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FURTHER INVESTIGATION OF RED MUD UTILIZATION IN HIGH-STRENGHT CONCRETE MIXTURES

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Abstract

Red mud is a waste material generated during the processing of bauxite into aluminum. However, its disposal and management present significant environmental challenges. This study investigates the utilization of red mud (RM) as a partial replacement for cement in High Compressive Strength Concrete (HCSC) at 10% and 20% replacement levels. Concrete mixes were prepared and tested for compressive strength at 7 and 28 days. The results indicate that both 10% and 20% RM replacement levels produced compressive strengths that slightly exceeded those of the control mix at both curing ages. These outcomes demonstrate that RM, at these levels, can be used effectively as a cement substitute in HCSC without compromising strength development. The findings contribute to the advancement of sustainable concrete technologies and highlight the potential of red mud as a technically viable supplementary material for high-performance structural applications.

Keywords: Cement replacement, Compressive strength, High compressive strength concrete, Red mud, Sustainable materials.

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1. Introduction

Concrete is the most widely utilized construction material globally, underpinning infrastructure, buildings, and industrial facilities. However, its environmental impact is significant, primarily due to the high carbon intensity of Portland cement production, which accounts for approximately 8% of global CO_2 emissions [1]. In response to increasing environmental concerns, there has been a concerted effort to identify sustainable strategies to reduce the carbon footprint of concrete. One promising approach is the partial substitution of cement with industrial by-products, leveraging circular economy principles to promote material efficiency and waste valorization [2].

Among various industrial by-products, red mud (RM) has garnered increasing attention as a potential supplementary material in construction. RM is a highly alkaline residue generated during the Bayer process for alumina extraction [3]. It is estimated that the production of one ton of aluminum results in approximately 0.3 to 2.5 tons of red mud [4], with global annual generation exceeding 300 million tons [5]. Despite its substantial environmental footprint—characterized by land disposal constraints, risks of groundwater contamination, and airborne dust emissions—less than 5% of red mud is currently reutilized [6]. As a result, the safe management and valorization of red mud have become critical areas of focus within environmental engineering and sustainable construction research.

The use of red mud (RM) as a partial cement replacement in concrete can support both sustainability objectives and material properties enhancement [7]. Chemically, RM is rich in oxides such as Fe_2O_3, Al_2O_3, and SiO_2, indicating potential pozzolanic activity under suitable activation conditions [8]. Nevertheless, its high alkalinity, presence of trace heavy metals, and variability in composition present technical challenges that require careful consideration during mix design and application. Given its high material demand, the construction industry is well positioned to serve as a major end-use venue for red mud utilization, offering a practical means to reduce the environmental burden associated with its disposal [9].

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In this context, the present study investigates the incorporation of red mud as a partial cement replacement in High Compressive Strength Concrete (HCSC), with a focus on replacement levels of 10% and 20%. The experimental program emphasizes the evaluation of workability and compressive strength development at 7 and 28 days, while also considering the broader sustainability implications of red mud utilization. This research contributes to the development of sustainable high-performance concrete technologies and addresses existing knowledge gaps related to the structural viability and functional performance of red mud in cementitious systems.

2. Literature Review

The incorporation of industrial by-products as supplementary cementitious materials (SCMs) in concrete has received increasing attention in recent decades due to their potential to enhance performance while reducing environmental impacts. Materials such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) have been extensively studied and adopted in practice for their contributions to mechanical strength, durability, and reduced cement consumption. In comparison, red mud (RM), a by-product of alumina production through the Bayer process, remains relatively underutilized despite being produced in substantial quantities and presenting significant environmental management challenges due to its high alkalinity and heavy metal content [6].

Previous research on the use of RM in concrete has primarily focused on evaluating its chemical composition, reactivity, and potential pozzolanic behavior. Studies have demonstrated that when finely ground, RM can participate in secondary hydration reactions under highly alkaline conditions, contributing to strength development and microstructural refinement [8]. For example, Liu and Poon [8] reported that replacing up to 40% of fly ash with RM in self-compacting concrete mixtures can result in acceptable mechanical performance. However, such outcomes typically require careful modification of mix parameters, particularly in relation to water demand and superplasticizer dosage, to ensure adequate workability and strength development.

