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Utilization of Recycled Industrial and Plastic Wastes as Cement and Aggregate Substitutes in Rigid Pavements

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***Abstract* - The growing concern over environmental degradation and the depletion of natural resources has prompted significant research into sustainable construction practices. This study explores the potential utilization of Electric Arc Furnace Slag (EAFS), an industrial by-product, and recycled plastic waste as partial substitutes for cement and coarse aggregate, respectively, in rigid pavement concrete. The primary objective is to enhance material efficiency, reduce environmental impact, and improve the mechanical performance of concrete used in highway infrastructure.**

An experimental program was designed to evaluate the suitability of EAFS as a cementitious material and plastic waste as a coarse aggregate replacement. Various mix proportions were developed using M40 grade concrete, and comprehensive laboratory testing was conducted to determine the compressive, flexural, and split tensile strengths at curing intervals of 7, 14, and 28 days. Standard characterization tests were also performed on individual materials to assess their physical and chemical properties in accordance with relevant IS codes.

The results indicate that a 20% replacement of cement with EAFS resulted in an increase of 4.58 MPa in 7-day compressive strength compared to control samples. Similarly, the optimum replacement level for coarse aggregate with plastic waste was found to be 2.5% for early strength (7 and 14 days) and 5% for long-term (28-day) performance. The study also includes a comparative analysis with theoretical data from previous research, validating the observed trends and confirming the structural viability of the proposed waste-based concrete mixes.

This research demonstrates that the incorporation of recycled industrial and plastic wastes in rigid pavement concrete not only supports environmental sustainability but also provides satisfactory performance in terms of strength and durability, making it a viable option for modern highway construction.

Keywords: Electric Arc Furnace Slag (EAFS), Plastic Aggregate, Rigid Pavement, Compressive Strength, Sustainable Concrete, Waste Utilization.

I. INTRODUCTION

With rising urbanization and economic development, the production and consumption of plastic have surged globally, leading to growing concerns over waste management. Improper disposal of such waste, including plastics, fly ash, rice husk ash, and Electric Arc Furnace Slag (EAFS), poses serious environmental and health challenges. Plastic waste, due to its long decomposition period and durability, can be effectively utilized in rigid construction, offering a sustainable alternative to traditional materials. When not managed properly, plastic waste contributes to environmental degradation, including contamination of the food chain, loss of biodiversity, unnecessary energy consumption, and financial losses. Similarly, storing EAFS in industrial areas can pose significant health risks to workers and create uncomfortable working conditions. Incorporating plastic waste and EAFS into rigid pavements presents an environmentally friendly and practical solution to reduce these materials in the environment. Their use in concrete construction not only addresses waste disposal issues but also enhances material performance, offering multiple benefits.

Figure 1.1: EAFS Passing 90μ Sieve

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Table 1.1: Characteristics and Applications of BF Slag and EAFS

	Characteristics	Applications
Blast Furnace Slag	Fertilizer component (CaO, SiO_2)	Calcium silicate fertilizer and Soil improvement
	Low Na_2O and K_2O	Raw material for cement clinker (replacement for clay)
	The strong latent hydraulic property when finely ground	Raw material for Portland blast furnace slag cement, Blending material for Portland cement, Concrete admixtures.
	Lightweight, large angle of internal friction, large water permeability	Material for civil engineering works, Ground improvement material (Backfill material, earth cover material, embankment material, road sub grade improvement material, sand compaction material, ground drainage layers, etc.)
ETFS	Fertilizer components (CaO, SiO_2, MgO, FeO)	Fertilizer and soil improvement
	Large angle of internal friction	Material for civil engineering works, ground improvement material (Material for sand compaction piles)
	FeO, CaO, and SiO_2 components	Raw material for cement clinker

Table 1.2: Chemical Composition of Electric arc Furnace Slag

Oxides	Electric arc Furnace Slag (EAFS) (Wt %)
SiO_2	13.2
Al_2O_3	6.17
Fe_2O_3	34.6
CaO	21.6
Na_2O	0.13
K_2O	-
TiO_2	0.57
MnO	5.77
MgO	3.75
SO_3	0.28
BaO	0.17
P_2O_5	0.34
Cr_2O_5	2.38
V_2O_5	0.13
Cl	-

