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Research Article

Wastewater Sludge

Performance Assessment of Concrete Using Paper and Wastewater Sludge to Replace Part of the Cement

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Along with deforestation and the use of fossil fuels, the cement manufacturing sector contributes significantly to carbon dioxide (CO_2) emissions. Additionally, the concrete industry is one of the major consumers of natural raw resources, which has an impact on environmental sustainability. In order to tackle these issues, this study examines the effects of partially substituting paper mill and wastewater sludge for cement in weight percentages of 5%, 10%, and 15% on the compressive, split tensile, and flexural strengths of concrete at 7 and 28 days of curing. According to experimental data, the 5% replacement mix showed better mechanical qualities than the control mix (0% replacement), suggesting that it could be a sustainable option in the manufacturing of concrete, even though higher replacement levels resulted in a decrease in strength. Strength was shown to decrease after 5%, underscoring the drawbacks of adding too much sludge. The viability of using industrial by-products in concrete to lessen reliance on cement and CO_2 emissions while preserving structural integrity is clarified by this study. By encouraging the use of waste materials in cement-based composites, the findings support the continuous efforts towards sustainable construction methods.

Keywords: cement partial replacement, paper mill sludge, wastewater sludge, compressive strength, split tensile strength, co2 emissions, workability, absorbed water

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1. Introduction

Concrete's strength, durability, and adaptability make it one of the most popular building materials in the world. However, there is a substantial environmental impact associated with its manufacture, especially the manufacturing of cement. About 7% of the world's carbon dioxide (CO_2) emissions come from the manufacturing of cement, mostly from the energy-intensive process of heating limestone to create clinker, the main component of cement [1]. Environmental deterioration is made worse by the concrete industry's heavy reliance on natural resources such aggregates, clay, and limestone, in addition to the environmental costs of producing cement [2]. As a result, there is an increasing need for substitute materials and techniques that might lessen concrete's impact on the environment and its dependency on limited natural resources.

The partial substitution of industrial by-products, particularly wastewater and paper mill sludge, for cement is one of the most promising strategies to address these issues [5] [6] [7] [8] [10]. Usually considered waste, these materials offer a chance to solve two important problems: lowering the carbon footprint of cement production and offering a sustainable waste management solution. In addition to lessening the environmental impact of cement, using these components in the manufacturing of concrete can help keep a lot of debris out of landfills.

1.1 Paper Mill Sludge

Paper mill sludge is a byproduct that occurs during the paper making process. It is created by turning wood pulp into paper using fibres, chemicals, and water. Cellulose fibres, minerals like silica, and occasionally even residues of heavy metals are among the organic and inorganic elements found in the sludge [3]. Paper mill sludge is typically disposed of by landfilling or cremation, but growing environmental pollution concerns have prompted academics to look into its potential as a cement substitute [4].

The silica content of paper mill sludge is a major factor in its consideration for use in concrete. Because of its well-known pozzolanic qualities, silica in concrete combines with calcium hydroxide to produce more calcium silicate hydrate (C-S-H), a substance that increases the concrete's strength and longevity [5]. By doing this, concrete's durability and compressive strength can be increased, increasing its resistance against deterioration and cracking over time. Additionally, by reducing the demand for raw materials and the carbon emissions linked to the cement industry, employing paper mill sludge as a partial substitute for cement helps to lessen the environmental effect of cement manufacturing.

1.2 Wastewater Sludge

When sewage and industrial effluents are treated, wastewater sludge is created as a byproduct. This sludge is made up of different minerals, organic stuff, and nutrients like nitrogen and phosphorus. Like sludge from paper mills, wastewater sludge is frequently considered a waste product and is either burned or dumped in landfills [9]. Recent studies, however, have shown that wastewater sludge possesses significant concentrations of lime and other important minerals that, when added to concrete, may give it pozzolanic qualities [10].

Wastewater sludge can help improve the mechanical qualities of concrete, especially its compressive and tensile strengths, when it is used to partially replace cement [11]. Wastewater sludge's lime component helps improve the cement paste-aggregate connection, making concrete stronger and longer-lasting [11]. Furthermore, by incorporating wastewater sludge into concrete, less sludge will need to be disposed of, providing an environmentally friendly waste management solution and solving sustainability issues facing the cement sector.