A primary technical challenge associated with the incorporation of red mud (RM) in concrete is its adverse effect on workability. The high specific surface area and internal porosity of RM substantially increase the water demand of cementitious mixtures [8]. If not properly addressed, this increased demand can negatively affect the fresh properties of concrete. To maintain adequate flowability, particularly in applications requiring high placement efficiency, the use of chemical admixtures—especially high-range water reducers—is typically required. Tang et al. [10] reported that in the absence of appropriate adjustments to water content or superplasticizer dosage, RM-modified concrete mixtures exhibit a marked reduction in slump flow. This reduction may limit the suitability of such mixtures for placement in heavily reinforced structural elements, where high workability is essential for proper compaction and uniform distribution.

The variability in red mud (RM) composition presents an additional challenge to its application in concrete. The chemical makeup of RM is influenced by the source of the bauxite ore and the specific conditions of the Bayer processing operation, resulting in differing concentrations of iron oxides, alumina, silica, and alkali salts [6]. Such variability in chemical composition can significantly affect the reactivity and compatibility of RM within cementitious systems. Consequently, comprehensive chemical characterization is required prior to its use, particularly in high-performance concrete applications where material consistency and predictable behavior are essential.

In terms of mechanical performance, the role of red mud (RM) in cementitious systems can range from that of an inert filler to an active pozzolanic material, depending on factors such as particle fineness, curing conditions, and the use of chemical or thermal activation methods [11]. Chen et al. [11] demonstrated that RM, when incorporated into geopolymer matrices, contributed significantly to strength development and heavy metal immobilization, indicating its potential for dual functionality. In conventional Portland cement systems, however, the extent of RM's reactivity is typically limited and is influenced by the activation energy and environmental conditions during curing.

Recent studies have explored red mud's potential role in strength development through secondary hydration or pozzolanic activity, particularly in geopolymer systems. However, its integration into conventional cement-based mixtures requires context-specific evaluation based on mix design and performance requirements.

In this regard, High Compressive Strength Concrete (HCSC) offers a distinct context for assessing red mud incorporation. HCSC exhibits significantly greater strength than conventional concrete, typically achieving 28-day compressive strengths exceeding 70–80 MPa and employing water-to-cement ratios below 0.35 [12]. The American Concrete Institute (ACI) defines high-strength concrete as having a specified compressive strength of 41 MPa or greater [13].

The use of red mud in HCSC is particularly relevant given the unique hydration characteristics of these mixtures. Due to their low water-to-binder ratios, HCSC mixtures often exhibit limited cement hydration, with reported degrees as low as 30–35% [14]. As a result, a substantial portion of the cement functions primarily as a micro-filler rather than as a reactive binder. Under such conditions, partially replacing cement with an inert or marginally reactive material like red mud may offer a viable strategy to reduce cement consumption without compromising mechanical performance.

The environmental implications of incorporating red mud (RM) in concrete production can be significant. Every ton of cement replaced by RM not only reduces the environmental burden linked to clinker production but also contributes to the safe management of a high-volume industrial by-product [6]. Previous studies, such as those by Wang and Liu [6], have highlighted the potential of RM to alleviate long-term environmental risks through its integration into construction materials.

3. Research Goals and Objectives

In response to these considerations, the primary objective of this research is to investigate the feasibility of utilizing red mud (RM) as a partial cement replacement in High Compressive Strength Concrete (HCSC). The experimental program focuses on two replacement levels, 10% and 20% by weight of cement, and assesses their impact on key performance parameters

A major goal is to evaluate the influence of red mud incorporation on the workability of HCSC, assessed through slump flow measurements. Workability is a crucial factor for high-strength concrete, especially when applied in elements with dense reinforcement, where proper consolidation must be achieved to ensure structural integrity.

Another critical objective is to assess the compressive strength development at early (7-day) and standard (28-day) curing ages. Compressive strength is a fundamental indicator of the mechanical performance of concrete, and this study aims to determine whether red mud addition results in a reduction, retention, or improvement in compressive strength relative to a control mix.

The scope of this research is limited to fresh and mechanical properties, specifically workability and compressive strength. Long-term performance characteristics, including durability, shrinkage, and chemical resistance, are not addressed and are identified as areas for future investigation.

4. Methodology

The methodology of this study was designed to investigate the effect of incorporating RM as a partial cement replacement in HCSC. Two replacement levels, 10% and 20% by weight of cement, were investigated and compared against a control mixture containing no RM.

