International Journal of Scientific Research and Engineering Development-– Volume 8 Issue 6, Nov-Dec 2025
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Performance Evaluation of Concrete Incorporating Steel Slag and Paper Sludge as Sustainable Construction Materials

Kamal Kant Katwal*, Nitisha Sharma**,
*(Department of Civil Engineering, Rayat Bahra University, Mohali (P.B.), India,
Email: katwal10124@gmail.com)
**(Department of Civil Engineering, Rayat Bahra University, Mohali (P.B.), India,
Email: nitisha.20384@rayatbahrauniversity.edu.in)

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Abstract:

Rapid industrial growth and urbanization have significantly increased the generation of industrial solid waste, creating serious environmental challenges, particularly in India. At the same time, the construction industry relies heavily on cement and natural aggregates, leading to high energy consumption and carbon dioxide emissions. To address these concerns, this study explores the use of waste iron slag as a partial replacement for natural fine aggregate and paper sludge (hypo sludge) as a partial replacement for cement in M25 grade concrete.

Concrete mixes with varying replacement levels were prepared and evaluated for key mechanical properties, including compressive strength, split tensile strength, and flexural strength, which are critical for rigid pavement and highway applications. The use of iron slag is intended to improve inter-particle bonding and abrasion resistance, while paper sludge contributes to reduced cement consumption and lower environmental impact. The results demonstrate that controlled incorporation of these waste materials can produce structurally viable concrete while promoting sustainable construction practices through resource conservation and waste utilization.

Keywords — **Sustainable Concrete, Steel Slag, Paper Sludge, Industrial Solid Waste Utilization.**

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I. INTRODUCTION

The construction industry is widely recognized as a major consumer of natural resources and a significant contributor to environmental pollution. Extensive use of cement and natural sand in concrete not only accelerates the depletion of non-renewable resources but also increases carbon emissions and ecological degradation. In recent years, growing awareness of sustainability has encouraged the use of industrial waste materials as partial replacements for conventional concrete constituents, offering both environmental and economic benefits.

Steel slag, a by-product of the steel manufacturing process, and paper sludge, generated from paper industries, are produced in large quantities and often disposed of in landfills, causing serious environmental concerns. Steel slag exhibits high density, angularity, and mechanical strength, which makes it suitable for partial replacement of fine aggregate. Paper sludge, when finely processed, can act as a supplementary cementitious or filler material; however, its influence on concrete performance depends largely on the percentage of replacement used.

In this study, an experimental investigation was carried out to evaluate the combined effect of steel slag and paper sludge on the strength characteristics of M25 grade concrete. Steel slag was used as a partial replacement for natural sand at a fixed level of 40%, while paper sludge was introduced as a partial replacement for cement at varying proportions of 0%, 5%, 10%, 15%, and 20%. Control concrete without any replacement was also prepared for comparison. The concrete specimens were tested at curing periods of 7 and 28 days to assess compressive strength, split tensile strength, and flexural strength.

The investigation was aimed at identifying an optimum replacement combination that enhances concrete performance while maintaining workability. The results demonstrate that the incorporation of steel slag improves the concrete microstructure and early strength, whereas paper sludge contributes positively up to a limited replacement level. Beyond the optimum percentage, a reduction in strength is observed due to weaker bonding and increased water demand. The study highlights the feasibility of using steel slag and paper sludge in concrete as sustainable alternatives to conventional materials.

II. METHODS

A. *OBJECTIVES OF STUDY*

- To explore the utilization of paper sludge as a supplementary cementitious material and to study its influence on the strength characteristics of concrete, along with examining the feasibility of using steel slag as an alternative to natural fine aggregate in concrete.
- To design and develop sustainable concrete mixes by partially replacing cement with paper sludge and fine aggregate with steel slag.
- To analyse the effect of different proportions of paper sludge and steel slag on the mechanical properties of concrete, such as compressive strength, split tensile strength, and flexural strength.
- To evaluate the overall performance of concrete incorporating steel slag and paper sludge in comparison with conventional concrete.
- To identify the optimum replacement levels of steel slag and paper sludge that result in acceptable strength and performance.
- To assess the potential environmental and economic benefits of using steel slag and paper sludge as sustainable construction materials.

B. *Material & Experimental Studies*

i. *Cement*

Ordinary Portland Cement of 43 grade was used as the primary binding material. The cement was fresh, free from lumps, and complied with IS: 8112-1989. Tests on consistency, setting time, fineness, soundness, specific gravity, and compressive strength confirmed its suitability for concrete production.

