iJRASET
International Journal For Research in
Applied Science and Engineering Technology

# INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

**Volume:** 13 **Issue:** XII **Month of publication:** December 2025

**DOI:** https://doi.org/10.22214/ijraset.2025.76289

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XII Dec 2025- Available at www.ijraset.com

# Study of Mechanical Properties of Concrete Using Municipal Solid Waste Incinerated Ash and Iron Ore Tailings as Sustainable Material Substitutes

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***Abstract: The present work focuses on the sustainable development of M25 concrete by partially replacing cement with Municipal Solid Waste Incinerated Ash (MSWIA) and by substituting natural sand with Iron Ore Tailings (IOT). A series of mixes were produced with MSWIA in the range of 5% to 20% and later IOT was introduced from 10% to 40% to study the changes in mechanical behaviour. For every combination, compressive strength cubes, split tensile cylinders and flexural beam specimens were tested after 28 days of curing. The results indicated that replacing 10% cement with MSWIA gave the highest improvement in compressive, split tensile and flexural strength when compared with the normal mix, while further replacement reduced the strength gradually. After fixing 10% MSWIA as optimum, replacement of sand with IOT showed maximum strength around 20% and then a slight reduction was noticed for higher percentages. From the overall observations, both MSWIA and IOT were found suitable for use at moderate levels and they contributed to strength enhancement as well as reduction of natural material consumption. Thus, the combined use of MSWIA and IOT provides a promising and eco-friendly alternative for conventional concrete without compromising required engineering performance.***
***Keywords: Municipal Solid Waste Incinerated Ash (MSWIA), Iron Ore Tailings (IOT).***

## I. INTRODUCTION

Globally, cement is the backbone of modern infrastructure: concrete largely composed of cement, sand, aggregates and water is among the most used human-made materials worldwide. The manufacture of cement, however, carries a huge environmental burden. Cement production is estimated to contribute roughly 7–8% of total anthropogenic $CO_2$ emissions worldwide. For each ton of cement produced, nearly 0.5–1 ton of $CO_2$ is released, depending on the production process and energy sources. Moreover, cement extraction and production lead to depletion of natural resources (limestone, sand, water), habitat disruption, heavy energy consumption, and dust and pollutant emissions making excessive reliance on cement increasingly unsustainable.

Recognizing these environmental and resource related drawbacks, we adopted Municipal Solid Waste Incinerated Ash (MSWIA) as a partial replacement for cement and/or fine aggregates in M25 grade concrete. Using MSWIA helps reduce the demand for raw materials, and lessens the high carbon footprint associated with cement manufacture and concrete production. By substituting part of the cement with MSWIA, not only does the mix become more sustainable but the burden on natural resource extraction and waste disposal is also mitigated. This aligns with the growing global push toward circular economy and waste-to-resource strategies in construction.

Further, using MSWIA supports waste reduction and environmental protection by valorising incineration residues that would otherwise end up in landfills or open dumps, contributing to environmental hazards. Incorporating MSWIA into concrete promotes resource efficiency. It recycles municipal solid waste by-products, reduces landfill volume. At the same time, if properly processed, MSWIA contributes mineral constituents that can support concrete strength and durability making this replacement a promising strategy both environmentally and technically.

MSWIA is the residual ash left after burning municipal solid waste in incinerators. It contains a variety of mineral components such as silica, alumina, calcium oxides, and other stable oxides when properly processed, provide binding in cementitious or concrete mixes. As detailed in the project documentation, MSWIA has been used in previous studies to partially replace cement showing potential in reducing environmental impact without severely compromising mechanical performance. Its adoption thus represents a practical and sustainable modification to conventional concrete mixes, especially management and resource conservation are critical concerns.

Based on preliminary trials and mix design optimization, we determined an optimal level of cement replacement using MSWIA that balances sustainability and concrete performance. This optimum ensures that mechanical properties such as compressive strength remain within acceptable limits while maximizing environmental benefits. The mix design adjusted that MSWIA replaced while keeping cement at a reduced but sufficient level. This approach reduces cement demand, lowers the embodied energy and $CO_2$ footprint of the concrete, and still meets the targeted M25 grade performance.

In addition to MSWIA, we also explore the use of Iron Ore Tailings (IOT) as an alternative fine aggregate. IOT is a by-product of iron ore mining and mineral processing, comprising finely ground rock particles that would otherwise remain as waste. Its mineral composition often rich in silica and alumina makes it suitable as a sand replacement in concrete mixes after proper processing. IOT thus offers an opportunity for waste valorisation, resource conservation, and reduction of pressure on natural river sand extraction a significant environmental and ecological concern in many regions.