1.3 Importance

The huge energy usage and carbon emissions of the cement sector pose serious obstacles to international sustainability initiatives [12]. In this regard, lowering the environmental effect of the building sector depends on identifying substitute materials for cement that preserve or even improve the performance of concrete. Two such options are wastewater sludge and paper mill sludge, both of which have the extra advantages of resource conservation and waste reduction.

Using industrial by-products like wastewater and paper mill sludge in place of cement can assist accomplish a number of significant environmental objectives [5] [9]. First of all, it lowers CO_2 emissions linked to the manufacturing of cement.

Utilising trash also reduces the need for raw materials like limestone, which lessens the need to remove natural resources and the resulting negative effects on the environment. Second, adding these waste elements to concrete aids in recycling and waste management by keeping a significant amount of industrial waste out of landfills [13]. From a performance standpoint, using these sludges in place of cement could improve concrete's strength, sustainability, and longevity [14]. Paper mill and wastewater sludge's chemical makeup can strengthen concrete's bonding qualities and lessen its vulnerability to cracking, guaranteeing that the material is sturdy and long-lasting [11] [15]. Additionally, the building sector may profit financially from the possible cost-effectiveness of partially substituting waste materials for Cement [16].

This study investigates the effects of replacing cement with paper mill sludge and wastewater sludge at varying percentages (5%, 10%, and 15% by weight) on the compressive strength, split tensile strength, and flexural strength of concrete after 7 and 28 days of curing. The goal is to assess the feasibility of these waste materials as sustainable cement replacements and contribute to ongoing efforts to make concrete production more environmentally friendly.

2. Materials Methods and Mix Design

The choice of ingredients, mix ratios, and testing procedures all have a big impact on the quality and functionality of concrete. Understanding the physical and chemical characteristics of alternative materials, such as wastewater and paper mill sludge, as well as how they affect the mechanical behaviour of concrete, is essential for using them as partial cement substitutes. This section explains the study's components, their properties, and the technique used to assess how cement replacement affected the concrete's flexural, split tensile, and compressive strengths.

2.1 Materials

2.1.1 Cement

Cement is a fine grey powder that, when mixed with water and materials such as sand or pozzolans, forms mortar and concrete.

The mixture of cement and water creates a paste that binds other materials together. In this study, ordinary Portland cement of 53 grade, conforming to IS: 12269-1987 [20], was used.

Table 1: Experimental Values of Cement

PHYSICIAL PROPORTIES OF GRADE OF CEMENT	RESULTS	REQUIREMENT AS PER IS:8112-1989
Specific gravity	3.15	3.10-3.15
Consistency	32.1	30-35
Initial setting time	90 min	Minimum 30 min
Final setting time	245 min	Maximum 600 min
Fineness of cement	4%	Less than 10%

2.1.2 Aggregates

Aggregates are essential components of concrete, providing body, reducing shrinkage, and contributing to the economy of the mix. Proper gradation of aggregates ensures minimal voids, requiring less paste to fill these voids, which leads to increased strength, reduced shrinkage, and greater durability.

Fine Aggregate:

The fine aggregate used was river sand conforming to Zone-II as per IS: 383-1970 [21]. The sand was washed and screened to eliminate deleterious materials and oversized particles. Sieve analysis and physical property evaluation of the fine aggregate were conducted, with the following results:

Table 2: Experimental Values of Fine Aggregate Properties

PHYSICAL PROPERTIES	TEST RESULTS
Specific gravity	2.6
Fineness modulus	2.6
Bulk density	1605 kg/m3
Water absorption	0.5%

Coarse Aggregate:

Coarse aggregates from a local crushing unit, with a nominal size of 20 mm, were used. These aggregates conform to IS: 383-1970 [21]. The material was sieved through various sieves (20 mm, 16 mm, 12.5 mm, 10 mm, and 4.75 mm) to obtain well-graded aggregates. The physical properties and gradation of coarse aggregates were evaluated, confirming to IS: 2386 (Part 1) – 1963 [23].