TABLE I
PHYSICAL PROPERTIES OF OPC-43 ACC CEMENT

S.No.	Characteristics	Values Obtained	Standard Values
1	Normal consistency	30.5%	-
2	Initial setting time (minutes)	124 minutes	Not less than 30
3	Final setting time (minutes)	256 minutes	Not greater than 600
4	Fineness (%)	2.6%	<10
5	Specific gravity	3.15	
6	Compressive strength (N/mm²) 3 days 7 days 28 days	23.3 34.10 46.40	>23 >33 >43
7	Soundness (mm)	1.5	10

ii. *Fine Aggregates*

Locally available river sand conforming to IS: 383-1970 (Zone-II) was used as fine aggregate. The material was oven-dried and subjected to sieve analysis to determine grading and fineness modulus. Physical properties such as specific gravity and grading characteristics satisfied codal requirements.

TABLE II
PHYSICAL PROPERTIES OF FINE AGGREGATE

S. No.	Characteristics	Value
1.	Specific gravity	2.60
3.	Fineness modulus	2.615
4.	Grading Zone	Zone-II

TABLE III
PHYSICAL PROPERTIES OF FINE AGGREGATE AT 40% REPLACEMENT

S. No.	Characteristics	Value
1.	Specific gravity	2.72
3.	Fineness modulus	2.898
4.	Grading Zone	Zone-II

iii. *Coarse Aggregate*

Crushed stone aggregates of nominal sizes 20 mm and 10 mm were used. The aggregates were tested for sieve analysis, specific gravity, water absorption, and moisture content as per IS: 2386. A combined grading ratio of 3:1 ensured proper particle distribution and packing density.

TABLE IV
PHYSICAL PROPERTIES OF COARSE AGGREGATE

S. No	Characteristics	Experimental value
1.	Specific gravity	2.65
2.	Water absorption	0.6
3.	moisture content	0.65%

iv. Water

Clean potable water free from harmful impurities was used for mixing and curing concrete. The water complied with IS: 456 requirements and supported proper hydration of cementitious materials. A controlled water–binder ratio was maintained to achieve desired workability, strength development, and durability performance.

v. Paper Sludge

Paper sludge, particularly hypo sludge, is an industrial by-product rich in calcium oxide. Due to high moisture content and poor workability in raw form, treated or incinerated paper sludge ash is preferred. Its controlled use as partial cement replacement contributes to waste utilization and sustainability.

Fig. 1. Sample of paper sludge (Hypo sludge)

TABLE V
PROPERTIES OF RAW HYPO SLUDGE

Sr.No.	Constituents	Cement Content (%)	Hypo sludge Contents (%)
1.	Lime (CaO)	62	46.2
2.	Silica (SiO2)	22	9
3.	Alumina (Al2O3)	5	3.6
4.	Magnesium (MgO)	1	3.33
5.	Calcium Sulphate	4	4.05

vi. STEEL SLAG

Steel slag is a non-metallic by-product generated during steelmaking processes such as BOF and EAF. Composed mainly of calcium silicates and metal oxides, it exhibits high density and angularity. After proper aging and stabilization, steel slag can be effectively used as aggregate in concrete.

Fig. 2. Sample of Steel Slag

TABLE VI
PHYSICAL PROPERTIES OF STEEL SLAG

Sr.No.	Constituents	Composition (%)
1.	Colour	Light to dark brown
2.	Shape	Highly angular
3.	Bulk density	1911.11 kg/m3
4.	Combustibility	Non-combustible
5.	Surface Texture	Rough
6.	Specific gravity	2.93

III. DESCRIPTION OF PROCESSES AND METHODOLOGIES

The study followed an experimental approach with the following key steps:

A. Concrete Mix Design:

The concrete mix design was developed in a systematic and phased manner to investigate the feasibility of utilizing steel slag and paper sludge as partial replacement materials in concrete. A reference control mix (M-S0) was prepared using ordinary Portland cement, natural fine aggregate, coarse aggregate, potable water, and a constant dosage of superplasticizer. This mix served as the benchmark for evaluating the performance of modified concrete mixes.

