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Eco-Innovative Use of Red Mud: Impact on the Compressive Strength of HSC

Ibrahim Alameri[1]
Assist. Prof. Dr., Civil Engineering
i.ameri@eiu.edu.ye

Ahmed Yafa'a[2]
Assoc. Prof. Dr., Arch. Engineering
dr.yafaa.ahmed@eiu.edu.ye

Mohammed Alhaifi
Prof. Dr., Civil. Engineering
dralhaifi@tu.edu.ye

Abstract

This study investigates the effect of partial replacement of Portland cement with red mud on the compressive strength of high-strength concrete (HSC). Red mud, an industrial by-product of alumina production, was replaced at ratios of 5, 10, 15, 20, 25, 30, and 35% by weight of cement. Compressive strength tests were performed on the produced concrete cubes. The results showed that a reference HSC mix (0% red mud) achieved a compressive strength of 85 MPa. However, red mud replacement reduced the compressive strength at all ratios, decreasing to 70 MPa at 5% and 56 MPa at 35%. In contrast to reported results for medium-strength concrete, where optimum red clay ratios (e.g., 10–20%) can maintain or increase strength, no such optimum ratio was observed for the high-strength concrete investigated here.

Keywords: Red Mud; Waste; High strength concrete; Compressive strength

1. Introduction

Concrete stands out as the most widespread construction material worldwide due to its strength, durability, and economic viability (Qureshi et al. 2022; Raj et al. 2024). However, the manufacturing process of its primary binder, Portland cement, is particularly energy-intensive and contributes greatly to global anthropogenic CO_2 emissions (Qureshi et al. 2022). This significant environmental impact drives the ongoing search within the construction sector for sustainable alternatives, especially supplementary cementitious materials capable of partially replacing cement (Jia et al. 2024). The use of supplementary cementitious materials aims to reduce the environmental burden caused by cement production and, in some cases, improve the properties of concrete (Shukla et al. 2023).

High-strength concrete (HSC), defined by high compressive strength (typically >50-60 MPa), allows for slender structural members and improved durability, however, its typically higher cement content can amplify environmental concerns associated with cement manufacturing.

Red mud, the residue of alumina extraction via the Bayer process, is a large-scale industrial by-product produced globally (Viyasun et al. 2021). Annual production amounts to millions of tons, posing significant challenges for safe disposal and long-term environmental management due to its high alkalinity (pH 10-12) and potential for contaminant leakage (Raj et al. 2024; Rupa et al. 2025; Shirodkar et al. 2023). Consequently, identifying effective methods to utilize red mud is a critical aspect of sustainable industrial development and waste management (Alameri and Oltulu 2020). Due to its chemical structure containing oxides of silicon, aluminum, iron and calcium, red mud has been investigated as a potential supplementary cementitious material in concrete formulations (Mahmoud 2025; Shirodkar et al. 2023).

Studies examining red mud as a partial cement replacement have yielded variable results, particularly regarding its effect on compressive strength, with most studies focusing on conventional or intermediate strength concrete grades (Alameri and Oltulu 2020; Shirodkar et al. 2023; Viyasun et al.

2021). Some studies suggest that incorporating red mud at lower replacement levels, typically specified as between 10% and 20%, can provide comparable or even improved strength compared to control mixtures (Venkatesh et al. 2020). These benefits are generally attributed to a physical packing effect where the fine red mud particles refine the pore structure and potential pozzolanic reactions contributing to the formation of hydration products (Ding et al. 2024; Mahmoud 2025; Ren et al. 2025). However, a consistent finding across studies is a decrease in strength at higher red mud percentages, typically above 15–20% (Ai et al. 2021; Shukla et al. 2023; Viyasun et al. 2021). The behavior of supplementary cementitious materials may differ significantly in the microstructural and chemical environment of HSC, which is characterized by its low water-binder ratio and dense matrix. Therefore, the primary objective of this study was to evaluate the effect of partially replacing cement with red mud at various percentages (5% to 35%) on the 28-day compressive strength development in high-strength concrete.

2. Materials and Methods

2.1. Materials

The primary materials used in this experimental investigation were red mud, Portland cement, coarse and fine aggregate, water, and superplasticizer. Eight concrete mixes were prepared. The control mix (M1) contained 0% red mud. In subsequent mixes (M2 to M8), red mud was partially replaced by Portland cement at ratios of 5%, 10%, 15%, 20%, 25%, 30%, and 35% of the total cementitious weight as listed in Table 1.

Table 1: Mix Designations and Red Mud Replacement Ratios

Group Code	Red Mud Ratio (%)	Cement Ratio (%)
M1	0	100
M2	5	95
M3	10	90
M4	15	85
M5	20	80
M6	25	75
M7	30	70
M8	35	65

2.2. Specimen Preparation and Curing

For each concrete mix, cubic samples of 15 cm × 15 cm × 15 cm were cast. After casting, the samples were removed from the mold after 24 h and cured in water at standard laboratory conditions for a period of 28 days before testing.

2.3. Compressive Strength Testing

Compressive strength tests were performed on 28-day cured cubic specimens using a calibrated pressure testing machine. The tests were performed following the procedures specified in the TS EN

12390-3 standard. The maximum load that each specimen could carry before fracture was recorded, and the compressive strength was calculated by dividing the maximum load by the cross-sectional area of the specimen.

3. Results and Discussion

The compressive strength results of high-strength concrete (HSC) mixtures using red mud as partial cement replacement are summarized in Table 2 and visualized in Figure 1.