In this study, sand in the concrete mix was partially replaced with processed IOT, using proportions determined during mix design optimization. This replacement aims to assess whether IOT can satisfactorily substitute natural fine aggregate without undermining workability, strength, or durability. The combined use of IOT (for sand replacement) and MSWIA (for cement or sand replacement) underscores our commitment to developing a sustainable, low carbon, waste inclusive concrete that aligns with environmental conservation and circular economy principles, while delivering acceptable engineering performance.

## II. REVIEW OF PAST STUDIES

Sivayogaraj A. et al. (2025) [1] study explains that MSWIA contains pozzolanic constituents capable of partially replacing cement and aggregate in concrete. The authors reported a gradual strength decrease at higher dosages, but highlighted that controlled replacement levels can still be used efficiently for sustainability-focused concrete mixes.

Rajender Reddy M. et al. (2025) [2] demonstrated that MSWI bottom ash has high cementitious oxides which can enhance compressive strength at optimum replacement levels, especially around 20%. Their work also confirms improvements in chloride resistance and sulphate performance, validating MSWIA as a beneficial partial cement substitute.

Hamada H. M. et al. (2025) [3] reviewed the use of iron ore tailings as a sustainable fine aggregate. The authors observed improved mechanical and durability behaviour while noting decreased workability due to particle fineness. Their study also highlighted sustainability benefits in terms of reduced mining waste.

Ji et al. (2025) [4] assessed compressibility and crushing behaviour of IOT, mainly focusing on tailings management and safety of tailing disposal systems. Their outcomes emphasized material behaviour and compaction performance rather than structural concrete applications.

Alnezami S. et al. (2024) [5] examined MSWI bottom ash by addressing aluminium content problems. The authors established that pre-treatment improves performance and allows replacement without serious expansion defects, supporting sustainable cement reduction strategies.

Yao J. et al. (2024) [6] focused on MSWIA in mortar, reporting improved resistance to chloride and sulphate environments with moderate replacement. Durability enhancement was observed, indicating the material's potential for long-term performance.

Skanda Kumar B.N. et al. (2024) [7] found that replacing sand with 20–50% IOT can improve compressive strength due to better particle interaction. Their study supports the use of IOT for mechanical enhancement with acceptable workability reduction in concrete.

Lu J. et al. (2023) [8] evaluated MSWIA for fine aggregate substitution and reported beneficial pore filling and microstructural development at moderate dosages. However, strength values remained lower than normal concrete at larger replacement percentages.

Murali Krishna Y. et al. (2023) [9] examined gradual replacement of sand with iron ore tailings and observed reduced workability along with strength improvement up to moderate percentages. Their results suggest optimum performance around the lower mid-replacement levels.

Tokgöz D.G. et al. (2023) [10] evaluated untreated MSWI ash as a cement replacement. The authors explained the need for treatment to control setting and improve strength, due to variable ash composition.

George G. et al. (2023) [11] showed notable strength improvement when sand is replaced with IOT at moderate to high ratios. Increased fineness and $Fe_2O_3$ content were identified as beneficial for hydration and packing of concrete.

Cheng et al. (2023) [12] confirmed that MSWIA possesses reactive oxide compounds useful for supplementary cementitious applications. Their experiments indicated improved ductility and multiple micro-cracking when used in engineered composites.

Arbili M. M. et al. (2022) [13] demonstrated that IOT has suitable particle size and specific gravity for sand substitution, improving packing density and strength at selected replacement proportions.

Zhang S. et al. (2020) [14] focused on optimal replacement ranges for MSWIA, mainly between 10–20% cement substitution. Their findings indicate improved mechanical and durability performance at these levels with noticeable reduction beyond the optimum range.

Vaiciene M. et al. (2022) [15] reviewed pozzolanic characteristics of MSWIA and reported compressive strength improvement at moderate replacement, while cautioning against higher content due to porous morphology of ash.

Li J. et al. (2021) [16] review outlined global MSWI ash production and reported that treated ash can replace cement up to 30% depending on particle activation. Their results highlighted environmental advantages and the importance of pre-processing.

Zhao J. et al. (2021) [17] explained the pozzolanic potential of IOT and emphasized ways of activating its reactivity through grinding or chemical treatment. The authors propose IOT for sustainable concrete while noting certain workability limitations.

Zhang Z. et al. (2020) [18] assessed iron tailings as sand replacement and confirmed comparable strength at moderate substitution. Shrinkage was identified as a challenge requiring mitigation, yet the environmental advantage was strongly supported.

