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# Experimental Investigation of Red Mud as a Sustainable Supplementary Cementitious Material in Concrete

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**ABSTRACT:** Massive usage of concrete in modern construction has led to a drastic increase in cement consumption and constitutes about 7–8% of global anthropogenic carbon dioxide (CO<sub>2</sub>) emissions. At the same time, the substantial production of red mud, a byproduct of the Bayer process in the aluminum sector, presents a severe environmental and disposal problem due to its high alkalinity and increasing volume. Previous studies have investigated the use of industrial by-products in concrete, but few experimental investigations have comprehensively examined the optimum use of red mud as a supplementary cementitious material (SCM) in structural concrete in a holistic manner. Hence, this research work has experimentally studied the effect of partial replacement of Ordinary Portland Cement (OPC) with red mud at 0%, 5%, 10%, 15%, and 20% replacement levels in M30 grade concrete. The properties of fresh and hardened concrete were evaluated by slump, compressive strength, split tensile strength, and flexural strength test, as per IS 1199 (Part 2):2018, s, as per IS 1199 (Part 2):2018, after 28 days of water curing as per applicable Indian Standards. The workability decreased with an increase in red mud content due to finer particle size and higher water requirements, with the slump decreasing by about 18.4% at a 20% replacement level. The optimum replacement level of 10% red mud resulted in an improvement of 9.8%, 18.5%, and 15.2% in the compressive strength, split tensile strength, and flexural strength, respectively, over the control mix. Above this level, strength decreased gradually due to the dilution of cement and an increase in porosity. The results indicate that red mud can be a sustainable supplementary cementitious material to decrease the consumption of cement, improve the mechanical properties, and promote the production of eco-friendly and resource-efficient concrete.

**KEYWORDS:** Red mud; sustainable concrete; supplementary cementitious material; industrial waste utilization; mechanical properties; compressive strength; green construction.

## I. INTRODUCTION

Concrete is the most used material in the building industry worldwide because it is strong in compression, durable, adaptable, and cost-effective. Every year the world produces well over 30 billion tons of concrete, a material essential for infrastructure, transportation, housing, hydropower, and industrial facilities. The concrete industry, despite its widespread use, raises significant environmental concerns [1]. Ordinary Portland Cement (OPC), the major binding material in concrete, requires high energy for production. Ordinary Portland Cement (OPC) is a major binder in concrete and a very energy-intensive material, contributing to about 7–8% of the global anthropogenic carbon dioxide (CO<sub>2</sub>) emissions. Producing clinker at high temperatures and mining natural resources like limestone and clay reduce resources, harm ecosystems, and require more energy. These problems have pointed out the need to seek sustainable solutions to reduce cement consumption and maintain the mechanical and durability properties of concrete. One of the most effective ways to improve the sustainability of concrete is to include supplementary cementitious materials (SCMs) that come from industrial by-products and waste materials [2]. Numerous SCMs such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash, and red mud have been widely employed and shown great potential to replace a part of cement with improvement in concrete performance. By their use, consumption of clinkers and greenhouse gas emissions are reduced, and the principles of resource conservation and circular economy are supported through the constructive reuse of industrial waste [3]. One of these materials is red mud, which has emerged as a prospective SCM because of its copious availability and increasing environmental significance. Red mud is an alkaline waste product of the Bayer process used to extract alumina from bauxite ore. It is mainly composed of

iron oxide ( $\text{Fe}_2\text{O}_3$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), titanium oxide ( $\text{TiO}_2$ ), calcium oxide ( $\text{CaO}$ ), and some alkali residues.

This waste means it could be used as a pozzolanic or filler material. Every year more than 180 Mt of red mud is generated worldwide, and over the previous decades, billions of tonnes have been amassed in disposal ponds. Red mud is very alkaline, and its storage and disposal need large land areas and may lead to soil contamination, groundwater pollution, and long-term environmental problems. Hence, the sustainable exploitation of red mud in cement-based materials has become an important research field of sustainable construction [4]. The previous research indicated using 10% red mud for renewal achieves the best compromise between sustainability and structural performance. The addition of red mud at low replacement levels can improve the mechanical performance of concrete through better particle packing, matrix densification, and restricted pozzolanic reactions. Only a few researchers have reported improvement in compressive strength, tensile strength, and durability when red mud is used as a replacement for 5-15% of cement [5]. The tiny particle size of red mud has the effect of inducing filler effects that reduce pore spaces and improve the interfacial transition zone (ITZ), while its aluminosilicate contents participate in secondary hydration reactions producing supplementary calcium silicate hydrate (C-S-H) gel. However, larger replacement levels usually lead to lower workability and strength due to the higher water demand, dilution of cementitious chemicals, and relatively lower hydraulic activity of red mud. In addition, the chemical and mineralogical composition of red mud is highly variable depending on the supply of bauxite and the alumina extraction procedure, resulting in conflicting results about the suitable replacement amount for structural concrete [6].