Plastic production has continued to grow rapidly, reaching over 460 million tonnes globally by 2023, up from just 2.3 million tonnes in 1950. A significant portion of this plastic is discarded after single use, contributing to large volumes of waste and severe environmental challenges. Currently, plastic waste makes up about 3% of total global waste annually, posing threats to ecosystems and wildlife. Improper disposal methods, such as landfill dumping, can result in soil and water pollution, clogging of drainage systems, harm to grazing animals, and degradation of land quality. Open dumping not only causes health hazards but also leads to inefficient use of limited land resources.

Incorporating plastic waste into road construction offers a promising solution to these challenges. Utilizing such materials in construction helps minimize environmental contamination and reduces the burden of plastic disposal. Waste plastics can be blended with construction materials or used to partially replace natural aggregates to produce environmentally sustainable alternatives. These modified materials often exhibit equal or superior mechanical properties such as strength and durability when compared to conventional, costly, and resource-intensive materials like Portland Cement. This approach aligns with sustainable development goals for 2023–24, promoting both resource efficiency and waste management.

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Figure 1.2: Plastic Aggregate

Table 1.3: Physical and Chemical Properties of Recycled Polyethylene

Ultimate Analysis	
C (%)	85
H (%)	13.8
N (%)	0
S (%)	0
O (%)	0
Ashes (%)	1
Moisture (%)	0.2
Low heating value (KJ/Kg)	45,500
Starting devolatilization temperature (°C)	250
Devolatization temperature (°C)	410
Particle density (kg/m^3)	940
Bulk density(kg/m^3)	570

II. LITERATURE REVIEW

Ahmad (2019) examined the dry density properties of concrete that use plastic wastes and polymer fiber to replace coarse aggregate, and then determined the concrete's compressive, tensile, and flexural strength, and finally compared the performance of concrete that uses plastic wastes and polymer fiber vs. concrete that only uses plastic wastes. Plastic wastes were used in concrete at percentages of 10%, 20%, and 30%, and polymer fiber at percentages of 2%, 4%, and 6%, respectively, in an extended experimental investigation. The polymer- modified concrete had a reduced density, according to the findings. Concrete's compressive and flexural strength is reduced when the waste polymer is used to replace cement. This is most likely owing to the fibers' bridging function.

Rahaman (2017) conducted an experiment on polystyrene polymer which is used as an alternative to coarse aggregate in partial replacement of brick aggregate. The use of polystyrene polymer is increasing day by day with economic growth. However, this polystyrene polymer is not decomposed and causes a serious environmental problem by increasing as solid waste. Therefore,

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an alternative process of recycling such materials as a coarse aggregate by partial use in concrete may reduce solid waste and make lightweight concrete. The conventional coarse aggregate in concrete was replaced with 0%, 5%, 10%, 15%, 20%, 30%, and 40% (by volume) of EPS, and the ordinary Portland cement was replaced with fly ash as the same percentage. A mix proportion of 1:1.68:2.49 with a water/cement ratio ranging from 0.35- 0.56 was used and polystyrene granules were cast, and specimens were tested at 7, 14, and28days after natural curing. Test results exhibited that the compressive strength, splitting tensile strength, and unit weight gradually decreases with the increase of recycled polymer aggregate and the water absorption decreased with the higher replacement of recycled polymer aggregate.

Suwansaard (2021) examined Plastic waste used with sand aggregate in mortar to improve several qualities of the mortar while also lowering pollution and solving the problem of natural sand scarcity. Polystyrene (PS) and high-density polyethylene (HDPE) wastes were investigated as possible sand substitutes in mortar. Water absorption, bulk dry density, flow value, and compressive strength of mortar containing these plastic wastes were all investigated. The thermal conductivity of wall models plastered with plastic waste-containing mortar was also examined. The following were the key findings: The particle sizes of the plastic debris and the sand were similar. The qualities of PS mortar were found to be superior to those of HDPE mortar. The water absorption of PS mortar was equivalent to that of the reference mortar; however, it was lower than that of HDPE mortar. The PS mortar has much better compressive strength than the HDPE mortar. The thermal conductivity of a wall plastered with PS mortar dropped as the PS content rose, whereas the thermal conductivity of a wall plastered with HDPE mortar increased as the HDPE concentration increased. According to the findings, 10 percent PS might be utilized as a partial substitute for sand in mortar and improve certain of the mortar's qualities.