## III. DESCRIPTION OF MATERIALS USED

### *A. Materials*

#### *1) Municipal Solid Waste Incinerated Ash (MSWIA)*

For the present investigation, Municipal Solid Waste Incinerated Ash (MSWIA) was collected from the Gargeyapuram disposal site located near Kurnool. Prior to its use in concrete ash has been muffle furnaced at 800°c for the removal of unburnt carbon particles and organic matters. The material exhibited a specific gravity of 2.2, indicating a relatively lighter nature compared to ordinary Portland cement. The physical properties are presented in Table 1.

Table I

Physical Properties of MSWIA.

| Properties | Results |
|---|---|
| 1. Specificgravity | 2.2 |
| 2. Finenessmodulus | 3.1 |
| 3. Water absorption | 1.2% |

#### *2) Fine and Coarse aggregate*

The fine aggregate employed in this study was procured from a nearby source and verified to satisfy the grading requirements specified in IS 383:2016. Based on sieve analysis, the sand was classified under Zone–II. For the coarse aggregate, coarse aggregate having a maximum size of 20 mm and downgraded using a well-graded mix of aggregates which helps to minimize voids, improve density, and to optimize performance and its characteristics were evaluated in accordance with the procedures outlined in IS 2386 (Part-III):1963. A summary of the tested material properties is presented in Table 2.

Table II

Physical Characteristics of Fine and Coarse Aggregates

| S. No | Properties | CoarseAggregate Values obtained | FineAggregateValues obtained |
|---|---|---|---|
| 1 | Type | 20mm (downgraded) | Natural |
| 2 | Specificgravity | 2.86 | 2.68 |
| 3 | Finenessmodulus | 4.88 | 2.867 |

#### *3) Iron Ore Tailings (IOT)*

Iron ore tailings are generated during the extraction and beneficiation of iron ore, where the mined material is crushed and processed to remove unwanted gangue minerals. During processing operations such as grinding, flotation, and magnetic separation, the valuable ore fraction is recovered, and the remaining slurry composed of fine mineral particles and process water becomes tailings. In the present work, the Iron Ore Tailings (IOT) were collected from the tailing ponds associated with iron ore extraction activities located at Rangapuram village near Bethamcherla in Kurnool district, Andhra Pradesh.

The material obtained from the site generally exhibits a reddish-brown colour due to the presence of iron-rich minerals. The physical properties are presented at Table 3.

Table III
Physical Characteristics of IOT

| Properties | Results |
|---|---|
| Bulkdensity<br>Looselycompacted<br>Compacted | <br>1225kg/m$^3$<br>1655kg/m$^3$ |
| Specificgravity | 2.73 |
| Finenessmodulus | 2.88 |

## IV. MIX PROPORTIONS

The control concrete (M0) was designed as a conventional OPC mix without any supplementary material and served as the benchmark for evaluating subsequent modifications. For the MSWIA series, cement was replaced at four levels, specifically 5%, 10%, 15%, and 20%, to study its influence on the mechanical behaviour and to establish the replacement threshold that provides the maximum strength improvement. After identifying the optimum MSWIA percentage based on compressive, split tensile and flexural performance, the corresponding mix was selected as the base for a second phase of modifications involving iron ore tailings. In this stage, the natural sand in the mix was systematically replaced with IOT at replacement levels of 10%, 20%, 30% and 40%, allowing a detailed assessment of the combined influence of MSWIA and IOT on concrete properties.

Altogether, the study included a complete series of primary mixes (cement replaced with MSWIA only) and secondary mixes (cement replaced by MSWIA and sand replaced by IOT simultaneously). Each mixture was proportioned using consistent water–cement ratio and overall binder content to ensure comparable performance. All mixes were batched, cast and cured under identical laboratory conditions, and the hardened specimens were tested at 7, 28 days to quantify changes in mechanical properties. The full composition of each mix, including binder replacement percentage and aggregate substitution level, is summarised in Table IV.