**Research Gaps**—Although many studies have been conducted on red mud concrete, most of them focused on individual properties such as compressive strength or durability, and there is little research on the comprehensive evaluation of fresh and hardened concrete properties under standard test conditions. Furthermore, there is no consensus on the optimal percentage of red mud replacement to achieve a balance between the workability and mechanical performance of structural-grade concrete. No experimental investigation has been carried out using Indian Standard criteria for evaluation of slump, compressive strength, split tensile strength, and flexural strength in one framework [7]. Uniqueness. The novelty of the present work is the systematic experimental investigation of red mud as a sustainable supplementary cementitious material in M30 grade concrete at 0%, 5%, 10%, 15% and 20% replacement levels by weight of cement following the standardized Indian Standard tests as per IS 1199 (Part 2):2018. The study considers replacement levels of 0%, 5%, 10%, 15%, and 20% of red mud under the standard Indian Standard tests as per IS 1199 (Part 2):2018 and associated testing protocols. In this study, unlike many earlier investigations that focus only on compressive strength, new concrete workability together with compressive, split tensile, and flexural strengths are completely studied to find out the appropriate replacement level for structural applications [8].

**Goals of Research**—The present study aims to assess the effect of red mud on the workability of fresh concrete, to study the effect of red mud on compressive strength, split tensile strength, and flexural strength, to determine the optimum replacement level of red mud for M30 grade concrete, and to assess the applicability of red mud as a sustainable supplementary cementitious material for structural construction [9].

**Research Contributions.** This research work presents experimental evidence for the effective exploitation of red mud as a partial replacement of cement to reduce cement consumption, minimize industrial waste disposal, save natural resources, and reduce the environmental impact of concrete production. The results will help move sustainable concrete technology forward, giving practical help to engineers, researchers, and policymakers as they seek environmentally responsible options for the future of infrastructure construction [10].

The whole research approach chosen in this work, covering literature review, material characterization, concrete mix proportioning, specimen preparation, curing, experimental testing, data analysis, and performance evaluation of red mud concrete, is presented in Figure 1.

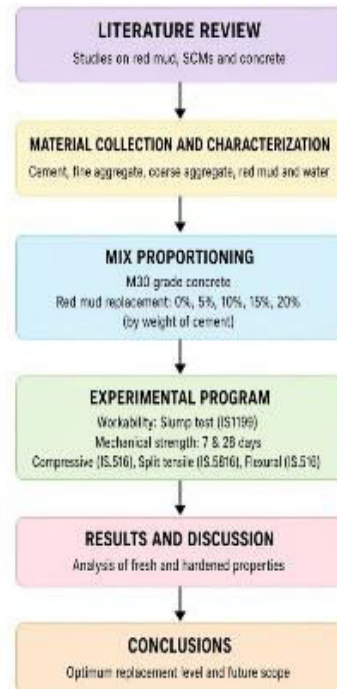


**Figure.1. Research Methodology Adopted in the Present Study**

## II. METHODS AND MATERIALS

This section describes the materials used, chemical properties of red mud, concrete mix proportions, specimen preparation, curing procedure, and experimental testing methods used to investigate the feasibility of using red mud as a sustainable supplementary cementitious material (SCM) in concrete. All the laboratory investigations were performed according to the respective Indian Standards (IS) for the consistency, reliability, and reproducibility of the experimental outcomes. To strengthen the statistical reliability of the investigation, three identical specimens were examined for each mechanical attribute at each replacement level, and the results provided are the average values [11].

### 2.1 Materials Used in the Investigation

The binder used was Ordinary Portland Cement (OPC 53 grade) according to IS 12269: 2013. The specific gravity of cement was 3.15, and the early strength developed was adequate for structural concrete use. Fine aggregate was natural river sand as per IS: 383-2016 zone II. The sand was clean, well graded and free of organic material. It had a fineness modulus of 2.70 and a specific gravity of 2.64. The coarse aggregate was crushed granite with a nominal maximum size of 20 mm. The total was in conformity to the grading standard of IS 383:2016. The specific gravity was 2.72 and the water absorption was 0.85% which gave the desired strength and durability. Concrete shall be mixed and cured with potable water in accordance with IS 456:2000. There were no hazardous salts, acids, alkalis, oils, or organic contaminants in the water that would adversely affect cement hydration [12].