Building on this foundation, **Singh et al. (2023)** explored the use of shredded PET bottles as partial sand replacements in mortar. Their study reported that PET-modified mortar showed improved thermal insulation and sufficient compressive strength for non-load-bearing applications, especially when PET content was limited to 5-10%. Similarly, **Kumar and Sharma (2023)** examined the use of LDPE plastic waste as fine aggregate replacement and found that mortars containing up to 8% LDPE exhibited acceptable mechanical properties and enhanced durability under sulfate attack conditions.

In addition, **Alam et al. (2024)** studied the incorporation of mixed plastic waste (a combination of PS, HDPE, and LDPE) into plaster mortar, concluding that the particle size compatibility between plastic waste and sand played a critical role in achieving workability and strength. Their results confirmed that PS waste offered better bonding and compressive strength than HDPE, aligning with Suwansaard's findings. However, they also noted that excessive replacement (beyond 15%) led to decreased strength due to poor interfacial bonding.

Thermal conductivity continues to be an area of interest. **Rao and Patil (2023)** conducted thermal performance analysis of walls plastered with plastic-enriched mortar and found that PS-enhanced mortar significantly reduced heat transfer, making it suitable for thermally efficient buildings in warm climates.

Overall, current research supports the use of plastic waste especially PS in improving certain characteristics of mortar such as thermal insulation, workability, and partial compressive strength retention. The optimal substitution rate generally lies between 5% and 10%, depending on the type of plastic used and the intended application. These advancements contribute to sustainable construction practices by reducing dependency on natural sand and offering a productive use for plastic waste.

2.1 Research Objective

- To explore effective alternatives to conventional coarse aggregate and cement for use in rigid pavement construction.
- To evaluate the impact of incorporating various waste materials on the strength characteristics of the concrete mix.
- To develop practical recommendations for utilizing plastic aggregates and Electric Arc Furnace Slag (EAFS) as partial replacements for coarse aggregate and cement, respectively, in rigid pavement applications.

III. MATERIALS AND METHODOLOGY

3.1 Materials Used

- **Cement:** Pozzolana Portland Cement (PPC), 43 grade, fly ash-based, was used. PPC contains 15-35% pozzolanic materials, offering improved durability.

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- **Fine Aggregate:** Locally sourced river sand conforming to IS: 383-2016 standards was used. The sand belongs to Grading Zone II, with a specific gravity of 2.83, 1% water absorption, and a fineness modulus of 2.61.
- **Coarse Aggregate:** Crushed stones with a maximum size of 20 mm were used. Plastic waste retained on a 12.5 mm sieve was partially used as a coarse aggregate replacement.

3.2 Material Testing

- **Normal Consistency (IS 4031-1988):** Determines the water content required for standard cement paste using Vicat's apparatus.
- **Setting Time (IS 4031-1988):** Measures initial and final setting times to assess cement's hydration behavior.
- **Soundness (IS 4031-1988):** Le-Chatelier test evaluates volume stability due to excess lime.
- **Fineness (IS 4031-Part 1-1996):** Assessed through sieve analysis to ensure cement particle uniformity.
- **Specific Gravity (IS 4031-1988):** Tested for cement, fine aggregate (using pycnometer), and plastic aggregates (wired bucket method).
- **Compressive Strength (IS 4031-1988):** Cubes (15 cm × 15 cm × 15 cm) were tested using UTM to evaluate load-bearing capacity.
- **Flexural Strength (IS 516-1959):** Rectangular beams (50 cm × 10 cm × 10 cm) were tested under third-point loading to measure bending resistance.
- **Tensile Strength (IS 5816:1999):** Cylinders (30 cm × 15 cm) were tested via split tensile method to evaluate tensile capacity.
- **Aggregate Impact Test (IS 2386-Part IV):** Measured toughness of plastic waste aggregates. Values <20% indicate high strength.
- **Los Angeles Abrasion Test (IS 2386-Part IV):** Assesses the wear resistance of aggregates. Acceptable limits vary from 40% to 60% based on pavement type.