Table IV
Replacement Mixes of MSWIA and IOT

| Mixes Designation | W/C ratio | Water kg/m$^3$ | Cement kg/m$^3$ | Coarse Aggregate kg/m$^3$ | Fine Aggregate kg/m$^3$ | MSWIA kg/m$^3$ |
|---|---|---|---|---|---|---|
| M0 Referencemix | 0.45 | 186 | 413 | 1239 | 677 | - |
| M1 (5%ofMSWIA) | 0.45 | 186 | 392.5 | 1239 | 677 | 20.65 |
| M2 (10%ofMSWIA) | 0.45 | 186 | 371.7 | 1239 | 677 | 41.3 |
| M3 (15%ofMSWIA) | 0.45 | 186 | 351.05 | 1239 | 677 | 61.95 |
| M4 (20%ofMSWIA) | 0.45 | 186 | 330.4 | 1239 | 677 | 82.6 |
| M5 (10%MSWIA +10%ofIOT) | 0.45 | 186 | 371.7 | 1239 | 609.3 | 41.3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| M6 (10%MSWIA+ 20%ofIOT) | 0.45 | 186 | 371.7 | 1239 | 541.6 | 41.3 |
| M7 (10%MSWIA +30%ofIOT) | 0.45 | 186 | 371.7 | 1239 | 473.9 | 41.3 |
| M8 (10%MSWIA +40%ofIOT) | 0.45 | 186 | 371.7 | 1239 | 406.2 | 41.3 |

## V. MECHANICAL PROPERTIES

This experimental study focuses on developing sustainable M25 grade concrete by incorporating Municipal Solid Waste IncineratedAsh (MSWIA) as a partial cement replacement and Iron Ore Tailings (IOT) as a substitute for natural fine aggregates. Municipal waste incineration residues and mining tailings normally contribute to large-scale land pollution, therefore utilizing these industrial by-products in concrete offers a dual advantage of waste minimization and conservation of natural resources. In this work, MSWIA was incorporated as a supplementary cementitious material by replacing cement at different proportions, while IOT was introduced as a fine aggregate replacement at various percentages in order to identify an optimum combination. The physical and chemical characteristics of both materials were studied to assess their compatibility and influence on the mechanical response of concrete.

To evaluate the mechanical performance of the concrete, three types of specimens were prepared, namely cubes measuring 100 mm × 100 mm × 100 mm for compressive strength, beams of 100 mm × 100 mm × 500 mm for flexural testing, and cylinders of 100 mm × 200 mm for split tensile strength. All specimens were tested after 7 & 28 days of curing, and the corresponding strength values were recorded. The obtained compressive, flexural and tensile results for the different mix combinations are presented in Table 5.

In this investigation, concrete specimens were prepared by partially replacing cement with Municipal Solid Waste Incineration Ash (MSWIA) at four different dosages, namely 5%, 10%, 15% and 20%, while iron ore tailings (IOT) were utilised as fine aggregate replacements at levels of 10%, 20%, 30% and 40%. The evaluation of mechanical properties across these mixes clearly indicated that the 10% MSWIA substitution provided the most favourable cement replacement level, delivering the highest improvement in strength parameters. Likewise, in the case of fine aggregate replacement, a peak performance was observed at 20% IOT content, beyond which the strength gradually decreased. This outcome confirms that moderate levels of both MSWIA and IOT contribute positively to concrete performance, while excessive replacement tends to dilute the matrix and reduce mechanical efficiency.

Table V
Assessment of Mechanical Properties

| Mixes Designation | Compressive Strength | %Variation | Split Tensile Strength | %Variation | Flexural Strength | %Variation |
|---|---|---|---|---|---|---|
| M0 (Referencemix) | 34.7 | - | 3.29 | - | 4.15 | - |
| M1 (5%ofMSWIA) | 35.9 | 3.46 | 3.38 | 2.74 | 4.22 | 1.69 |
| M2 (10%ofMSWIA) | 37.5 | 8.05 | 3.73 | 13.38 | 4.29 | 3.37 |
| M3 (15%ofMSWIA) | 34.03 | 1.93 | 3.26 | 0.91 | 4.14 | 0.24 |
| M4 (20%ofMSWIA) | 29.5 | 14.96 | 3.09 | 6.08 | 3.85 | 7.23 |

| | | | | | | |
|---|---|---|---|---|---|---|
| M5(10%MSWIA+10 %ofIOT) | 35.1 | 1.15 | 3.21 | 2.43 | 3.96 | 4.58 |
| M6(10%MSWIA+20 %ofIOT) | 36.2 | 4.33 | 3.40 | 3.35 | 4.34 | 4.57 |
| M7(10%MSWIA+30 %ofIOT) | 32.36 | 6.74 | 3.19 | 3.04 | 4.01 | 3.37 |
| M8(10%MSWIA+40 %ofIOT) | 30.63 | 11.75 | 3.13 | 4.86 | 3.9 | 6.02 |