In this study, red mud collected from an alumina refinery using the Bayer process was investigated as an alternative cementitious material. The raw red mud was air-dried, ground, and sieved with a 90  $\mu$ m sieve to obtain homogeneous particle size before use [13]. The tiny particles were predicted to increase the packing of particles and reduce the pore spaces in the cement matrix. The reactive aluminosilicate phases can contribute to subsequent hydration processes.

Table.1. Physical Properties of Constituent Materials

| Material                          | Standard      | Important Properties                                                    |
|-----------------------------------|---------------|-------------------------------------------------------------------------|
| OPC 53 Grade Cement               | IS 12269:2013 | Sp. gr. = 3.15                                                          |
| River Sand (Zone II)              | IS 383:2016   | Sp.gr. = 2.64; Fineness modulus = 2.70                                  |
| Crushed Granite Aggregate (20 mm) | IS 383:2016   | Sp. gr. = 2.72; Water absorption = 0.85%                                |
| Potable Water                     | IS 456:2000   | Suitable for concrete mixing and curing                                 |
| Red Mud                           | Bayer Process | Fine powder (<90 $\mu\text{m}$ ); reddish-brown; sp. gr. $\approx$ 3.10 |

## 2.2 Chemical Composition of Bauxite Residue

Red mud is a highly alkaline industrial waste product produced during the extraction of alumina from bauxite ore. The chemical composition is dictated by the mineralogical features of the host bauxite and the extraction method [14]. Red mud mainly consists of iron oxide ( $\text{Fe}_2\text{O}_3$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), silica ( $\text{SiO}_2$ ), calcium oxide ( $\text{CaO}$ ), titanium dioxide ( $\text{TiO}_2$ ), and sodium oxide ( $\text{Na}_2\text{O}$ ) [14]. The high content of  $\text{Fe}_2\text{O}_3$  gives the typical color of reddish, and  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  are responsible for the pozzolanic potential of the material. Filler effects are promoted by the fine particle size that improves particle packing and reduces pore connectivity, resulting in a denser cement matrix. However, because of the porous morphology and large surface area, an increase in the amount of red mud also increases water consumption, which decreases workability at higher replacement levels [15].

Table.2. Typical Chemical Composition of Red Mud

| Oxide                   | Composition (%) |
|-------------------------|-----------------|
| $\text{Fe}_2\text{O}_3$ | 38.5            |
| $\text{Al}_2\text{O}_3$ | 18.2            |
| $\text{SiO}_2$          | 14.6            |
| $\text{CaO}$            | 9.5             |
| $\text{TiO}_2$          | 6.8             |
| $\text{Na}_2\text{O}$   | 4.3             |
| $\text{MgO}$            | 2.1             |
| Loss on Ignition (LOI)  | 6.0             |



Figure.2. Constituent Materials Used in the Study

Figure 2 Main materials used to prepare concrete: (a) OPC 53 Grade cement, (b) processed red mud powder, (c) natural river sand, and (d) crushed granite coarse aggregate.

### 2.3 Concrete Mix Design

The concrete mixtures were designed for M30 grade concrete as per the recommendations of IS 10262:2019. The ratio of water to cementitious material was kept constant at 0.45 for all the mixes in the experiment in order to make a valid comparison [16].

Five concrete mixes were made by replacing cement with red mud at 0% (control mix), 5%, 10%, 15%, and 20% by weight of cement [17]. These replacement levels were based on existing literature and preliminary trial mixes that had shown that moderate red mud contents could increase mechanical performance and reduce the negative impacts on workability. The amounts of aggregates and mixing water were kept constant to study the effect of red dirt on the behavior of concrete.

### 2.4 Preparation of Concrete Specimens for Testing

Firstly, the dry ingredients, such as cement, red mud, fine aggregate, and control mix, were mixed mechanically for around 2–3 min to get a homogeneous blend. After that, water was added slowly to the mixture, and mixing was continued for another 3 min to get a homogeneous concrete mixture [18]. In three equal levels, the fresh concrete was put into clean steel molds, and each layer was compressed with a laboratory table vibrator to remove the entrapped air and to achieve adequate consolidation [19].

The specimens cast were the following:

- Compression test cubes of 150 × 150 x 150 mm.
- Split tensile strength of 150 mm x 300 mm cylinders.
- Beams of 100x100x500 mm for flexural strength.

After casting, specimens were covered with polyethylene sheets for 24 h, removed from the molds, and transferred to a curing tank [20].