Figure 3.1: Los Angeles Abrasion Test

3.3 Mix Design

The objective of this study is to replace cement with waste material that is plastic waste and coarse aggregate with EAFS in different proportions in road construction. As a result, the mix design of M40 grade concrete was carried out in accordance with Indian specifications, particularly IRC 15, IRC 44 and IS: 10262-2019. The amount of concrete required for 1 cubic meter can be calculated using these codes.

3.4 Stipulation for Proportioning

a) Grade designation-M40
b) Type of cement -PPC43grade
c) Type of mineral admixture-Fosroc Aura mix 350 Super plasticizer
d) Maximum nominal size aggregate=20mm
e) Workability (Slump)=75mm

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3.4.1 Test Data for Materials

1) Cement used=PPC43
2) Specific gravity of cement=3.07
3) Specific gravity of slag=3.17
4) Specific gravity of coarse aggregate=2.85
5) Specific gravity of fine aggregate =2.82
6) Water Absorption
   Coarse aggregate=0.65%
   Fine aggregate = 1%
7) Free Moisture
   Coarse aggregate=2-0.65=1.35%
   Fine aggregate=5-1=4%

3.4.2 Target Strength

Fck=fck+1.65s

= 40+1.65*5

=48.25 N/mm^2

3.4.3 Air Content

20 mm, entrapped air=1% (table3)

Volume of entrapped air = 0.01 m^3

3.4.4 Selection of W/C Ratio

Mix Calculation

a) Total Volume=1m^3
b) Volume of entrapped air in wet concrete=0.01m^3
c) Volume of Cement
   = (Mass of cement/SG of cement)*1/1000
   = (411/3.07)*1/1000
   = 0.134 m^3
d) Volume of Water = (mass of water/SG of water)*1/1000
   = (148/1)*1/1000
   = 0.148m^3
e) Volume of super plasticizer = 0.0036m^3
f) Volume of aggregate (g) =1-0.01-0.134-0.148-0.0036
   =0.704m^3
g) Mass of coarse aggregate=g*volume of coarse aggregate*specific gravity of coarse aggregate*1000
   =0.704*0.65*2.85*1000
   =1304kg/m^3
h) Mass of Fine Aggregate =0.704*0.35*2.82*1000=695kg/m^3

Mix Proportions of Concrete for 1m^3

Cement	=411Kg/m^3
Water	=148kg/m^3
Fine Aggregate	=695kg/m^3
Coarse Aggregate	=1304kg/m^3

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Chemical Admixture	=4.1kg/m^3
Water Cement Ratio	=0.36

Estimation of the Quantity of Concrete Mix

The calculations of concrete as per unit volume shall be measured as follows:
The volume of cubes = 0.15m*0.15m/0.15m*3 = 0.01012 m^3
Cement=411×0.01012=4.16kg/ m^3
Sand=695×0.01012= 7.03kg/m^3
Aggregate =1304×0.01012=13.19kg/m^3
Water=148 ×0.01012=1.49 kg/m^3

IV. RESULT ANALYSIS

4.1 Test Result for the Materials

Table 4.1 Different Test Results for the Materials

S. No	Experiments	Results
1	Normal Consistency Test	32%
2	Initial Setting Time	120 minutes
3	Final Setting Time	5 hour30 minutes
4	Soundness of Cement	1mm
5	Fineness of Cement	1%
6	Specific Gravity of Cement	3.13
7	Specific Gravity of Fine Aggregate	2.82
8	Specific Gravity of Coarse Aggregate	2.85
9	Specific Gravity of EAFS	3.13
10	Aggregate Impact test on Plastic Waste	0%
11	Los Angeles Abrasion Test	0%

4.2 Compressive Strength Test of EAFS for 28 Days

The optimal value of compressive strength for 28 days was found for 30% replacement of cement by EAFS for laboratory testing.