### A. *Compressive Strength of MSWIA and IOT*

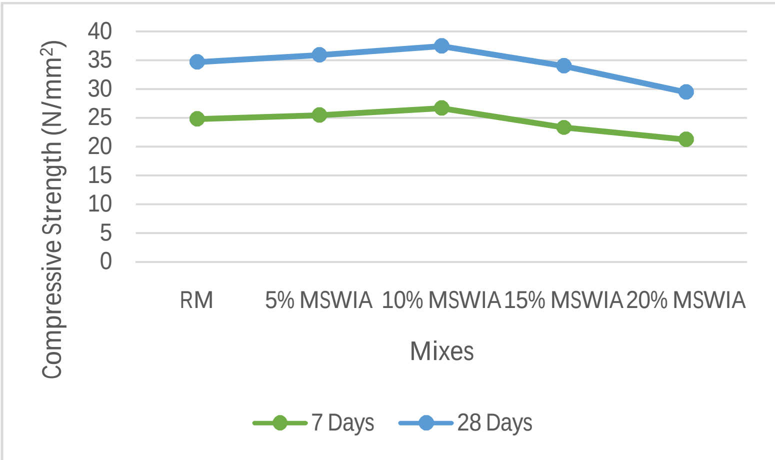
#### 1) *Compressive Strength of cement with different % of MSWIA as replacements*

In this series, cement was replaced with MSWIA at 5%, 10%, 15% and 20%, and the highest compressive strength of 37.5 MPa was observed at 10% replacement, indicating this level as the optimum dosage for the mix. Beyond this percentage, a gradual reduction in strength was noticed at both early and later ages, confirming that excessive MSWIA addition tends to dilute the cementitious content and adversely affect the mechanical performance.

Table VI

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 24.8 | 34.7 |
| 5% MSWIA | 25.46 | 35.9 |
| 10% MSWIA | 26.7 | 37.5 |
| 15% MSWIA | 23.3 | 34.03 |
| 20% MSWIA | 21.23 | 29.5 |

Compressive Strength of cement with different % of MSWIA as replacements

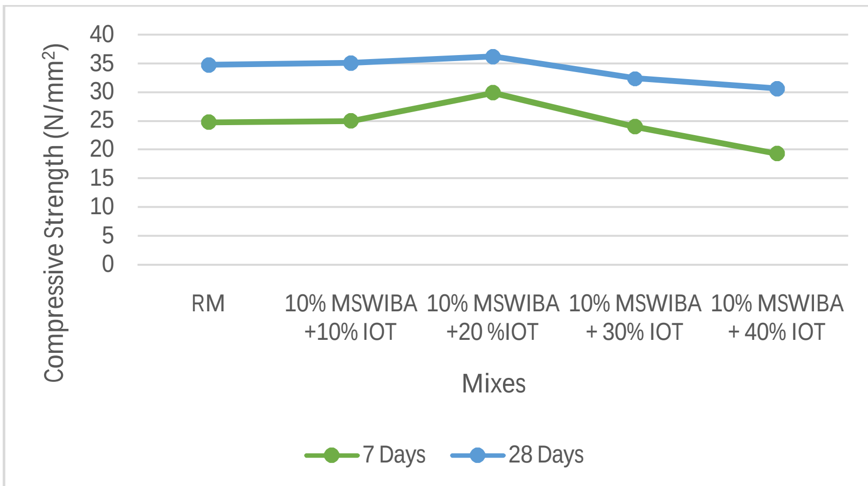



#### 2) *Compressive Strength of sand with different % of IOT as replacements by keeping 10% MSWIA as optimum*

In this set of mixes, sand was substituted with iron ore tailings at 10%, 20%, 30% and 40%, along with 10% MSWIA as optimum and the highest performance was obtained at 20% replacement, where the compressive strength reached a maximum value of 36.2 MPa.

Table VII
Compressive Strength of sand with different % of IOT as replacements+10% MSWIA

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 24.8 | 34.7 |
| 10% MSWIA +10% IOT | 25.0 | 35.1 |
| 10% MSWIA +20 %IOT | 29.9 | 36.2 |
| 10% MSWIA + 30% IOT | 24.0 | 32.36 |
| 10% MSWIA + 40% IOT | 19.3 | 30.63 |