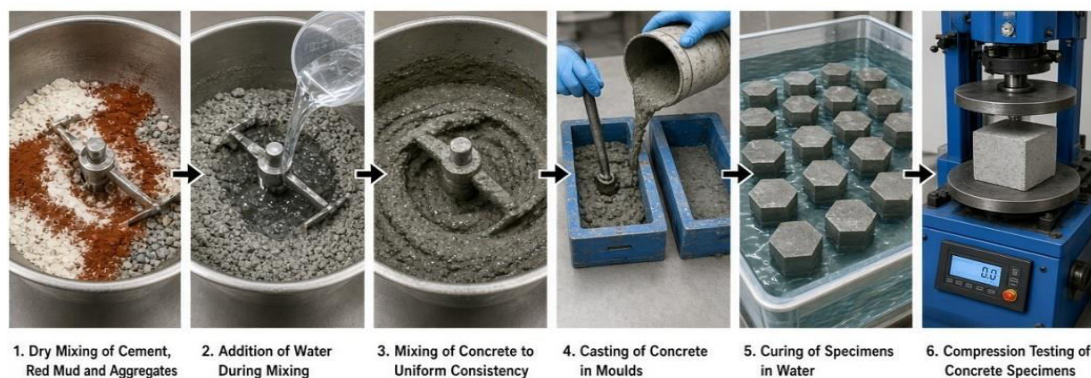


**Figure.3. Specimen Preparation and Testing Procedure**

The sequence of concrete mixing, casting, curing, and testing, as per IS 1199 (Part 2):2018, used in the experimental inquiry is shown in Fig. 3.

### 2.5 Curing process

All specimens were cured in water to a depth of total immersion between  $27 \pm 2^\circ\text{C}$  and  $28 \pm 2^\circ\text{C}$  up to the ages for testing. The mechanical properties were determined after 7 and 28 days of cure. The proper curing allowed sufficient hydration of cementitious materials, reduced variability due to moisture, and enhanced reproducibility of the experimental results.

### 2.6 Experimental Test Methods

Fresh concrete workability was determined in terms of the slump cone test as per IS 1199 (part 2): 2018. The hardened concrete specimens were tested in accordance with the following Indian Standards:

- Compressive Strength: IS 516 (Part 1/Sec 1): 2021
- Split Tensile Strength: IS 5816:1999.
- Flexural Strength: IS 516 (Part 2/Sec 1):2021 using the two-point loading method.

For each test and each replacement level, three specimens were evaluated to improve statistical reliability, and the mean value with standard deviation was used for the analysis. In addition, the experimental findings were compared to establish the optimum level of red mud substitution and to assess the viability of red mud as a sustainable supplementary cementitious material for structural concrete applications.

### **III. RESULTS AND DISCUSSION**

This section presents and discusses the experimental results obtained from the workability, compressive strength, and split tensile strength tests of concrete with varying percentages of red mud as SCM. The observed behavior is interpreted considering the physical properties, the particle size distribution, the filler effect, and the limited pozzolanic activity of the red mud. The experimental results are statistically analyzed and compared with previous studies to find the optimum replacement level for sustainable structural concrete.

#### **3.1 Workability**

The slump cone test as per IS 1199 (Part 2):2018 is used to measure the workability of fresh concrete. Average slump values of the five concrete combinations are reported in Table 3, and the overall trend is shown in Figure 4 [21].

The experimental results show that the slump decreases gradually with the increase of red mud replenishment. The maximum value of the slump was 82 mm for the control concrete (RM0) and a minimum of 56 mm for the mixture with 20% red mud (RM20), which was an overall reduction of about 31.7%. The decline in workability is mainly due to the smaller particle size and larger specific surface area of red mud, which demand more water in the concrete mix. Furthermore, the irregular and porous particle morphology of red mud absorbs part of the mixing water, which reduces the free water available for lubrication between cement paste and aggregates [22].

All mixtures showed satisfactory cohesiveness even with the slump loss. Investigation revealed no definite segregation or bleeding. The slump values of concrete mixes containing 5% and 10% red mud were 78 mm and 73 mm, respectively, which were acceptable for reinforced concrete application. The replacement levels of 15% and 20% resulted in relatively stiffer mixes, which needed more vibration during casting [23].

These findings are in agreement with previous experiments that indicated that the workability of concrete is generally affected by the increase in red mud content due to its angular shape, high fineness, and high water absorption properties. In practice, this decrease in workability can be successfully compensated by optimal mix design or incorporation of superplasticizers, with no major impact on mechanical performance [24].