In the first phase of the experimental program, steel slag was used as a partial replacement of natural fine aggregate at replacement levels of 10%, 20%, 30%, 40%, and 50% by weight, corresponding to mixes M-S1 to M-S5. During this phase, the cement content, coarse aggregate content, water–binder ratio, and plasticizer dosage were kept constant to isolate the effect of steel slag incorporation. The reduction in natural sand was balanced by an equivalent increase in steel slag content to maintain overall aggregate volume consistency.

Based on the observed performance, 40% steel slag replacement was identified as the optimum level. In the second phase, this optimum steel slag content was kept constant, and cement was partially replaced with paper sludge at levels of 5%, 10%, 15%, and 20% by weight, represented by mixes M-S6 to M-S9. The cement quantity was reduced proportionally with increasing paper sludge content, while the total binder content, coarse aggregate, water content, and admixture dosage were maintained constant. This approach ensured uniform workability and enabled a clear evaluation of the combined effects of steel slag and paper sludge on the mechanical and durability properties of concrete.

TABLE VII
QUANTITY OF MATERIALS REQUIRED

S. No.	Mix	Steel slag (%)	Paper sludge (%)	Cement (kg)	Sand (kg)	Coarse Aggregate (kg)	Steel slag (kg)	Paper sludge (gm)	Water (kg)	Plasticizer (gm)
1	M-S0	0	0	7.695	13.77	23.93	0	0	3.46	77
2	M-S1	10	0	7.695	12.39	23.93	1.38	0	3.46	77
3	M-S2	20	0	7.695	11.01	23.93	2.76	0	3.46	77
4	M-S3	30	0	7.695	9.63	23.93	4.14	0	3.46	77
5	M-S4	40	0	7.695	8.26	23.93	5.51	0	3.46	77
6	M-S5	50	0	7.695	6.89	23.93	6.88	0	3.46	77
7	M-S6	40	5	7.310	8.26	23.93	5.51	385	3.46	77
8	M-S7	40	10	6.925	8.26	23.93	5.51	770	3.46	77
9	M-S8	40	15	6.540	8.26	23.93	5.51	1155	3.46	77
10	M-S9	40	20	6.156	8.26	23.93	5.51	1539	3.46	77

B. Workability by slump test:

The workability of fresh concrete mixes was assessed by performing the slump test and compaction factor test in accordance with the procedures specified in IS: 1199–1959. For the slump test, the slump cone was thoroughly cleaned and placed on a smooth, level, and non-absorbent surface. The cone was filled with fresh concrete in four equal layers, each layer being compacted by 25 blows using the rounded end of a 16 mm diameter tamping rod, with the blows uniformly distributed over the cross-section.

After the top layer was compacted, the excess concrete was struck off level with the top of the mould using a trowel. The mould was then lifted vertically upwards in a steady manner without any lateral or rotational movement. The slump was measured immediately as the difference between the height of the mould and the height of the highest point of the subsided concrete.

C. Casting and Curing of Specimens:

The concrete constituents were proportioned by weight and mixed in a mechanical mixer in accordance with the procedures prescribed in IS 516:1959. Initially, cement, fine aggregate, steel slag, and paper sludge were dry mixed to obtain a uniform and homogeneous blend free from segregation or lumps. Subsequently, the required quantity of coarse aggregate was added and mixing was continued until a consistent and workable concrete mix was achieved.

Cube specimens were cast for the determination of compressive strength as per IS 516:1959, while cylindrical specimens were prepared for split tensile strength testing in accordance with IS 5816:1999. Beam specimens were also cast for flexural strength evaluation as specified in IS 516. After casting, the specimens were stored in the moulds under moist conditions and de-moulded after 24 hours. The specimens were then cured by immersion in clean water at room temperature for curing periods of 7 and 28 days prior to testing.

D. Testing Of Specimens

i. Compressive Strength Test

The compressive strength test was conducted on concrete cube specimens in accordance with IS 516:1959 to evaluate the strength development of mixes incorporating steel slag and paper sludge as partial replacements of fine aggregate and cement, respectively. Cube specimens of size 150 × 150 × 150 mm were removed from the curing tank after 7 and 28 days of moist curing, surface moisture and adhering particles were wiped off, and the specimens were placed centrally in a compression testing machine of 200-tonne capacity. The cubes were positioned such that the load was applied on faces perpendicular to the casting direction, with the axes of the specimens aligned with the centre of thrust of the spherically seated platen. The load was applied without shock and increased continuously at a uniform rate of 14 N/mm² per minute until failure occurred. The maximum load carried by each specimen was recorded, and the compressive strength was calculated as the ratio of the maximum load to the loaded cross-sectional area. The average of three specimens was reported as the compressive strength of each concrete mix.