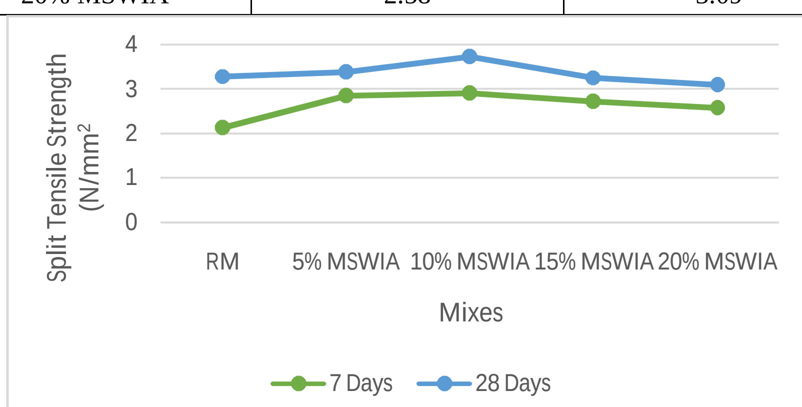



*3) Split Tensile Strength of cement with different % of MSWIA as replacements*

For the split tensile strength tests, MSWIA was introduced as a cement replacement at levels of 5%, 10%, 15% and 20%, and the maximum strength was achieved at 10% substitution, recording 2.91 MPa at 7 days and 3.73 MPa at 28 days.

Table VIII
Split Tensile Strength of cement with different % of MSWIA as replacements

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 2.13 | 3.29 |
| 5% MSWIA | 2.85 | 3.38 |
| 10% MSWIA | 2.91 | 3.73 |
| 15% MSWIA | 2.72 | 3.26 |
| 20% MSWIA | 2.58 | 3.09 |



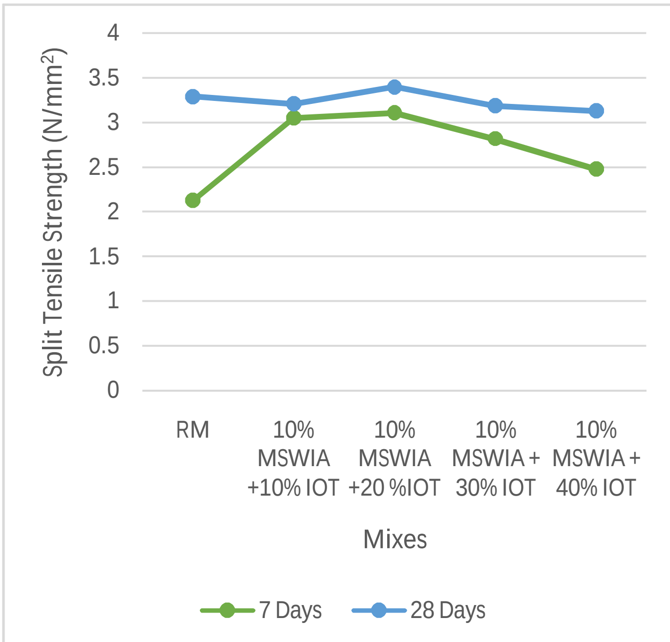
*4) Split Tensile Strength of sand with different % of IOT as replacements by keeping 10% MSWIA as optimum*

The split tensile strength results show that when 10% MSWIA was kept constant, replacing sand with 10%, 20%, 30% and 40% IOT produced varying behaviour. The highest values of 3.11 MPa at 7 days and 3.40 MPa at 28 days were obtained at 20% IOT, while higher replacements resulted in reduced strengths. This confirms that around 20% IOT provides the most favourable split tensile performance in combination with 10% MSWIA.

Table IX

Split Tensile Strength of sand with different % of IOT as replacements+10% MSWIA

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 2.13 | 3.29 |
| 10% MSWIA +10% IOT | 3.05 | 3.21 |
| 10% MSWIA +20 %IOT | 3.11 | 3.40 |
| 10% MSWIA + 30% IOT | 2.82 | 3.19 |
| 10% MSWIA + 40% IOT | 2.48 | 3.13 |