#### **3.2 Strength in Compression**

The compressive strength of concrete was evaluated on 150×150×150 mm cube specimens after 28 days of water curing according to IS 516 (Part 1/Sec 1):2021. The average results obtained from three specimens of each mixture are given in Table 3. The results indicate that the partial substitution of cement by red mud significantly affects the compressive strength of concrete. The average compressive strength of the control mix (RM0) was 38.2 MPa. The strength climbed to 39.8 MPa at 5% replacement and attained a maximum value of 42.0 MPa at 10% replacement, which was an enhancement of about 9.9% as compared with traditional concrete [25].

The enhancement observed at the lower replacement levels is mostly attributed to two complementing mechanisms. The first one is the filler effect of the ultrafine red mud particles, which fills the micro-voids of the cement matrix, leading to a denser internal structure and the reduction of the pore connectivity. Secondly, the silica- and alumina-rich components of red mud undergo limited pozzolanic reactions, which consume calcium hydroxide liberated during cement hydration and generate additional calcium silicate hydrate (C–S–H) gel. This subsequent hydration enhances the interfacial transition zone (ITZ) of cement paste and aggregates, resulting in better load-carrying capacity of concrete. Compressive strength exhibited a progressive reduction beyond the optimum amount of replacement. The strength was reduced to 40.5 MPa at 15% replacement and further to 36.8 MPa at 20%, which is around 3.7% less than the control concrete. The reduction is mainly due to a decrease in cementitious compounds, the non-formation of

hydration products, and an increase in porosity due to the addition of excess red mud. Higher replacement levels also increase water demand, therefore decreasing matrix compactness and mechanical performance [26].

The results generally indicate using 10% red mud for renewal achieves the best compromise between sustainability and structural performance. The results generally indicate that using 10% of red mud for renewal achieves the best compromise between sustainability and structural performance. The best compromise between sustainability and structural performance is achieved by using 10% red mud for renewal. The optimum replacement levels identified in several recent studies are close, in the range of 8%-15%, indicating that moderate use of red mud is beneficial for enhancing the strength of concrete and reducing the cement consumption [27].

Table.3. Fresh and Mechanical Properties of Red Mud Concrete

| Mix ID | Red Mud (%) | Slump (mm) | Compressive Strength (MPa) | Split Tensile Strength (MPa) | Flexural Strength (MPa) |
|--------|-------------|------------|----------------------------|------------------------------|-------------------------|
| RM0    | 0           | 82         | 38.2 ± 0.5                 | 3.62 ± 0.06                  | 4.58 ± 0.08             |
| RM5    | 5           | 78         | 39.8 ± 0.4                 | 3.88 ± 0.05                  | 4.86 ± 0.07             |
| RM10   | 10          | 73         | 42.0 ± 0.4                 | 4.29 ± 0.04                  | 5.30 ± 0.06             |
| RM15   | 15          | 65         | 40.5 ± 0.5                 | 4.05 ± 0.05                  | 5.01 ± 0.07             |
| RM20   | 20          | 56         | 36.8 ± 0.6                 | 3.49 ± 0.07                  | 4.46 ± 0.09             |

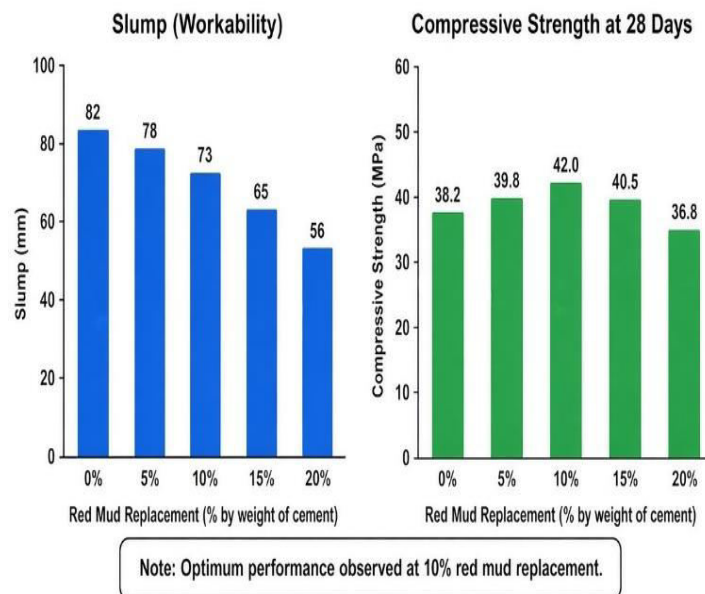


Figure.4. Comparison of Workability and Compressive Strength of Red Mud Concrete

The fluctuation of slump and compressive strength with the increase of red mud replacement. Figure 4 illustrates how the slump and compressive strength fluctuate with increasing red mud replacement. in Figure 4. The workability declined progressively due to the finer particle size and higher water demand of red mud. The compressive strength increased up to 10% replacement because of the enhanced particle packing and secondary hydration and then deteriorated at higher replacement levels [28].