Table 4.2: Compressive Strength by Using Slag for 28 Days

% Replacement of Slag	Sample1 (MPa)	Sample 2 (MPa)	Sample3 (MPa)	Laboratory Average (MPa)
0%	35.6	36.3	36.5	36.1
10%	40.1	35.4	29.2	34.9
20%	32.3	38.2	34.9	35.0
30%	39.1	40.2	41.2	40.1
40%	35.4	37.2	34.8	35.8

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4.3 Comparison between Previous Research and Laboratory Data for 28 Days Compressive Strength of EAFS

The optimal value of compressive strength for 28 days was found for 30% replacement of cement by slag for the laboratory testing whereas the optimal value was found for unmodified concrete in the research paper. There is an increment in compressive strength value of 28 days for laboratory testing compared to the previous paper. There is an increase of 9 MPa in compressive strength value for 30% replacement of EAFS by cement in laboratory testing compared to the previous paper.

Table 4.3: Laboratory and Theoretical Compressive Strength Comparison of 28 Days

% Replacement of Slag	Laboratory Average (MPa)	Theoretical Average (MPa)	Incremental Value
0%	36.1	32.44	3.66
10%	34.9	26.83	8.07
20%	35.0	31.47	3.53
30%	40.1	31.1	9
40%	35.8	31.71	4.09

4.4 Representation of Laboratory and Theoretical Average (28 Day)

The maximum strength was found for 30% replacement of EAFS in the laboratory but in previous research, the efficient strength was found for unmodified concrete.

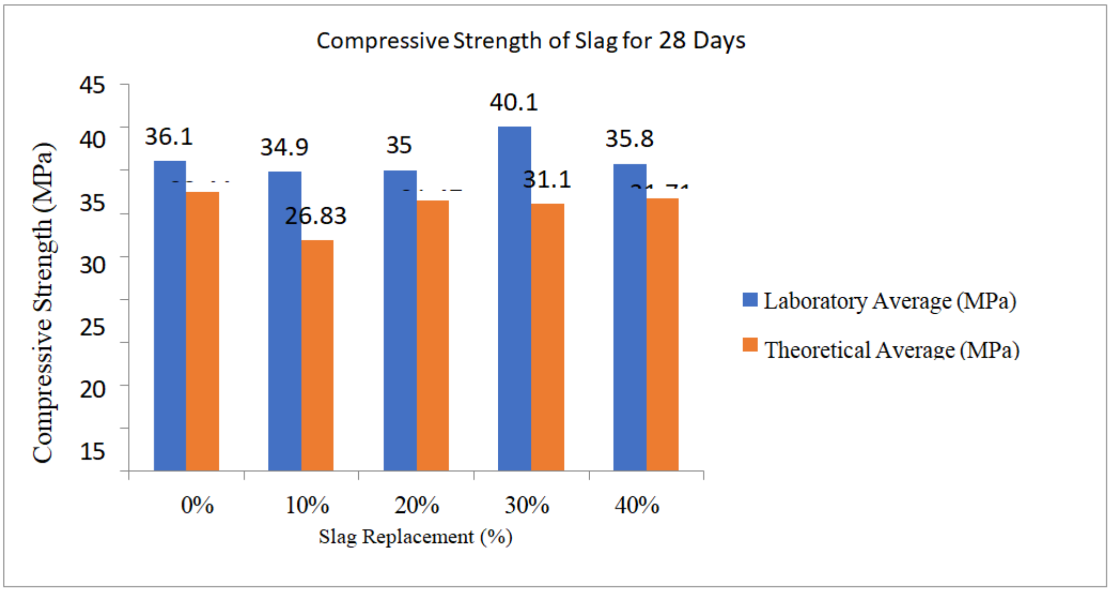

Figure 4.1: Graph of Compressive Strength vs. % Slag replacement for 28 Days

4.5 Split Tensile Strength Test of Plastic Aggregate for 28 Days

For fig 4.17 at 7.5% replacement of coarse aggregate by plastic aggregate for 28 days there is an increment of 33.8% of split tensile strength. The optimal value of tensile strength for 28 days was found for 7.5% replacement of plastic waste by coarse aggregate in laboratory testing and in the research paper. This may be due to the Cement aggregate ratio, because aggregates are the primary source of concrete strength, raising the cement-to-aggregate ratio will boost strength. Better grade aggregates absorb less water, allowing more water to be used for cement hydration.