The concrete mix designs were developed in accordance with the guidelines of the American Concrete Institute (ACI) for high-strength concrete. A water-to-binder (w/b) ratio below 0.30 was maintained across all mixtures to achieve target 28-day compressive strengths exceeding 70 MPa.

The concrete mixtures were proportioned to maintain consistent binder content and aggregate volume across all experimental groups, allowing for a direct assessment of the effect of red mud at different replacement levels (10% and 20%) on concrete performance, as shown in Table 2.

Standardized testing procedures were employed to evaluate both fresh and hardened properties. Slump flow was measured in accordance with ASTM C1611 [15] to assess workability, while compressive strength was determined at 7 and 28 days following ASTM C39 [16], representing early-age and standard-age strength development, respectively.

This experimental design was implemented to minimize variability unrelated to RM content, thereby ensuring that the observed differences in performance could be attributed primarily to the influence of red mud incorporation.

Table 1. Proposed mixes per cubic meter

MATERIAL	BASE	10%	20%
CEMENT (KG)	900	810	720
HRWR (KG)	26	26	26
#4 CRUSHED SAND (KG)	634	634	634
SILICA FUME (KG)	120	120	120
WATER (LT)	300	300	300
FLY ASH (KG)	180	180	180
RED MUD REPL. (KG)	0	61	122

4.1. Materials

All materials were selected in accordance with the performance requirements for high-strength concrete. The binder system consisted of Type I Portland cement, Class F fly ash, and silica fume. Crushed limestone sand was used as the fine aggregate, and a high-range water-reducing admixture (HRWR) was incorporated to ensure adequate workability.

The RM used in this study was sourced from the Alcoa alumina processing facility in the USA, where it is produced as a solid slurry by-product of the Bayer process. Prior to its incorporation into mortar mixtures, the RM underwent a standardized pre-treatment procedure. The material was first oven-dried at 105 °C to eliminate residual moisture, followed by mechanical grinding to reduce particle size. The ground material was then sieved to obtain fine particles passing a No. 200 sieve (75 μm), ensuring particle size compatibility with cementitious materials, see Fig. 1. The dry density of the processed RM was measured at 1,073 kg/m³. The chemical composition of the red mud, determined by X-ray fluorescence (XRF) analysis, is presented in Table 2.

Fig. 1. Red mud utilized

5. Experimentation

Concrete batches were prepared following the methodology outlined. Initially, dry mixing of the cementitious materials — Portland cement, fly ash, silica fume, and red mud — was performed for two minutes to ensure uniform distribution. Following this, approximately 80% of the mixing water and the total HRWR dose were added, and the materials were mixed for three minutes. Crushed sand and the remaining water were introduced thereafter, followed by an additional five minutes of mixing. A rest period of three minutes was allowed before the final mixing phase of five minutes.

Table 2. Chemical Composition of the red mud used in this research

Oxide	% Weight
Fe_2O_3	30.40%
Al_2O_3	16.20%
TiO_2	10.11%
SiO_2	11.14%
CaO	0.00%
Na_2O	2.00%
other	30.15%

Fresh concrete was tested immediately following mixing. Slump flow measurements were conducted in accordance with ASTM C1611 [15] to evaluate the effect of red mud (RM) incorporation on the workability of HCSC. For high-strength, self-consolidating concrete, a slump flow of at least 600 mm was targeted to ensure adequate flowability, see Fig. 2.

Fig. 2. Slum Flow test

Concrete specimens for compressive strength testing were prepared using cylindrical molds with dimensions of 100 mm in diameter and 200 mm in height. Following 24 hours of initial moist curing, the specimens were demolded and subsequently stored in water at a temperature of 25 ± 2 °C until the designated testing ages. Compressive strength was evaluated at 7 and 28 days in accordance with ASTM C39 [16]. For each mixture and curing age, four specimens were tested, and the average compressive strength was calculated and reported, see Fig. 3.

Throughout the experimental process, environmental conditions, mixing times, and curing parameters were controlled rigorously to reduce variability and ensure that the observed results could be attributed to the red mud replacement levels.