### 3.3. Splitting Tensile Strength

Split tensile strength Split tensile strength was determined on 150×300 mm cylinder specimens as per IS 5816: 1999. The mean test results are reported in Table 3. The addition of red dirt has a substantial effect on the tensile behavior of concrete. The split tensile strength of the control mixture was 3.62 MPa, whereas the concrete with 10% red mud

cement had the maximum value of 4.29 MPa, which is an improvement of about 18.5%. This improvement is mainly due to the better densification of the matrix, the increased interfacial bonding between the cement paste and the aggregates, and the further development of C-S-H gel by the limited pozzolanic activity of red mud. These techniques are effective for delaying the onset of cracks and the growth of cracks under tensile stress. The tensile strength was slightly reduced after the optimum replacement level [29]. However, the strength of the red mud mix of 15% was higher than the control concrete. The results show that the resistance to cracking can be effectively improved by appropriate amount of substitution. The loss of cementitious chemicals and increase in internal porosity caused the reduction in tensile strength at 20% replacement. Statistical significance: The coefficients of variation of all experimental data were less than 5%, which showed the high reproducibility and consistency of the laboratory study [30]. According to one-way analysis of variance (ANOVA) at a significance level of  $p < 0.05$ , compressive and split tensile strengths increased significantly when compared to the control mixture after 10% red mud replacement. This indicates that the observed improvement in strength is due to the addition of red dirt and not an experimental error [31].

### **Comparison with Previous Work**

The present findings are in excellent agreement with earlier published research revealing optimum red mud replacement amounts of 8% to 15%. The better performance of concrete Previous researchers have attributed the better performance of concrete to improved particle packing, matrix densification, and reduced pozzolanic reactions. Previous researchers have attributed the better performance of concrete to improved particle packing, matrix densification, and reduced pozzolanic reactions. However, high substitution is associated with lower workability and strength attributed to dilution of cement and higher water demand. associated with lower workability and strength due to cement dilution and higher water demand. The present work deals with detailed evaluation of new concrete qualities and strengths, namely compressive, split tensile, and flexural strength as per Indian testing standards, and comparison of these results with previous investigations. The findings validate the best trade-off in terms of mechanical performance, workability, sustainability, and practical applicability of M30 grade structural concrete with 10% red mud substitution.

## **IV. RESULTS AND DISCUSSIONS**

### **4.1 Bending strength**

Flexural strength is an important mechanical attribute for concrete members subjected to bending loads such as stiff pavements, bridge decks, industrial floors, precast members, and reinforced concrete beams. In the present examination, flexural strength was evaluated on  $100 \times 100 \times 500$  mm beam specimens under two-point loading as per IS 516 (Part 2/Sec 1): 2021. Average results of three specimens for each mix are shown in Table 3. The experimental results revealed that the addition of red dirt had a substantial effect on the flexural behavior of concrete. The control mix (RM0) has shown a mean flexural strength of  $4.58 \pm 0.08$  MPa after 28 days of curing. The flexural strength increased to  $4.86 \pm 0.07$  MPa by using 5% red mud as a replacement of cement, which was an increase of about 6.1%. The maximum flexural strength of  $5.30 \pm 0.06$  MPa was achieved at 10% red mud replacement, which was an increase of ~15.7% over the control concrete. The increase in flexural strength is mainly attributed to the micro-filler effect and the lower pozzolanic activity of red mud. The ultrafine particles fill effectively the micro-voids of the cement paste, which leads to a denser matrix and lower capillary porosity. Additionally, the silica and alumina contained in red mud further react with the calcium hydroxide released from cement hydration to form further calcium silicate hydrate (C-S-H) gel.

The secondary hydration enhances the interfacial transition zone (ITZ) between cement paste and aggregate. This improves the cracking resistance and the load-carrying capacity under flexural stress. However, beyond the optimum level, the flexural strength gradually decreased with the increase in the replacement level. The flexural strength was 5.01 MPa for the 15% replacement mixture and was reduced to 4.46 MPa for the 20% replacement mixture, slightly lower than the control concrete. The decline can be due to the dilution of the cement, the higher water consumption, the incomplete hydration, and the creation of a somewhat porous microstructure. Similar observations were reported in subsequent studies where it was established that modest red mud replacement enhances the mechanical performance, but excessive replacement has an undesirable effect on the strength growth. The coefficient of variation for the flexural strength was less than 4%, indicating that the testing results had good repeatability. The improvement obtained at 10% red mud replacement was statistically significant as proven by the statistical evaluation by one-way ANOVA ( $p < 0.05$ ) when compared to the control mix.