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Table 4.4: Split Tensile Strength by Using Plastic Waste for 28 Days

% Replacement of Plastic Aggregate	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Laboratory Average (MPa)
0%	3.1	3	3.4	3.2
2.5%	3.2	3.3	3.3	3.3
5%	3.8	4	4.2	4
7.5%	3.9	4.2	4.5	4.2

4.6 Comparison between Previous Research and Laboratory Data for 28 Days Split Tensile Strength of Plastic Aggregate

It was observed that the split tensile strength value increases with an increase in percentage replacement of coarse aggregate by plastic aggregate in laboratory testing whereas in the previous paper the split tensile strength increases to 5% replacement of plastic aggregate. There is a decrement of 0.24MPa of split tensile strength value at 5% replacement of coarse aggregate by plastic aggregate.

Table 4.5: Split Tensile Strength by Using Plastic Waste for 28 Days

% Replacement of Plastic Aggregate	Laboratory Average (MPa)	Theoretical Average(MPa)	Incremental Value
0%	3.2	2.71	0.49
2.5%	3.3	2.83	0.47
5%	4	3.76	0.24
7.5%	4.2	3.64	0.56

4.7 Representation of Laboratory and Theoretical Average (28 Days)

For fig 4.18 the highest value was recorded for 7.5% replacement of coarse aggregate by plastic aggregate for laboratory testing of split tensile strength value for 28 days. The minimum value was observed for normal concrete in laboratory testing.

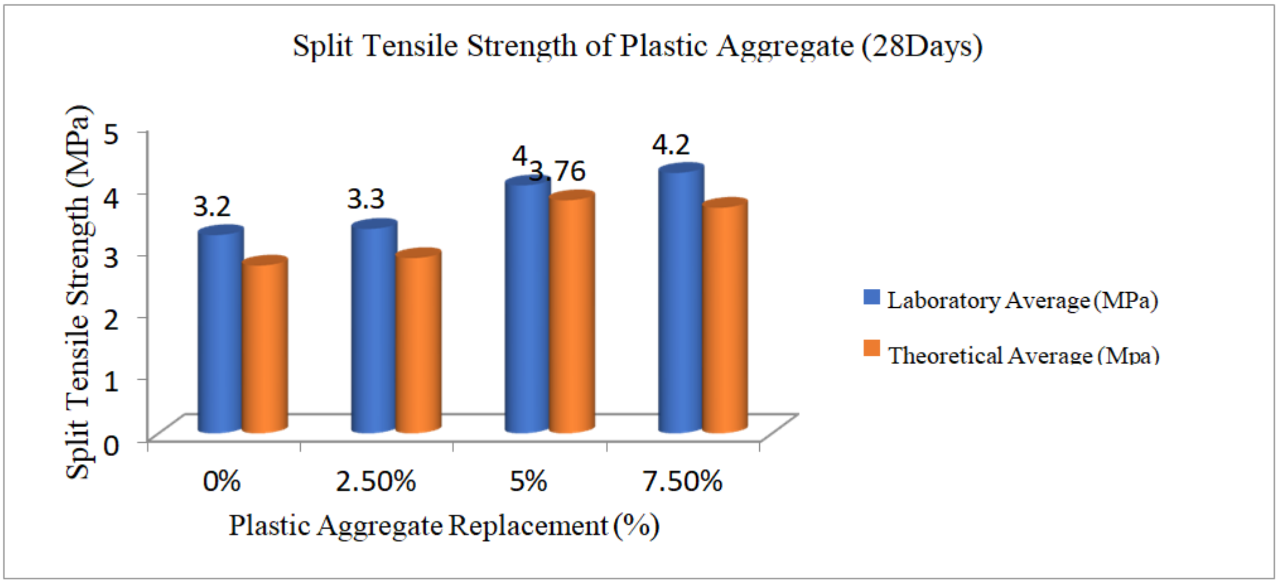

Figure 4.2: Graph of Tensile Strength 28 Days vs.% Replacement of Plastic Aggregate