6. Findings

The incorporation of red mud (RM) into High Compressive Strength Concrete (HCSC) mixtures affected the fresh properties, particularly workability. Slump flow testing revealed a progressive reduction in flowability with increasing RM content. The control mixture exhibited a slump flow of 900 mm, while the 10% and 20% RM mixtures achieved values of 880 mm and 850 mm, respectively, as shown in Fig. 4. Although the inclusion of RM resulted in decreased flowability, all mixtures maintained slump flow values exceeding the 600 mm threshold typically associated with self-consolidating concrete (SCC), as specified in ASTM C1611. These results indicate that RM can be incorporated at moderate replacement levels without significantly compromising the workability requirements of high-performance concrete mixtures.

Fig. 3. Compressive strength test

Compressive strength testing demonstrated that the incorporation of red mud (RM) at 10% and 20% replacement levels had no adverse effect on the strength development of High Compressive Strength Concrete (HCSC). At 7 days, the control mixture achieved an average compressive strength of 66 MPa, while the 10% and 20% RM mixtures recorded strengths of 67 MPa and 64 MPa, respectively. At 28 days, the control reached 87 MPa, with the 10% RM mix attaining 89 MPa and the 20% RM mix reaching 87 MPa, see Fig. 5. These results indicate that both RM-modified mixtures have maintained strength levels comparable to or exceeding the control mix. The slight increase observed in the 10% RM mix suggests a filler effect and potential microstructural densification resulting from the incorporation of fine RM particles.

Overall, the experimental results confirm that RM can be utilized as a partial cement replacement in HCSC without compromising key performance parameters. The 10% replacement level yielded the most favorable balance between workability and strength, supporting the feasibility of RM as a sustainable supplementary material in high-performance concrete applications.

7. Discussion

The experimental results demonstrated that red mud (RM) can be incorporated into High Compressive Strength Concrete (HCSC) mixtures without significantly impairing workability. Although a slight reduction in slump flow was observed with increasing RM content, all mixtures achieved values exceeding the 600 mm threshold typically associated with self-consolidating concrete. These findings suggest that the increased water demand associated with RM can be effectively mitigated through appropriate admixture dosing and mix design adjustments. The observed decline in flowability is consistent with previous studies, which attribute this behavior to the high specific surface area and porosity of RM particles, both of which contribute to reduced workability in cementitious systems [8], [17].

The compressive strength results were particularly promising. Both the 10% and 20% red mud (RM) replacement levels achieved strength values comparable to, and in one case exceeding, those of the control mixture at both 7 and 28 days. Notably, the 10% RM mix exhibited a modest increase in compressive strength relative to the control, indicating that the fine RM particles may contribute to microstructural densification or serve as nucleation sites that promote cement hydration. This behavior is consistent with findings reported in previous studies, which have attributed strength enhancement to the pozzolanic reactivity or filler effect of red mud under specific conditions [8], [11].