Table 3: Experimental Values of Coarse Aggregate Properties

PHYSICAL PROPERTIES	TEST RESULTS
Specific gravity	2.8
Fineness modulus	7.11
Water absorption	0.13%
Bulk Density	1700 kg/m3

2.1.3 Water

The water used for mixing concrete was potable, with a pH value between 6 and 8. It was free from organic matter and solid contents within permissible limits as per IS: 456-2000 [22] and conformed to IS: 3025-1964 [26].

2.1.4 Additional Materials

Sludge from a paper mill in Bhimavaram, Andhra Pradesh, was gathered. This waste product, which was produced during the papermaking process, was utilised in different proportions to partially replace cement. Using a random sample technique, the sludge was collected from landfills and sludge drying beds.

Table 4: Properties of Collected Paper Mill Sludge

PROPERTY	VALUE
Colour	Greyish Brown
Texture	Fine, Granular, Slightly Sticky
Moisture Content	45%
Bulk density	0.75 g/cm3
Ph Value	7.5

Wastewater sludge was collected from a wastewater treatment plant in Vijayawada, Andhra Pradesh. It was gathered randomly from sludge drying beds and landfill regions, just as paper mill sludge. This sludge, which contains organic and inorganic components, was utilised to partially replace cement at various levels.

Table 5: Properties of Collected Wastewater Sludge

PROPERTY	VALUE
Colour	Black
Texture	Slippery sticky Viscous
Moisture Content	60%
Bulk density	0.85 g/cm3
Ph Value	7.9

When collected, wastewater sludge and paper mill sludge both had high moisture contents. The following pre-treatment procedure was applied to the sludge samples in order to prepare them for usage as a cement substitute:

Sun-Drying: To eliminate extra moisture, the collected sludge samples were spread out and exposed to the sun.

Crushing: The dry sludge was manually crushed into smaller particles using hammers and concrete cylinders.

Sieving: Larger particles were removed from the crushed sludge using a 150-micron sieve.

Grinding: The sieved sludge was finely ground with a sand hammer.

Final Sieving: The finely ground sludge was put through a 90-micron sieve to ensure that the particle size was comparable to cement for efficient replacement.

Ordinary Portland cement (OPC 53 grade), natural aggregates, and potable water were used in this investigation to ensure that the Indian Standard criteria were met. To determine their potential as cement substitutes, the wastewater and paper mill sludges were gathered, pre-processed, and characterised. To make sure they were compatible with the design of the concrete mix, their physical characteristics—such as their pH levels, bulk density, and moisture content—were investigated.

These industrial waste materials were transformed into fine powders that could partially substitute cement by a methodical drying, grinding, and sieving procedure. Following the preparation and characterisation of the raw materials, the mix design step ensures that the right amounts of cement, aggregates, water, and sludge replacements are used to produce concrete with the required strength, workability, and durability.

In order to assess the performance of concrete that included wastewater sludge and paper mill sludge as partial cement replacements, three main mechanical strength tests were carried out using a Universal Testing Machine (UTM). In order to find out the concrete's load-bearing capacity, the compressive strength test was conducted on cube specimens using a UTM that applied an axial load that increased progressively until failure. In order to evaluate the material's resistance to cracking, the split tensile strength test was conducted on cylindrical specimens using a diametrical compressive load to create indirect tensile stress. Finally, to assess the concrete's resistance to bending failure, the flexural strength test was performed on beam specimens utilising a two-point loading configuration on the UTM, guaranteeing a pure bending state. In order to ensure accuracy and dependability in the evaluation of concrete strength, the process and computations for these three tests were completed in compliance with the standard specification IS 516-1959 [27].

2.2 Mix Design

Because M30 and M40 grade concrete are widely used in structural applications and have different strength characteristics, they were chosen for this study. While M40, a high-strength concrete, is favoured for bridges, high-rise buildings, and heavy-load structures, M30, a medium-strength concrete, is frequently employed in residential and commercial construction. Examining the impacts of wastewater sludge (WWS) and paper mill sludge (PMS) as partial cement substitutes in these two grades aids in determining their acceptability for varying strength levels. Because M40 requires more strength and has a lower water-to-cement ratio than M30, it offers a more rigorous assessment of the effects of sludge replacement on performance.