#### 4.2 Failure Mode Analysis

The failure characteristics during the compressive, split tensile, and flexural testing give useful information about the structural behavior of red mud concrete. Figure 5 shows typical failure modes. The control specimens failed suddenly in a brittle manner under the compressive pressure with significant diagonal cracking and localized crushing around the loading surfaces. Instead, the concrete with 5–10% red mud produced a relatively smaller crack width and progressive failure mechanism before ultimate collapse. The higher compressive resistance due to the increased cement matrix density with adjusted red mud addition improved the stress redistribution and retarded the fracture propagation. In the split tensile test, the control cylinders developed a single longitudinal crack that propagated rapidly along the loading diameter. On the other hand, the samples with red mud showed delayed crack initiation and reduced widths [32]. The enhancement of MP is due to the better packing of particles and the increased bond strength between the wet cement matrix and aggregates, leading to better tenshydration, resistance, and retardation of crack formation [33].

In the flexural specimens, comparable activity was observed. The control beams failed due to a major vertical crack initiated from the tension face at mid-span. However, the 10% red mud beams showed several fine cracks before collapse and better crack dispersion with higher energy absorption capability. This behavior indicates that the optimum integration of red mud improves the matrix continuity, reduces the stress concentration, and thus improves the resistance to the fracture propagation. The observed failure modes generally suggest that moderate substitution of red mud enhances matrix integrity and controls the formation of cracks, and a more gradual mechanism of failure occurs in contrast to ordinary concrete.

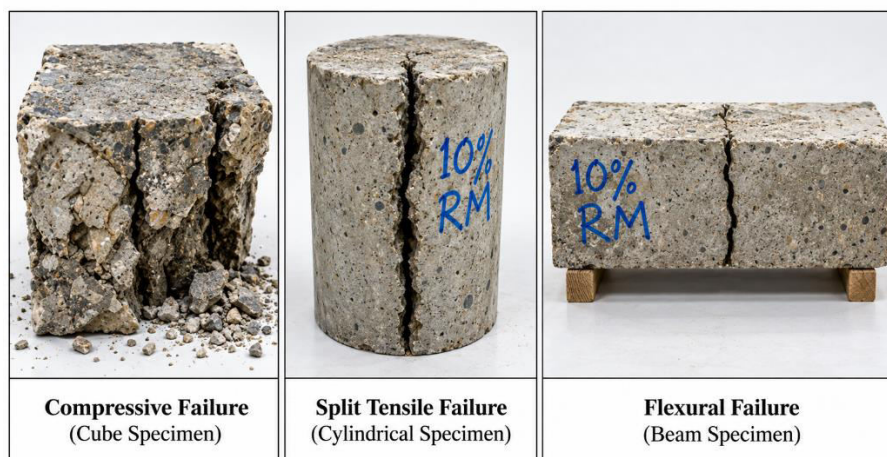


Figure.5. Typical Failure Modes of Red Mud Concrete

Figure 5 shows the typical failure modes in

- (a) compressive strength test,
- (b) split tensile strength test,
- (c) flexural strength test, and
- (d) crack propagation patterns in concrete with varied amounts of red mud.

#### 4.3 Contradiction to Previous Studies

The experimental results achieved in the present examination are in good agreement with recently published research on utilization of red mud in sustainable concrete. It has been widely reported that moderate replacement levels enhance concrete performance due to improved particle packing, matrix densification, and secondary hydration reactions, whereas excessive replacement lowers strength due to higher water demand and cement dilution [34].

5-15% replacement (Deifalla et al., 2023), 10% replacement (Ahmad et al., 2022), and This present paper deals with detailed study on workability, compressive strength, split tensile strength and flexural strength by Indian standard testing procedures and comparison with the previous studies. The optimum mix showed an enhancement of about 9.9%,

18.5%, and 15.7% in compressive strength, split tensile strength, and flexure strength, respectively. The results verified the positive effect of moderate red mud addition on performance of concrete and consumption of cement [35].