ii. Flexural Strength Test

The flexural strength of concrete was determined to assess the tensile behaviour of concrete under bending, which is critical for evaluating crack resistance and structural durability. The flexural strength test was conducted on prism specimens in accordance with IS 516:1959 for all concrete mixes at curing ages of 7 and 28 days. Beam specimens of size 500 × 100 × 100 mm were removed from the curing tank, and their bearing surfaces were cleaned to ensure proper contact with the supporting and loading rollers. The specimens were placed in the flexural testing machine such that the load was applied on the top surface as cast, under two-point loading with rollers spaced 13.3 cm apart. The longitudinal axis of each specimen was carefully aligned with the axis of loading, and no packing material was used between the specimen and the rollers. The load was applied gradually without shock and increased continuously at a rate corresponding to an extreme fibre stress of approximately 7 kg/cm² per minute (about 180 kg/min) until failure occurred. The maximum load sustained by the specimen was recorded, and the flexural strength was calculated using the provisions specified in IS 516:1959.

iii. Split Tensile Strength Test

The split tensile strength of concrete was determined in accordance with the provisions of IS 516:1959 to evaluate the tensile behaviour of concrete indirectly. Cylindrical specimens of size 150 mm diameter and 300 mm height were removed from the curing tank after 7 and 28 days of water curing, and surface moisture was wiped off prior to testing. The specimens were placed horizontally in a compression testing machine of 200-tonne capacity such that the load was applied along the vertical diameter, perpendicular to the direction of casting. The axes of the specimens were carefully aligned with the centre of thrust of the spherically seated plates to ensure uniform stress distribution. The load was applied gradually and without shock at a constant rate of 2.4 N/mm² per minute until failure occurred. The maximum load at failure was recorded, and the corresponding split tensile strength was calculated as per IS 516:1959.

IV. RESULT AND DISCUSSION

A. Workability Test Result

The slump test results indicate a progressive reduction in workability with increasing replacement levels of steel slag and paper sludge in the concrete mixes. The control mix (M-S0) and mix M-S1 exhibited the highest slump value of 80 mm, indicating good workability at lower replacement levels. As the steel slag content increased up to 40% and 50% (M-S4 and M-S5), the slump gradually decreased to 70 mm and 65 mm, respectively, which can be attributed to the angular shape and rough surface texture of steel slag increasing internal friction. With the incorporation of paper sludge at 5–10% cement replacement (M-S6 and M-S7), the slump remained constant at 65 mm, suggesting that the use of a plasticizer helped maintain workable consistency. However, at higher paper sludge contents of 15% and 20% (M-S8 and M-S9), the slump further reduced to 60 mm and 55 mm, respectively, due to the higher water absorption and finer nature of paper sludge, which increased water demand and reduced workability.

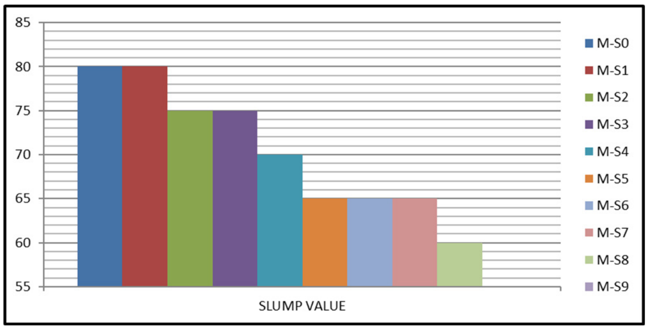

Fig. 3. Slump Value of All Designed Mix

B. Compressive Strength Test result

The experimental results indicate that at 7 days of curing, concrete with 40% replacement of sand and no cement replacement exhibited a reduction in compressive strength of 8.43% compared to the control mix. However, the inclusion of paper sludge as partial cement replacement improved early-age strength, with increases of 10.02% and 17.58% observed at 5% and 10% cement replacement, respectively, for a constant 40% sand replacement. Beyond this optimum level, a decline in strength was noted, with gains reducing to 9.20% at 15% cement replacement and becoming marginal (0.92%) at 20% replacement. At 28 days of curing, concrete containing 40% sand replacement without cement substitution showed a modest strength increase of 3.80%. Further enhancement in compressive strength was achieved with 5% and 10% cement replacement, yielding increases of 5.15% and a maximum of 8.65%, respectively. However, higher levels of cement replacement led to a reduction in strength, with only a 2.70% gain at 15% replacement and an overall decrease of 1.99% at 20% cement replacement.