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V. CONCLUSION

- The partial replacement of EAFS with cement and coarse aggregate with plastic waste was done with a different ratio of 10%, 20%, 30%, and 40% by weight of cement and 2.5%, 5%, and 7.5% by weight of coarse aggregate respectively.
- For laboratory testing and research paper, the compressive strength value increased up to 30% replacement of cement by EAFS for 7 days. There is an increment of 19.1% of compressive strength value for 7 days up to 30% replacement of cement by EAFS compared to unmodified concrete in laboratory testing. This may be due to adding admixtures to concrete to boost its compressive strength. The maximum compressive strength was found for 30% replacement of cement by EAFS for 28 days in the laboratory. In the research paper, when the percentage of slag replaced is increased, the compressive strength for 28 days decreases. For unmodified concrete, the optimal value was obtained.
- The flexural strength of concrete (M40) was found optimum for 20% replacement of cement in the lab for 7, 14, and 28 days in the laboratory but in a research paper, the best replacement was found for 40%.
- In laboratory testing for 7 days, the optimal value of tensile strength was discovered for 10% and 40% slag replacement, but in the research report, the ideal value was only identified for 40% slag replacement. The form, size, and surface roughness of steel slag aggregate may have contributed to the increase in strength.
- The compressive strength of plastic replaced aggregate was found optimum for 2.5% replacement in the laboratory whereas in the research paper the maximum strength was for 5% replacement of coarse aggregate.
- The optimal value for flexure strength for 7days was found for 2.5% replacement of coarse aggregate by plastic waste in laboratory testing and in the research paper. There is an increment of 17.14% of flexure strength value for 7 days up to 5% replacement compared to unmodified concrete. It shows a linear variation in flexure strength value and percentage replacement of coarse aggregate by plastic waste up to 5% replacement of plastic waste. The highest value for flexure strength value for 14 days was recorded for unmodified concrete. The decrease in flexure strength value for an increase in percentage replacement of plastic waste may be due to weak bonding between cement and both natural aggregate and plastic aggregate. The optimal value for flexure strength for 28 days was found for 5% and 7.5% replacement of coarse aggregate by plastic waste in laboratory testing.
- The split tensile strength was found at an efficient 5% replacement for 7, 14, and 28 days.
- The use of waste plastic materials as aggregates in concrete is a viable option for addressing the challenges associated with the safe disposal of an increasing volume of waste plastic materials.
- It saves a lot of energy and reduces the use of natural resources to make new products by using discarded materials. The reason for the variation in optimal values for different mixes is due to the cement-aggregate bonding. Both coarse and plastic particles attach to cement, although the bond strength varies. The bond strength of concrete is also affected by the water-cement ratio, aggregate size, and cement grade. As these parameters change, differences in the findings occur. A strong bond of the given nature is indicated by an increase in strength, while a weak tie is shown by a reduction in strength.

5.1 Scope of Work

This research explores the sustainable development of rigid pavements through the partial replacement of conventional materials with Electric Arc Furnace Slag (EAFS) and plastic waste. The study involves material testing of cement, fine and coarse aggregates, EAFS, and plastic waste to evaluate properties like specific gravity, setting time, water absorption, and fineness. M40 grade concrete was designed using IS and IRC codes, replacing cement with EAFS in proportions of 10% to 40% and coarse aggregates with plastic waste at 2.5%, 5%, and 7.5%. Specimens were tested for compressive, flexural, and split tensile strength at 7, 14, and 28 days. Results were analyzed and compared with existing literature to determine optimal replacement levels for improved performance. The scope includes validating waste materials for structural use, reducing environmental impact, and developing practical recommendations for incorporating industrial by-products and plastic waste in pavement construction, promoting sustainability and resource efficiency in the civil engineering sector.

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