**Table.4. Comparison of Present Study with Previous Investigations**

| Study                   | Red Mud Replacement (%) | Major Findings                                                                         | Comparison with Present Study                                     |
|-------------------------|-------------------------|----------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| Ahmad et al., (2022)    | 5–15                    | Improved compressive strength and durability                                           | Similar optimum replacement range                                 |
| Deifalla et al., (2023) | 10                      | Enhanced matrix densification and strength                                             | Comparable strengthening mechanism                                |
| Li et al., (2024)       | 10–15                   | Increased strength but reduced workability at higher dosages                           | Similar trend observed                                            |
| Zhao et al., (2024)     | 10                      | Improved mechanical performance and sustainability                                     | Consistent with present findings                                  |
| <b>Present Study</b>    | <b>10</b>               | Highest compressive, split tensile, and flexural strengths with acceptable workability | Optimum balance between mechanical performance and sustainability |

The results indicate that red mud can be used as a sustainable cementitious material for structural concrete. The mechanical performance was improved and the cement consumption was reduced when 10% of cement was replaced by red mud, thereby reducing the carbon footprint of concrete production. Moreover, the positive use of red mud solves environmental problems related to the disposal of the leftovers of the Bayer process and promotes circular economy principles through the valorization of industrial waste. From the engineering perspective, concrete with 10% of red mud can be successfully used for rigid pavements, precast concrete products, masonry blocks, industrial flooring, retaining walls, low- and medium-rise buildings, and other structural applications with moderate to high strength. The reduction of workability is acceptable, and the material can be used with superplasticizers when higher workability is required according to the standard construction procedure. Further studies are needed to assess the long-term durability of red mud concrete in aggressive environments like chloride ingress, sulfate attack, carbonation, freeze–thaw cycles, alkali–silica reactions, and high temperature. Detailed microstructural characterization by Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray Spectroscopy (EDS), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), Mercury Intrusion Porosimetry (MIP), and Thermogravimetric Analysis (TGA) can provide more insight on hydration mechanisms and pore structure development. Furthermore, life-cycle assessment (LCA), embodied carbon analysis, techno-economic evaluation, and field-scale validation need to be performed to enable widespread use of red mud concrete in sustainable infrastructure projects.

## V. CONCLUSION

The present work experimentally investigates the viability of using red mud as a sustainable supplemental cementitious material (SCM) in M30 grade concrete by replacing Ordinary Portland Cement (OPC) at replacement levels of 0%, 5%, 10%, 15%, and 20%. The effect of red mud on workability and mechanical properties of concrete was studied as per Indian standard test methods. The main findings can be summarized as follows:

1. The workability decreased gradually with the increase of red mud amount due to the fine particle size, higher specific surface area, and higher water demand of red mud. The slump value was decreased from 82 mm for the control mix to 56 mm at 20% replacement, which is a total reduction of about 31.7%. This reduction was observed. However, all the mixes were cohesive and were suitable for casting with proper compaction.
2. The best overall mechanical performance was observed for the optimum replacement percentage of 10% red mud replacement level (RM10). The RM10 after 28 days of curing showed an increase of 9.9% in compressive strength (42.0 MPa compared to 38.2 MPa of control concrete), 18.5% in split tensile strength (4.29 MPa compared to 3.62 MPa of control concrete), and 15.7% in flexural strength (5.30 MPa compared to 4.58 MPa of control concrete).
3. The observed gain in strength is attributed to the micro-filler effect of fine particles of red mud, better packing of particles, densification of the matrix, and some pozzolanic reaction leading to the formation of additional calcium

silicate hydrate (C-S-H) gel. But replacement above 10% showed a reduction in mechanical performance due to dilution of cement, an increase in water demand, and an increase in internal porosity.

4. The study indicates that the substitution of long-term red mud can reduce the cement consumption and improve the engineering performance of sulfate-resistant concrete. Such a method allows positive use of an admixture, reduces disposal in landfills, saves natural resources, reduces the carbon footprint of concrete manufacturing, and reaches the objectives of a circular economy and sustainable construction.

5. The red mud concrete developed can be utilized for rigid pavements, precast concrete elements, masonry blocks, industrial flooring, low- and medium-rise buildings, and other structural and non-structural concrete elements needing improved mechanical performance and environmental sustainability.

6. Future studies should be focused on the long-term durability of red mud concrete regarding chloride ingress, attack of sulfate, carbonation, freeze-thaw cycle, and elevated temperature. Advanced microstructural characterization (SEM, XRD, FTIR, TGA) is to be performed for better understanding of hydration mechanisms. Furthermore, life cycle assessment (LCA), carbon emissions, and techno-economic evaluation are proposed to make red mud-based concrete applicable for large-scale sustainable infrastructures.

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