TABLE VIII
COMPRESSIVE STRENGTH AFTER 7 DAYS AND 28 DAYS

S. No	Mix Design	Average Compressive Strength after 7 days	Average Compressive Strength after 28 days
1	M-S0	19.45	32.60
2	M-S4	17.81	33.84
3	M-S6	21.40	34.28
4	M-S7	22.87	35.42
5	M-S8	21.24	33.48
6	M-S9	19.63	31.95

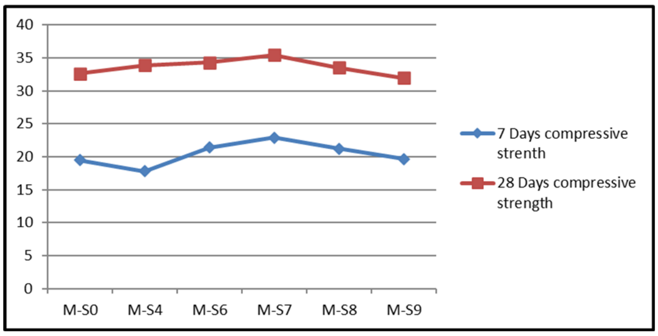

Fig. 4. Comparison between Compressive Strength of 7 and 28 days

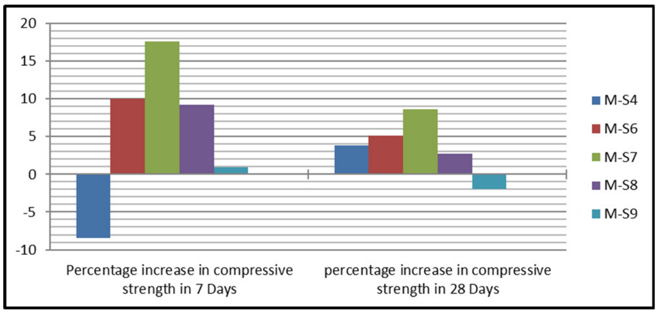

Fig. 5. Percentage Change in Compressive Strength

C. flexural Strength Test result

The flexural strength results demonstrate a clear influence of combined sand and cement replacement levels at both curing ages. At 7 days, concrete with 40% sand replacement and no cement replacement exhibited an increase in flexural strength of 4.60% compared to the control mix. Further enhancement was observed with the incorporation of paper sludge as partial cement replacement, achieving increases of 10.04% and a maximum of 12.13% at 5% and 10% cement replacement, respectively, while maintaining 40% sand replacement. Beyond this optimum level, the flexural strength showed a declining trend, with a reduction of 2.93% at 15% cement replacement and a pronounced decrease of 12.55% at 20% replacement. At 28 days of curing, a marginal increase of 2.42% was recorded for concrete with 40% sand replacement and no cement replacement. The flexural strength improved further to 6.45% and reached a maximum increase of 8.60% at 5% and 10% cement replacement, respectively. However, higher cement replacement levels resulted in reduced performance, with only a 2.15% gain at 15% replacement and an overall reduction of 2.15% at 20% cement replacement.

TABLE IX
FLEXURAL STRENGTH AFTER 7 DAYS AND 28 DAYS

S. No	Mix Design	Average Flexural Strength 7 days	Average Flexural Strength 28 days
1	M-S0	2.39	3.72
2	M-S4	2.50	3.81
3	M-S6	2.63	3.96
4	M-S7	2.68	4.04
5	M-S8	2.32	3.80
6	M-S9	2.09	3.64