The steps involved in the design of concrete mix as per IS: 10262-2009[24] is a follow,

Table 6: The results of the Pre-mix Design Tests

Stipulations for proportioning	
Grade designation	M30 and M40
Type of cement	OPC 53 grade confirming to IS 12269:1987 [13]
Maximum nominal size of aggregate	20 mm
Exposure condition	Severe (for reinforced concrete)
Degree of supervision	Good
Minimum cement content	320 Kg/m3
Type of aggregate	Crushed angular aggregate
Maximum cement content	450 Kg/m3
Workability	25-50 mm
Test data for Materials	
Specific gravity of cement	3.15
Specific gravity of Coarse aggregate	2.8
Specific gravity of Fine aggregate	2.6
Sieve analysis of Coarse aggregate	conforming to table 2 of IS 383
Sieve analysis of Fine aggregate	Conforming to grading zone 3 of table 4 of IS 383

From the detailed design calculation, we obtained the mix proportion ratio as follows.

Table 7: Mix Proportion Ratio of M30 & M40

GRADE DESIGNATION	M30	M40
CEMENT	1	1
FINE AGGREGATES	1.76	1.68
COARSE AGGREGATES	3.52	3.07,
W/C RATIO	0.45	0.38

3. Preparation and Casting of Specimens

Concrete specimen preparation and casting are essential steps in guaranteeing the precision and dependability of experimental findings. Concrete's strength and longevity are strongly impacted by proper mixing, casting, and curing methods. Concrete specimens for this investigation were made using the M30 and M40 mix designs, adding wastewater sludge and paper mill sludge in different proportions to partially replace cement.

Table 8: Mix Proportions for the M30 Concrete Specimens

S. NO.	MIX COMBINATION	SLUDGE PERCENTAGE (%)	CEMENT (Kg/ m3)	FINE AGGREGATES (Kg/m3)	COARSE AGGREGATES (Kg/m3)	SLUDGE (Kg/ m3)
1.	PC	0	370	652.015	1304	0
2.	PS_5 (or) WS_5	5	351.5	652.015	1304	18.5
3.	PS_10 (or) WS_10	10	333	652.015	1304	35
4.	PS_15 (or) WS_15	15	314.5	652.015	1304	55.5

In order to systematically indicate the replacement quantities of wastewater sludge and paper mill sludge, various notations were applied to the concrete mixes in this investigation. The control mix was referred to as PC (Plain Concrete) since it was not replaced. The types and percentages of replacement were used to define the notations for the mixtures that included sludge as a partial cement substitute. Concrete mixes PS_5, PS_10, and PS_15 use 5%, 10%, and 15% paper mill sludge in place of cement, respectively. In a similar vein, W_5, WS_10, and WS_15 stand for 5%, 10%, and 15% replacement of wastewater sludge, respectively. For convenience of identification and analysis, these notations were used consistently to concrete grades M30 and M40.

Table 9: Mix Proportions for the M40 Concrete Specimens

S. NO.	MIX COMBI NATION	SLUDGE PERCEN TAGE (%)	CEMENT (Kg/ m3)	FINE AGGRE GATES (Kg/m3)	COARSE AGGRE GATES (Kg/m3)	SLUDGE (Kg/ m3)
1.	PC	0	410	686.868	1273.608	0
2.	PS_5 (or) WS_5	5	389.5	686.868	1273.608	20.5
3.	PS_10 (or) WS_10	10	369	686.868	1273.608	41
4.	PS_15 (or) WS_15	15	348.5	686.868	1273.608	61.5

3.1 Casting of Specimens

3.1.1 Cubes

- The dimensions of specimen for cube are of 150mm x 150mm x 150mm.
- For each trail 6 cube specimens were casted- 3 for 7days and 3 for 28 days.
- This was conducted separately for both paper mill sludge and wastewater sludge replacements in M30 and M40 concrete grades to evaluate Compressive strength.

3.1.2 Cylinders

- The dimensions of the cylindrical specimen are of Height 300 mm and diameter 150 mm.
- For each trail 6 cube specimens were casted- 3 for 7days and 3 for 28 days.
- This was conducted separately for both paper mill sludge and wastewater sludge replacements in M30 and M40 concrete grades to evaluate Split tensile strength.