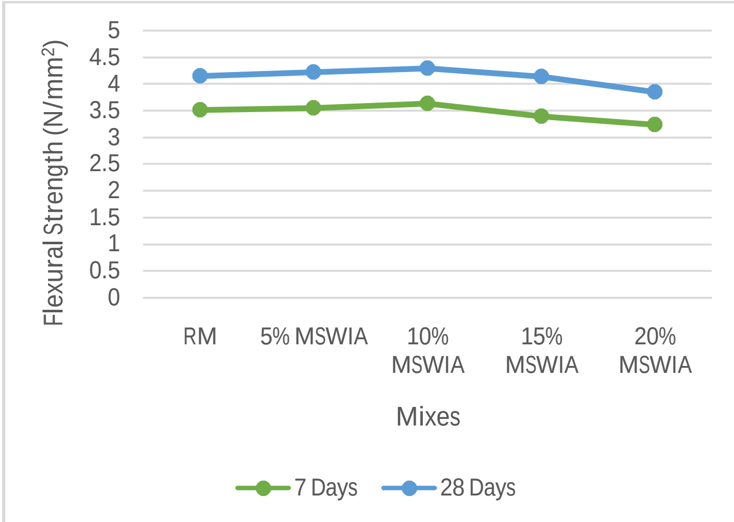

*5) Flexural Strength of cement with different % of MSWIA as replacements*

The flexural strength results show that replacing cement with MSWIA improved performance up to the 10% level, where the highest values of 3.63 MPa at 7 days and 4.29 MPa at 28 days were achieved compared to the reference mix (3.51 and 4.15 MPa). Beyond this level, the strengths gradually decreased, indicating that 10% MSWIA provides the most favourable flexural behaviour.

Table X

Flexural Strength of cement with different % of MSWIA as replacements

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 3.51 | 4.15 |
| 5% MSWIA | 3.55 | 4.22 |
| 10% MSWIA | 3.63 | 4.29 |
| 15% MSWIA | 3.39 | 4.14 |
| 20% MSWIA | 3.24 | 3.85 |



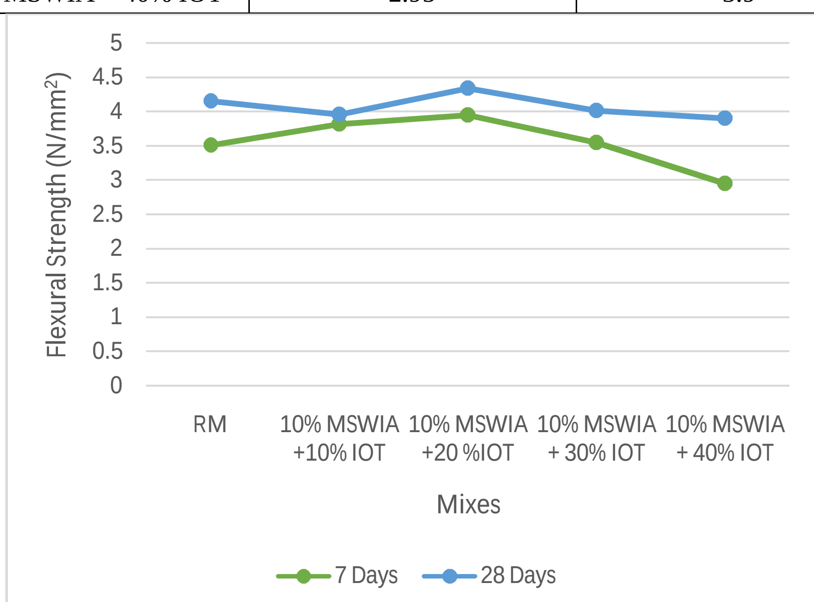

*6) Flexural Strength of sand with different % of IOT as replacements by keeping 10% MSWIA as optimum*

The flexural strength results show that keeping MSWIA at 10% and varying IOT produced the highest performance at 20% IOT, where values reached 3.95 MPa at 7 days and 4.34 MPa at 28 days, compared with the reference strength of 3.51 MPa and 4.15 MPa. Although a slight improvement was observed at 10% IOT, further increases to 30–40% resulted in gradual strength reduction. Overall, 20% IOT in combination with 10% MSWIA provided the most favourable flexural behaviour.

Table XI

Flexural Strength of sand with different % of IOT as replacements+10% MSWIA

| Mixes | 7 Days | 28 Days |
|---|---|---|
| RM | 3.51 | 4.15 |
| 10% MSWIA +10% IOT | 3.82 | 3.96 |
| 10% MSWIA +20 %IOT | 3.95 | 4.34 |
| 10% MSWIA + 30% IOT | 3.55 | 4.01 |
| 10% MSWIA + 40% IOT | 2.95 | 3.9 |



## VI. CONCLUSIONS

The outcomes of the experiments conducted in this study can be summarized as follows:

*1)* In the present investigation, cement was partially replaced with MSWIA at varying levels ranging from 5% to 20% in OPC. The results show that the optimum mechanical performance occurs at a 10% replacement level. At this percentage, the compressive strength, split tensile strength, and flexural strength reach 37.5 MPa, 3.73 MPa, and 4.29 MPa, respectively, representing increases of 8.5%, 13.3%, and 3.37% compared with the control mix (M0).