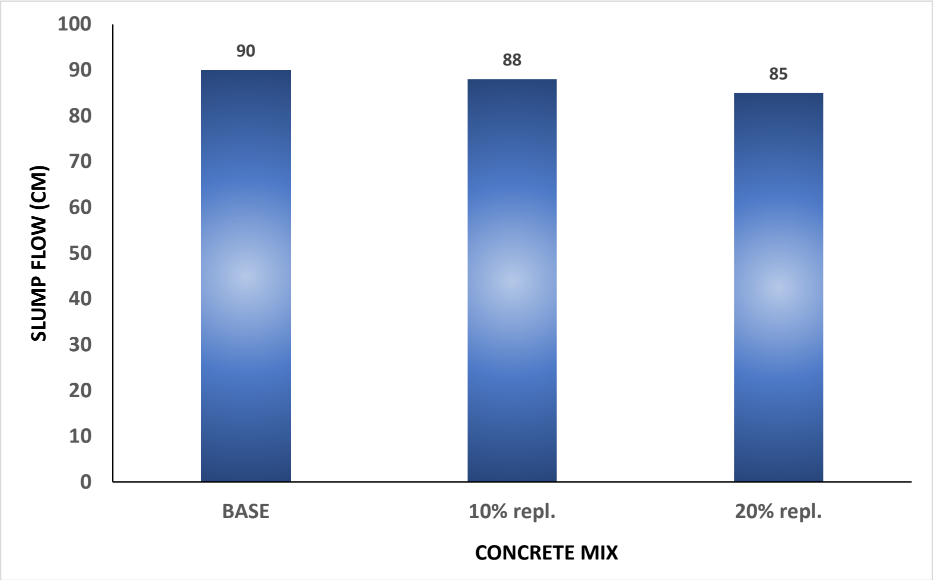

Fig. 4. Slum Flow results

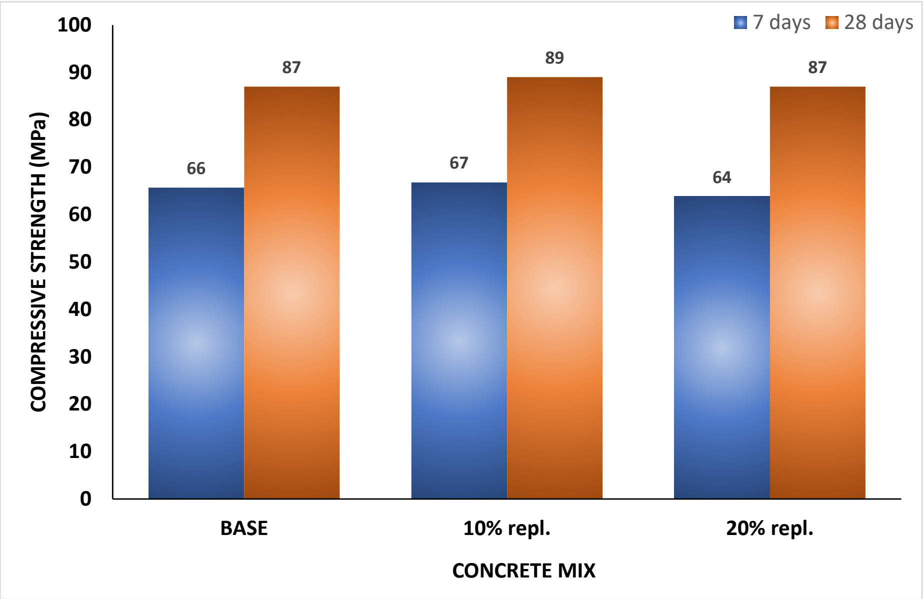

Fig. 5. Compressive strength results in MPa

An important observation from the experimental results is that the incorporation of red mud (RM) did not impede early-age strength development. At 7 days, RM-modified mixtures exhibited compressive strength values comparable to the control, suggesting that the presence of RM did not adversely affect initial hydration kinetics. This contrasts with other pozzolanic materials, such as fly ash, which are often associated with delayed strength gain at early curing ages. The fine particle size and oxide composition of RM may have contributed to the observed early strength performance by promoting particle packing and facilitating nucleation during the early stages of cement hydration. This characteristic is particularly advantageous in applications requiring early formwork removal or accelerated construction schedules.

Furthermore, the slight reduction in workability observed at the 20% red mud (RM) replacement level was not associated with a corresponding decrease in compressive strength. This decoupling between fresh and hardened properties is noteworthy, as it indicates that although RM influences the rheological behavior of the mix, it does not adversely affect the mechanical performance of High Compressive Strength Concrete (HCSC) when used at moderate replacement levels. These findings suggest potential for further optimization of admixture strategies or the development of advanced rheology control measures to facilitate higher RM incorporation without compromising constructability or structural performance.

Overall, the results support the hypothesis that a portion of the cement in High Compressive Strength Concrete (HCSC) acts primarily as a filler and can be partially replaced with red mud (RM) without compromising structural performance. The ability to maintain compressive strength with only minor reductions in workability demonstrates the viability of RM as a supplementary material for high-performance concrete applications. These findings reinforce the potential for integrating RM into sustainable construction practices and underscore the need for further investigation into its influence on long-term durability, microstructural characteristics, and other performance-related properties.

8. Conclusions

This study demonstrated that red mud (RM) can be used as a partial cement replacement in High Compressive Strength Concrete (HCSC) at 10% and 20% replacement levels without compromising key performance metrics. While RM incorporation resulted in a modest reduction in slump flow, all mixtures maintained workability within the range required for self-consolidating concrete. Compressive strength was preserved or slightly improved, with the 10% RM mix achieving an optimal balance between fresh and hardened properties. These findings validate RM as a technically viable and sustainable supplementary material for high-performance concrete. Further research is recommended to evaluate its long-term durability and microstructural development.

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