3.1.3 Beams

- The dimensions of the beam specimens are 500 mm × 100 mm × 100 mm.
- For each trial, 2 beam specimens were cast—one for testing at 7 days and one for testing at 28 days.

This was conducted separately for both paper mill sludge and wastewater sludge replacements in M30 and M40 concrete grades to evaluate flexural strength.

4. Results and Discussion

4.1 Workability of Concrete

The workability of concrete is observed by the Slump Cone method.

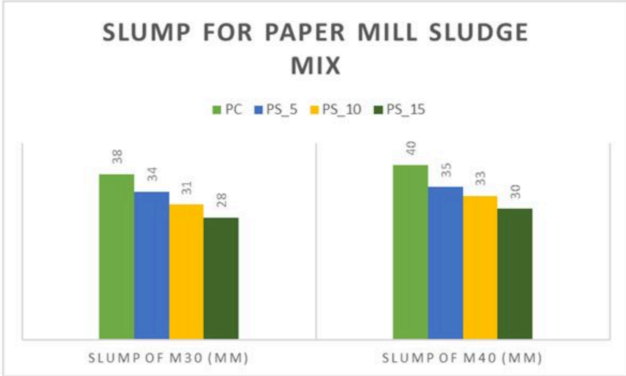

Figure 1: Slump obtained for wastewater sludge mix of M30 and M40 concrete.

The results of the slump test clearly show that as the amount of sludge replacement increases, workability decreases. With slump values ranging from 38–41 mm for M30 and 40–41 mm for M40, the control mix (PC) had the highest slump values, indicating good workability. However, the slump values progressively dropped as the replacement amounts of wastewater sludge (WS) and paper mill sludge (PS) increased, indicating a decrease in the fluidity of the mix. The slump values only slightly decreased at 5% replacement (PS_5 and WS_5) as compared to the control mix, suggesting that workability is not greatly impacted by little sludge replacement.

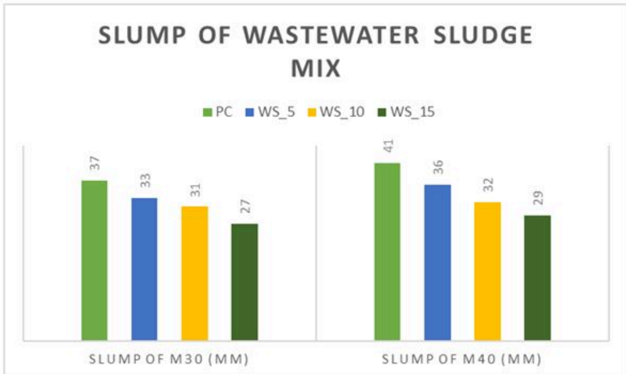

Figure 2: Slump obtained for wastewater sludge mix of M30 and M40 concrete.

Conversely, the slump values decreased to 27-29 mm for M30 and 29-30 mm for M40 with 15% replacement (PS_15 and WS_15), indicating a significant decline in workability. This decrease is explained by the sludge materials' increased capability to absorb water, which makes the mix stiffer by lowering the amount of free water available [17]. The findings indicate that while greater replacement levels (15%) need adjusting the water content or using superplasticizers to increase mix fluidity, lower replacement levels (5%–10%) of sludge retain adequate workability.

4.2 Compressive Strength

The test results are presented here for the compressive strength of 7 days and 28 days of testing. The water cured specimens are eliminated from moisture content by surface drying before testing in Compression Testing Machine**.**

There is a discernible pattern in the compressive strength data for concrete of grades M30 and M40 that has wastewater sludge (WS) and paper mill sludge (PS) substituted. By achieving 38.9 MPa for M30 and 50 MPa for M40 at 28 days, the control mix (PC) showed the highest compressive strength and provided a baseline for assessing the effect of sludge replacement. The 5% replacement (PS_5) showed the maximum compressive strength with the introduction of paper mill sludge, reaching 41.9 MPa (M30) and 53 MPa (M40) at 28 days. This suggests that a tiny amount of sludge can increase strength because of better hydration and pozzolanic activity. The strength at 10% replacement (PS_10) was 40.1 MPa (M30) and 47.5 MPa (M40) at 28 days, which was somewhat lower than PS_5 but still higher than the control mix. Nevertheless, the compressive strength dramatically decreased at 15% replacement (PS_15), especially in the M30 mix, with 28-day values of 32.5 MPa for M30 and 44.4 MPa for M40, indicating that excessive sludge replacement impairs concrete performance.