*2)* After identifying the optimum MSWIA content, sand was partially substituted with IOT. The highest strength values were obtained at a 20% IOT replacement. At this level, the compressive strength, split tensile strength, and flexural strength were recorded as 36.2 MPa, 3.40 MPa, and 4.57 MPa, showing improvements of 4.33%, 3.35%, and 4.57% over the reference mix (M0).

*3)* Overall, the study demonstrates that the maximum strength is achieved when 10% of cement is replaced with MSWIA, after which the strength gradually decreases up to the 20% level. When IOT is used as a partial replacement for sand, the optimum performance occurs at 20% replacement, beyond which strength begins to decline as the replacement reaches up to40%. In all optimal mixes incorporating MSWIA and IOT, the compressive strength remains higher than that of the reference concrete.

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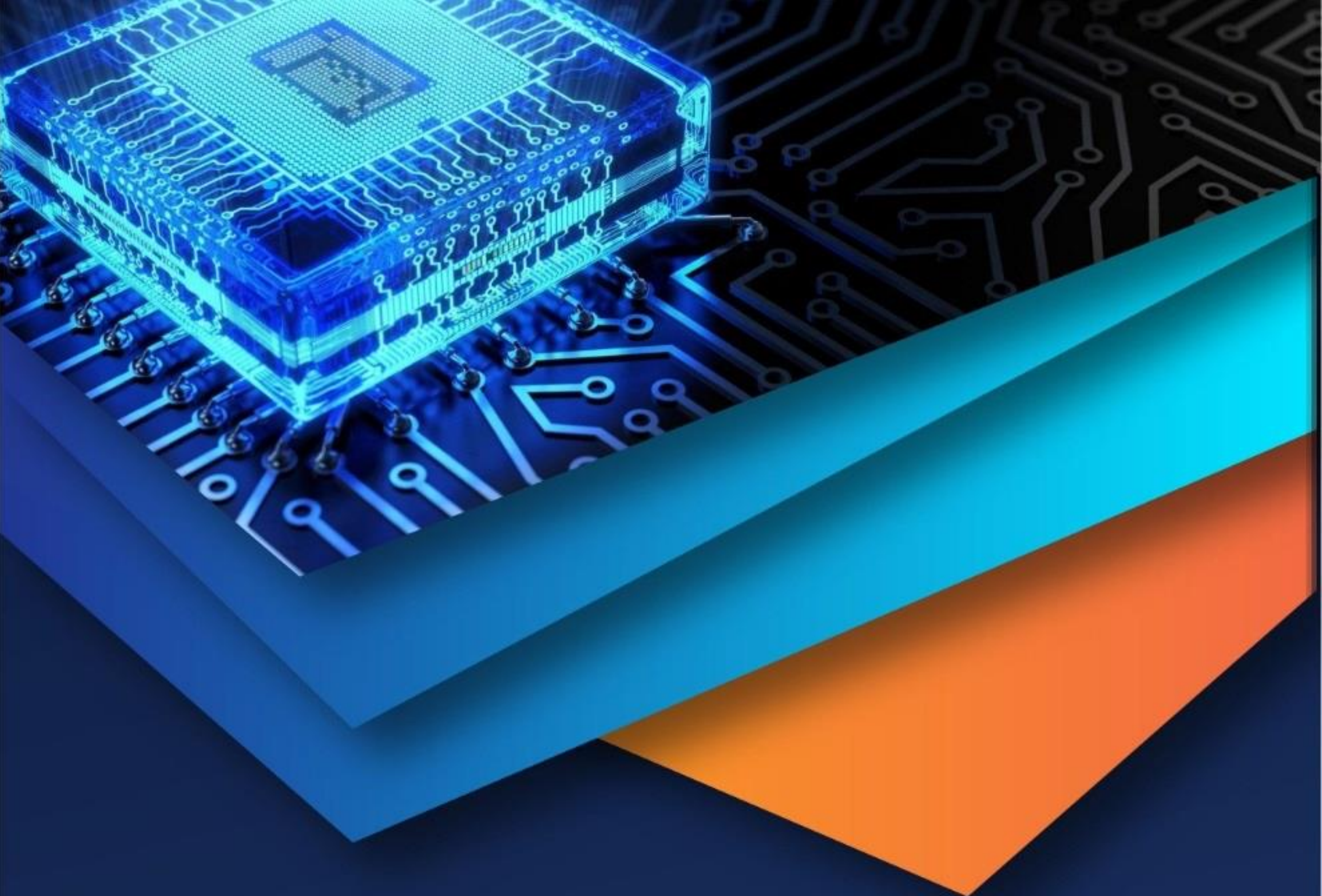


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