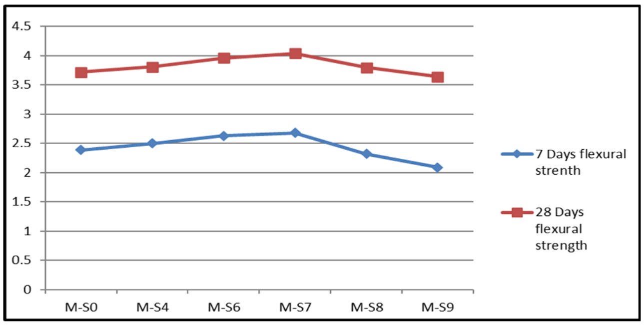

Fig. 6. Comparison between 7 and 28 days Flexural Strength

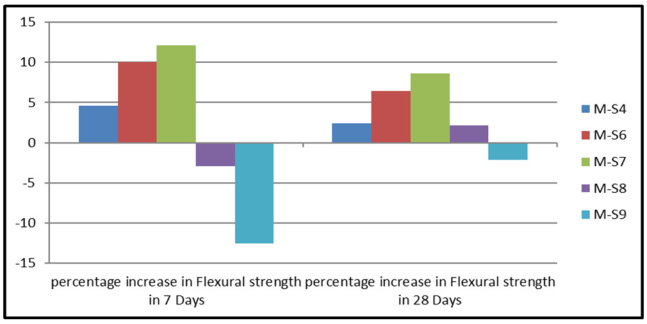

Fig. 7. Percentage Change in Flexural Strength

D. Split Tensile Strength Test

The split tensile strength results indicate a varied response of concrete to the combined replacement of sand and cement at different curing ages. At 7 days, concrete with 40% sand replacement and no cement replacement exhibited a slight increase in split tensile strength of 2.75% compared to the control mix. However, with the introduction of paper sludge as partial cement replacement, the split tensile strength decreased by 1.10% at 5% replacement and remained nearly unchanged at 10% replacement. A significant reduction in tensile strength was observed at higher replacement levels, with decreases of 12.64% and 26.37% recorded at 15% and 20% cement replacement, respectively. In contrast, at 28 days of curing, concrete containing 40% sand replacement and no cement substitution showed a noticeable increase in split tensile strength of 4.95%. Further improvement was achieved with 5% and 10% cement replacement, resulting in strength increases of 6.59% and a maximum of 7.14%, respectively. Beyond this optimum range, the split tensile strength declined, with a reduction of 2.20% at 15% cement replacement and a substantial decrease of 21.43% at 20% replacement.

TABLE X
SPLIT TENSILE STRENGTH AFTER 7 DAYS AND 28 DAYS

S. No	Mix Design	Average Split Tensile Strength 7 days	Average Split Tensile Strength 28 days
1	M-S0	1.82	3.28
2	M-S4	1.87	3.37
3	M-S6	1.84	3.40
4	M-S7	1.84	3.41
5	M-S8	1.59	3.24
6	M-S9	1.34	3.64

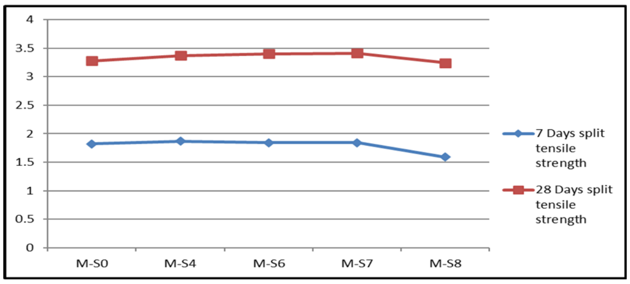

Fig. 8. Comparison between 7 and 28 days Split Tensile Strength

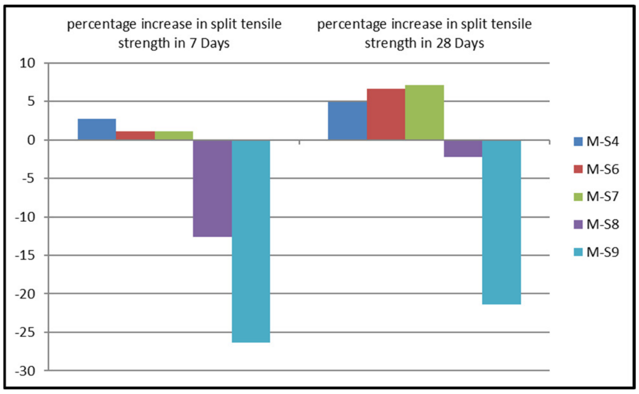

Fig. 9. Percentage Change in Split Tensile Strength

V. CONCLUSION AND RECOMMENDATION

The construction industry is a major contributor to environmental degradation due to the extensive consumption of non-renewable natural resources and the generation of ecological pollution. The reuse of industrial wastes has emerged as a viable solution for environmental protection and the development of cost-effective and sustainable construction materials. In the present investigation, the influence of steel slag and paper sludge as partial replacements of sand and cement, respectively, was examined at different replacement levels, namely 0%, 40% sand with 0% cement, 40% sand with 5% cement, 40% sand with 10% cement, 40% sand with 15% cement, and 40% sand with 20% cement. The performance of these concrete mixes was evaluated through compressive strength, split tensile strength, and flexural strength tests at curing ages of 7 and 28 days. The results obtained were compared with the control mix to assess the effect of incorporating steel slag and paper sludge on the mechanical strength characteristics of concrete.