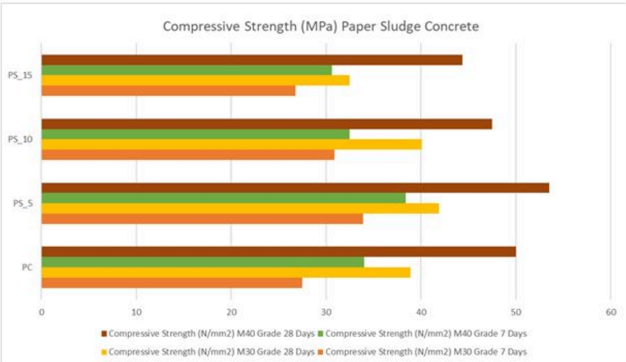

Figure 3: Compressive strengths for paper sludge concrete

The replacement of wastewater sludge showed a similar pattern. Compressive strength rose above the control mix at 5% replacement (WS_5), reaching 42.125 MPa (M30) and 51.95 MPa (M40) after 28 days. The strength values at 28 days were 40.02 MPa (M30) and 46.3 MPa (M40) when the replacement level was raised to 10% (WS_10); these values were marginally lower than WS_5 but still similar to the control mix. A significant drop in compressive strength was noted at 15% replacement (WS_15), with values of 35.216 MPa (M30) and 41.26 MPa (M40) at 28 days, suggesting that a higher sludge concentration had a negative effect on concrete strength.

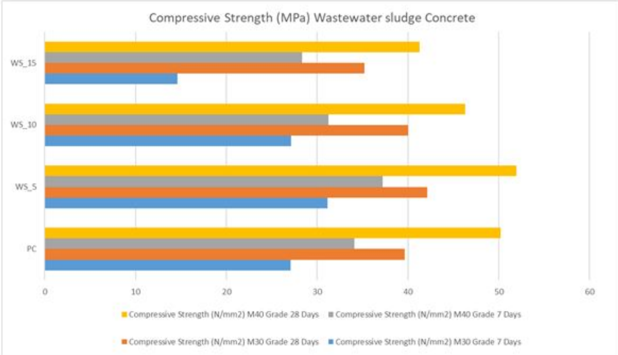

Figure 4: Compressive strengths for wastewater sludge concrete

Overall, the findings indicate that for both M30 and M40 classes, a 5% substitution of PS or WS for cement increases compressive strength, whereas a larger substitution results in a decrease in strength. This decrease at larger percentages is explained by the sludge's increasing organic content and amorphous form, which impair bonding and weaken the concrete matrix [18]. Perhaps as a result of variations in composition and particle shape, paper sludge showed somewhat higher strength retention than wastewater sludge. As a result, 5% replacement is found to be the ideal amount, guaranteeing a balance between strength improvement and sustainability; replacements above 10% are not advised because they impair mechanical performance.

4.3 Split Tensile Strength

For both M30 and M40 grade concrete, the split tensile strength of concrete mixes including wastewater sludge (WS) and paper sludge (PS) was assessed at 7 and 28 days. According to the results, the control mix (PC) had the highest split tensile strength at 7 and 28 days, with values of 2.45 MPa and 3.12 MPa for M30 grade and 3.79 MPa and 4.68 MPa for M40 grade.

