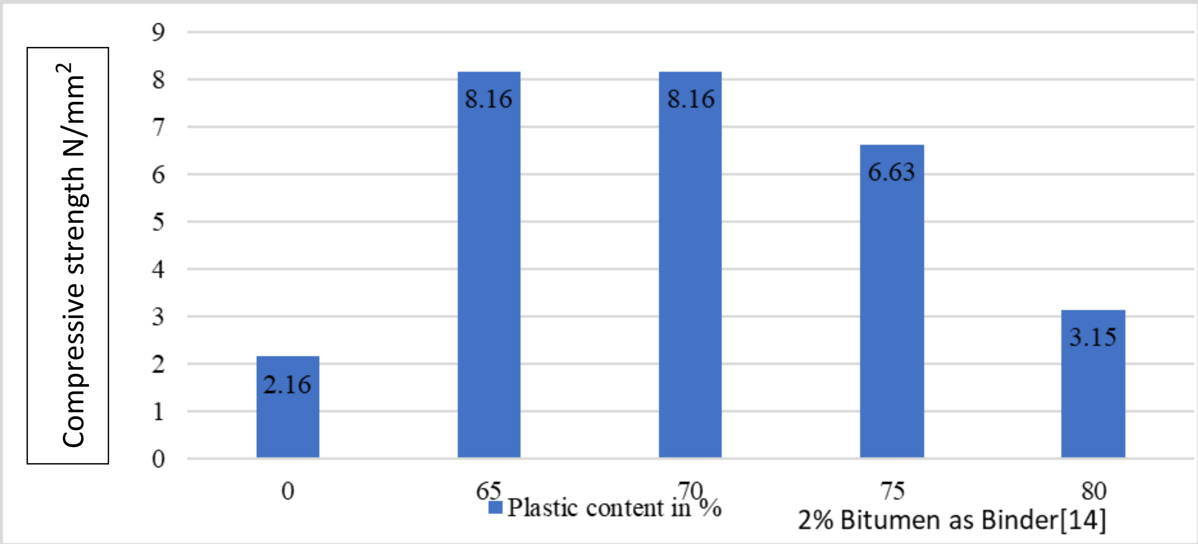

Fig 4: Bricks Compressive Strength

Research was done to find out how adding steel filings to the burnt clay brick mixture affected the mixture's compressive strength, density, and water absorption capacity.

In order to improve building materials and conserve resources, the study also looked at the advantages of incorporating debris from blacksmiths' workshops. It is evident from **Figure** 5. That the brick's compressive strength increases with varying percentages of debris from blacksmiths' workshops material (Kadhone et al., 2022b)which is in accordance with IS code 1077:1992.

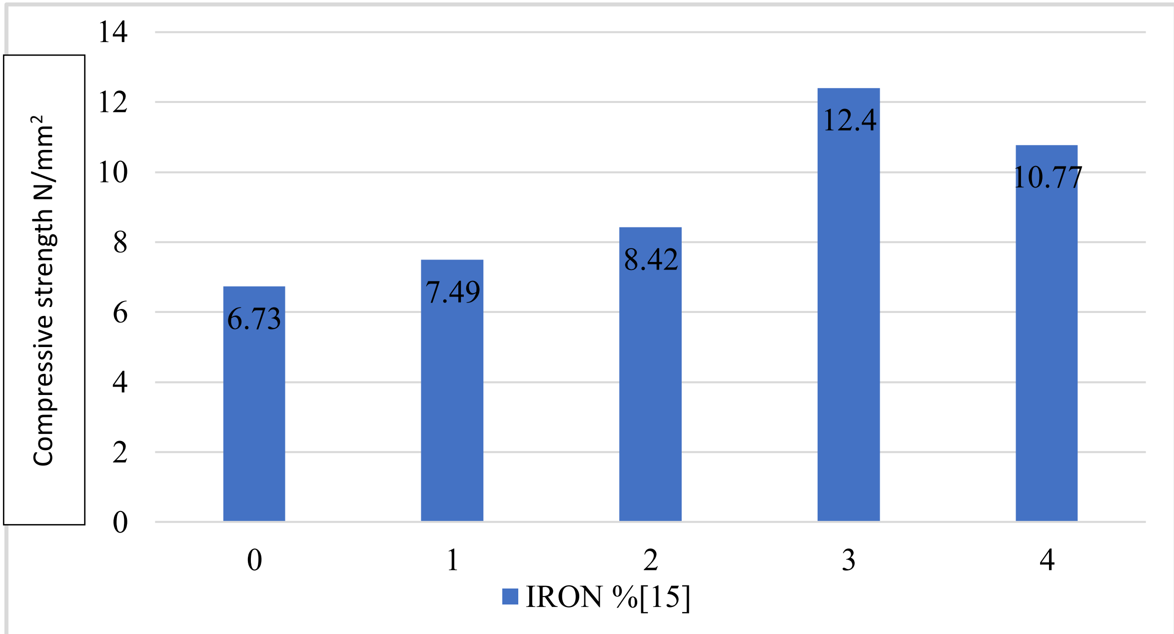

Fig 5: Compressive Strength with Various Mixture

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3. Environmental Impact

An evaluation of the environmental effects of these materials, as opposed to conventional materials, that will be utilized in the civil engineering field, taking into account the potential for waste diversion, embodied energy, carbon footprint, monitoring the state of the environment, and other aspects that need further study.

3.1. Applications and Future Directions

Durability, affordability, and sustainability are just a few advantages of using waste plastic to make building materials. In order to maximize the performance of construction materials generated from waste plastic and discover new applications, research and development efforts must continue. Investigating cutting-edge production techniques, improving material qualities, In general, using waste plastic to make building materials presents viable ways to tackle sustainability issues in the construction sector, all the while advancing the ideas of the circular economy, lowering dependency on finite resources, and evaluating environmental effects over the course of a product's lifecycle.

3.2. Challenges and Opportunities

Plastic waste-derived building materials have many advantages, but there are drawbacks as well as potential because recycled plastic feedstock varies in composition and properties, it can be difficult to ensure consistent quality and performance of construction materials made from it. Novel construction materials made from plastic waste may also have difficulties meeting building codes and regulatory standards, necessitating extensive testing and certification to guarantee compliance with safety and performance requirements. Due to misconceptions regarding the caliber, dependability, and visual appeal of plastic-based building materials, it can be difficult to overcome skeptics and win over stakeholders, such as architects, engineers, builders, and consumers.

4. Conclusions

In conclusion, the building sector has a potential opportunity to innovate sustainably through the use of waste plastic to create construction materials. Through the utilisation of technological advancements, stakeholder collaboration, and increased understanding of the advantages of construction materials derived from plastic, we may surmount challenges and realise the complete potential of this burgeoning industry. Using these materials allows us to design durable, resource-efficient structures that satisfy the demands of both the present and the future, in addition to reducing the amount of plastic pollution. It is crucial that we prioritize research, make infrastructure investments, and foster an atmosphere of supportive policies that encourage innovation and adoption as we continue to investigate and improve these materials. In the end, we can create a constructed environment that is more resilient and sustainable by adopting building materials derived from waste plastic.

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