Table 2: Compressive Strength Results at 28 Days

Group Code	Red Mud Ratio (%)	Compressive Strength (MPa)
M1	0	85
M2	5	70
M3	10	64
M4	15	69
M5	20	61
M6	25	59
M7	30	58
M8	35	56

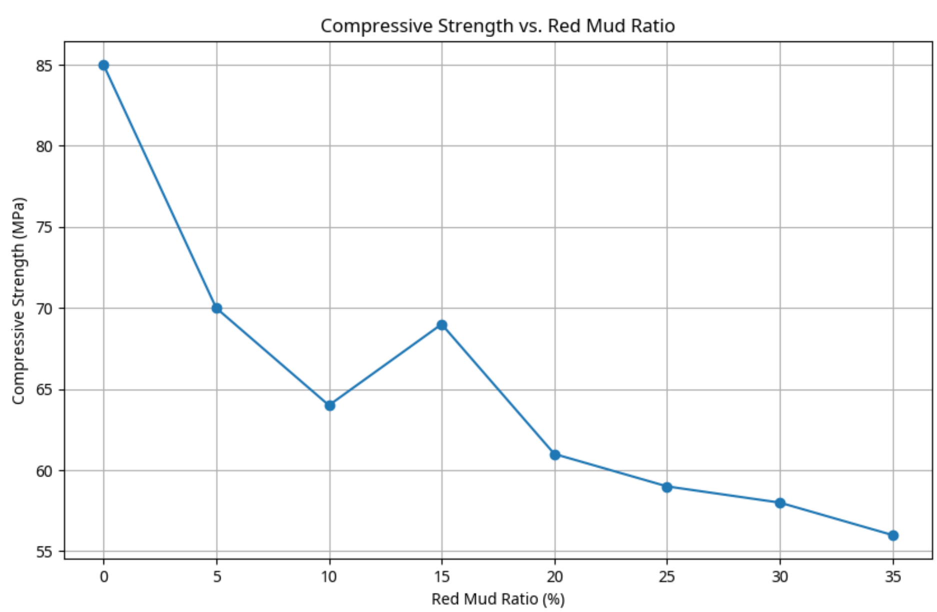

Fig. 1: Effect of Red Mud Replacement Ratio on 28-Day Compressive Strength of HSC

The experimental data show a clear trend: the control mixture (M1) achieved the highest compressive strength at 85 MPa. However, the use of red mud as a partial cement replacement resulted in a continuous decrease in compressive strength at all tested percentages (5% to 35%). At the lowest replacement level (M2) of 5%, the strength decreased significantly to 70 MPa, corresponding to a decrease of approximately 17.6% compared to the control mixture. As the red mud content increased, the compressive strength generally continued to decline, reaching 64 MPa at 10% (M3), 61 MPa at 20% (M5), 59 MPa at 25% (M6), 58 MPa at 30% (M7), and a minimum of 56 MPa at the highest replacement level of 35% (M8). A slight deviation was observed at 15% replacement (M4), where the compressive strength (69 MPa) was slightly higher than that of the 10% mixture (64 MPa), but this value remained significantly lower than the reference compressive strength and did not change the overall downward trend shown in Figure 1.

This finding stands in notable contrast to numerous studies conducted on conventional or moderate-strength concrete (e.g., M30 grade), where partial replacement of cement with red mud has often shown potential benefits at lower percentages. For instance, Viyasun et al. (2021) reported increased strength properties in M30 concrete with up to 20% red mud replacement. Similarly, Shirodkar et al. (2023) identified 10% red mud as the optimal replacement level for enhancing compressive strength and durability in their M30 concrete study. Venkatesh et al. (2020) also found optimal mechanical properties at 5% (untreated) and 10% (treated) red mud replacement in their concrete mixes.

The discrepancy likely arises from fundamental differences between high-strength and medium-strength concrete, particularly the significantly lower water-to-binder (w/b) ratio and the denser, less permeable microstructure inherent in high-strength concrete. In moderate-strength concrete with higher w/b ratios and more porous structures, the fine particles of red mud can exert a beneficial physical filler effect, occupy voids and refine the pore structure. Additionally, some pozzolanic activity, where reactive silica and alumina in red mud react with calcium hydroxide (CH) from cement hydration, might contribute to the formation of additional calcium silicate hydrate (C-S-H) and calcium aluminate silicate hydrate (C-A-S-H) gels over time, further enhancing strength.

However, in the highly optimized and dense matrix of HSC, these potential benefits appear to be negated or overshadowed. The physical filler effect is less pronounced because the initial packing density is already high, and the available void space is minimal. In addition, replacing highly reactive cement particles with less reactive or inert red mud particles weakens the overall binder matrix and disrupts the continuity of the hydration products, leading to the observed reduction in compressive strength, even at low replacement levels. Moreover, the inherent characteristics of the specific red mud used are critical. High concentrations of certain components, particularly alkalis (like Na_2O), can negatively impact hydration processes and long-term durability.

4. Conclusion

Based on the experimental results regarding the partial replacement of cement with red mud (5% to 35% by weight) in high-strength concrete, the following conclusions can be drawn:

- The use of red clay as a partial cement replacement resulted in a continuous decrease in the 28-day compressive strength of HSC compared to the reference mix (85 MPa). The strength gradually decreased from 70 MPa at 5% replacement to 56 MPa at 35% replacement.
- No optimum replacement ratio was observed to achieve maximum compressive strength within the tested range (5-35%). The highest compressive strength was achieved using 0% red mud.
- This study highlights that the effects of red mud are largely dependent on the grade of concrete. Despite its potential benefits in some applications, its use as a direct cement replacement in high-strength concrete has resulted in reduced compressive strength. Future research should focus on exploring potential activation or pretreatment methods to improve HSC performance.

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