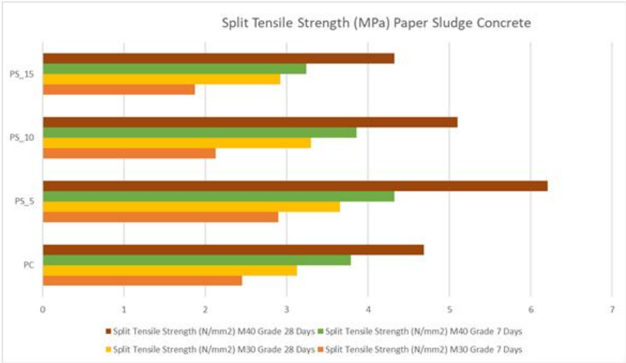

Figure 5: Split tensile strengths for paper sludge concrete

The split tensile strength increased somewhat when 5% sludge replacement was added, indicating that tensile properties are not adversely affected by a little replacement level. At 7 and 28 days, respectively, the PS_5 and WS_5 mixes recorded strengths of 2.9 MPa and 3.65 MPa for M30 grade and 4.32 MPa and 4.68 MPa for M40 grade. However, a decrease in tensile strength was noted as the replacement amount rose to 10% and 15%. With values of 1.87 MPa and 2.92 MPa for M30 grade and 3.24 MPa and 4.32 MPa for M40 grade at 7 and 28 days, respectively, the PS_15 and WS_15 mixes had the lowest split tensile strengths.

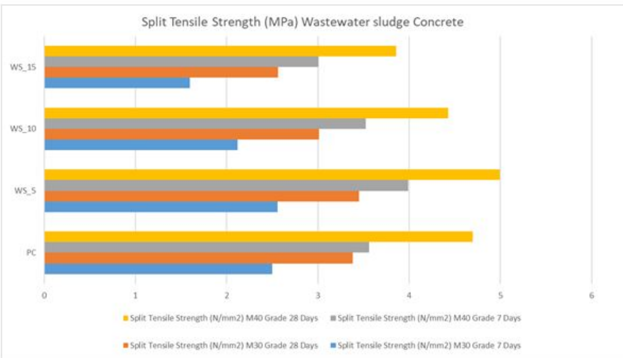

Figure 6: Split tensile strengths for wastewater sludge concrete

The weak bonding properties and increased water absorption tendency of sludge materials, which lead to reduced interfacial adhesion within the concrete matrix, are responsible for the drop in split tensile strength with increasing sludge content [19]. Higher replacement levels caused a progressive decrease in tensile strength, but lower replacement levels preserved adequate tensile strength. This suggests that there is an ideal replacement percentage beyond which mechanical performance is compromised.

4.4 Flexural Strength

When evaluating how well concrete performs under bending loads, flexural strength also referred to as the modulus of rupture is a crucial factor. Tests of flexural strength were performed on several concrete mixtures that included wastewater and paper sludge as partial substitutes for cement. Both M30 and M40 grade concrete outcomes were examined after seven and twenty-eight days of curing.

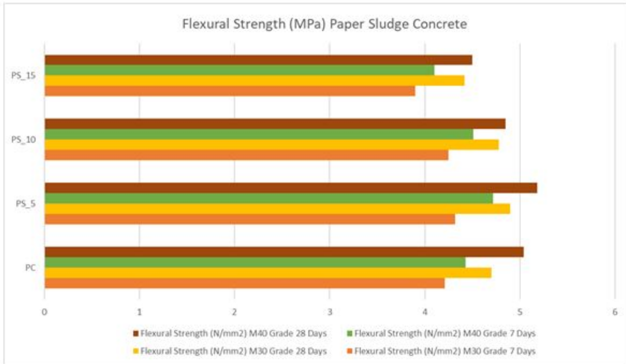

Figure 7: Flexural strengths for paper sludge concrete

For varying replacement amounts (5%, 10%, and 15%), the flexural strength of concrete containing paper sludge was assessed and contrasted with the control mix (PC). The findings, as displayed in the bar chart, generally indicate that strength increases with an ideal replacement amount and decreases with an excessive sludge concentration.

The control mix's (PC) flexural strength at 7 days was 4.21 MPa for M30 and 4.43 MPa for M40. Flexural strength rose marginally to 4.32 MPa (M30) and 4.72 MPa (M40) for a 5% replacement of paper sludge (PS_5), suggesting that strength is not substantially compromised by a modest replacement. However, the strength further increased to 4.25 MPa (M30) and 4.51 MPa (M40) at 10% replacement (PS_10), indicating improved performance at early curing stages.