A. Conclusions

Based on the results obtained from the present experimental investigation, the following conclusions are drawn:

- Partial replacement of fine aggregate with steel slag improved the concrete microstructure and enhanced strength properties up to an optimum replacement level, beyond which strength started to decline.
- Replacement of fine aggregate with steel slag showed an increase in early-age strength up to about 20%, after which a reduction in strength was observed with further increase in steel slag content.
- A replacement level of 40% fine aggregate with steel slag produced compressive strength comparable to or slightly higher than conventional M25 concrete and was therefore adopted for further investigations.
- At 40% steel slag replacement, the incorporation of paper sludge as partial cement replacement resulted in improved compressive, split tensile, and flexural strengths up to an optimum level of 10% cement replacement, compared to mixes with 0%, 5%, 15%, and 20% paper sludge.
- The maximum compressive strength was achieved at 40% steel slag and 10% paper sludge replacement; further increase in paper sludge content beyond 10% led to a reduction in strength due to weaker bonding within the concrete matrix.
- Flexural and split tensile strengths also followed a similar trend, with peak values recorded at 10% paper sludge replacement, followed by a noticeable decline at higher replacement levels.
- Early-age strength development was enhanced in mixes containing steel slag and paper sludge, with the highest 7-day to 28-day strength gain observed for concrete incorporating 40% steel slag and 10% paper sludge.
- Workability decreased progressively with increasing steel slag content due to its angular shape and rough surface texture, and further reduced with higher paper sludge replacement owing to its finer nature and higher water absorption, despite the use of a plasticizer.
- Cement replacement with paper sludge up to 10% did not adversely affect concrete performance; however, higher replacement levels resulted in increased water demand and a reduction in mechanical strength properties.

B. Limitations

The following limitations were identified during the present experimental investigation:

- Steel slag was obtained in large, boulder-like form, requiring crushing and processing into suitable aggregate sizes, which may increase energy consumption and processing effort.
- Paper sludge contains high moisture content and requires adequate drying or thermal treatment prior to use, which may be time-consuming and may involve additional processing requirements.
- The incorporation of steel slag and paper sludge increased water demand, thereby necessitating the use of chemical admixtures to maintain acceptable workability.
- The chemical composition of paper sludge may vary depending on the source and manufacturing process of the paper industry, which can influence concrete performance and limits the development of a universally applicable mix design.
- The improvement in flexural and split tensile strength was limited compared to compressive strength, indicating that further optimization and long-term studies are required before application in higher structural performance requirements.

C. Recommendation & Future Scope

Based on the conclusions drawn from the experimental investigation, it is recommended that steel slag can be safely used as a partial replacement of fine aggregate up to 40% without adversely affecting the mechanical performance of concrete. At this replacement level, the concrete exhibited comparable or improved compressive strength relative to conventional M25 concrete. Further, the incorporation of paper sludge as a partial replacement of cement up to an optimum level of 10% is recommended, as it resulted in enhanced compressive, flexural, and split tensile strengths. Replacement levels beyond 10% are not recommended due to the observed reduction in strength and workability.

For future research, detailed studies on durability-related properties such as water absorption, permeability, sulphate resistance, and chloride penetration are recommended to assess long-term performance. Further investigations may also focus on microstructural analysis to understand the bonding and hydration mechanisms in steel slag–paper sludge concrete. Optimization of admixture dosage to improve workability at higher replacement levels, evaluation of long-term strength development, and field-scale performance studies are also suggested before large-scale practical implementation.

ACKNOWLEDGMENT

My sincere gratitude to Dr Nitisha Sharma: Analysed and interpreted the data related to the study on "the replacement of fine aggregate with steel slag and the replacement of cement with paper sludge". He critically examined previous data in this field, provided substantial input in shaping the manuscript, and played a key role in writing and refining the review paper. His expertise was instrumental in ensuring the accuracy and depth of the analysis.

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