Strength development persisted at 28 days, with PC reaching 4.7 MPa (M30) and 5.04 MPa (M40). It was confirmed that a little quantity of paper sludge favourably helps to flexural resistance when the 5% paper sludge mix achieved 4.9 MPa (M30) and 5.18 MPa (M40). A small decrease to 4.42 MPa (M30) and 4.50 MPa (M40) was seen in the 15% replacement mix (PS_15), indicating that a higher sludge content can result in a weaker binding within the concrete matrix.

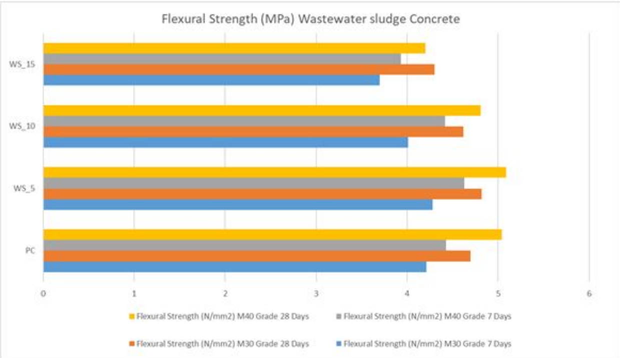

Figure 8: Flexural strengths for wastewater sludge concrete

The wastewater sludge concrete mixes showed similar patterns. A flexural strength of 4.21 MPa (M30) and 4.43 MPa (M40) was observed by the control mix (PC) after 7 days. This strength steadily increased to 4.7 MPa (M30) and 5.09 MPa (M40) at 28 days. At 7 and 28 days, the 5% wastewater sludge replacement (WS_5) produced 4.28 MPa (M30) and 4.63 MPa (M40), respectively, and 5.09 MPa (M40) and 4.82 MPa (M30). This suggests that a tiny portion of wastewater sludge does not substantially impede the development of strength.

The flexural strength, however, decreased to 3.7 MPa (M30) and 3.93 MPa (M40) at 7 days at higher replacement levels (WS_15), with a slight increase to 4.3 MPa (M30) and 4.20 MPa (M40) at 28 days. This demonstrates that due to possible cavities and weakened bonding, excessive wastewater sludge incorporation may reduce the concrete's resistance to bending loads.

Overall, there were tendencies in both paper sludge and wastewater sludge concrete where flexural strength increased with an ideal replacement (about 5%) and decreased with an excessive replacement (15%). When compared to wastewater sludge mixes, paper sludge mixes often demonstrated a marginally higher retention of flexural strength, suggesting that they had better filler and bonding qualities in the cement matrix.

In terms of real-world applications, it can be said that replacing up to 5% of the sludge with either paper or wastewater sludge helps to preserve or marginally improve the flexural qualities. However, returns decrease when replacement exceeds 10%, possibly as a result of increased matrix porosity and weakened interfacial adhesion. Additional microstructural examination would be necessary to validate the impact of sludge on the internal structure of the concrete.

5. Conclusion

With an emphasis on compressive, split tensile, and flexural strengths, this study investigated the effects of partially substituting cement in concrete with paper and wastewater sludge. The findings show that filler action, pozzolanic activity, and better microstructure all contribute to improved mechanical characteristics with a minimal sludge replacement of 5%. However, the strength starts to decrease when the sludge concentration rises over this point because of a decrease in the amount of active cement, insufficient C-S-H gel formation, and weakened matrix bonding.

Strength levels start to decline beyond 5% to 10%, which is the ideal range for sludge replacement. Through microstructural analysis, durability evaluations, and long-term strength assessments, future research should concentrate on precisely determining the ideal percentage. Additionally, studies on carbonation effects, sulphate resistance, and water absorption would shed more light on the long-term performance of concrete that has sludge mixed into it. Understanding the chemical changes in the cementitious matrix can be aided by advanced characterisation methods like TGA/DSC, XRD, and SEM.

Furthermore, evaluating the financial and ecological advantages of employing sludge in the manufacturing of concrete would encourage its widespread use, fostering environmentally friendly building methods while resolving waste management issues.

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