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Influence of Red Mud on workability, Setting Time, and Strength in Cementitious Mixes for 3D Printing Applications

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Abstract **-** This study investigates the printability and performance of cementitious mortar mixtures with varying proportions of red mud (RM) as a partial ordinary Portland cement (OPC) replacement, targeting optimal parameters for 3D printing applications. RM, a by-product of aluminum production, was incorporated in place of cement at levels ranging from 0% to 40%, with the aim of evaluating its impact on workability, setting time, and compressive strength of printed structures. Multiple tests, including flow table and slump tests, were conducted to assess flowability and extrudability, with results indicating that a slump range of 6.5 to 11.5 mm and a flow table spread of 165 to 190 mm provided ideal conditions for consistent printing quality. Notably, setting times increased slightly with RM addition, attributed to RM's fine particle size and high water demand, which delayed initial hydration reactions. Compressive strength decreased as RM content increased, highlighting the need for precise water content adjustments to balance flowability with structural integrity. Visual inspections indicated improved extrudability and layer cohesion with higher RM content, supporting findings on the enhanced rheological properties of RM-modified mixes. These results provide important insights for optimizing 3D-printable OPC-based materials incorporating industrial by-products, contributing to sustainable construction methods and advancements in additive manufacturing technology.

Keywords**:** 3D printing; Red mud; Cement replacement; workability.

1. Introduction

The advancement of 3D printing technologies for cementitious materials is a key driver of innovation in improving modern construction [1, 2]. As the construction industry seeks more sustainable practices, the incorporation of industrial by-products like red mud (RM) in cementitious mixes has emerged as a promising solution, aligning with goals of waste minimization and resource efficiency. RM, an alumina-refining by-product, is produced in vast quantities globally and poses environmental disposal challenges. Its integration as a partial cement replacement in construction materials not only offers potential environmental benefits but also brings unique properties that may affect mix workability, hydration, and strength development.

Achieving the right balance of flowability, setting time, and strength is critical in formulating mixtures suitable for 3D printing. Prior research highlights that particle packing and rheological adjustments in mixes containing fine particles can improve extrusion consistency and layer cohesion, which is essential for reliable 3D-printed structures [3-7]. In this study, nine mix compositions were formulated with OPC replacement levels up to 40% by RM, accompanied by iterative adjustments in water content to optimize workability for printing. The flow table and slump tests were utilized to assess flowability, while setting time and 28-day compressive strength tests provided further insights into the impacts of RM on both workability and long-term performance.

2. Experimental Program

2.1 Source Materials

The primary binder utilized in this research was ordinary Portland cement (OPC), which served as the foundational material for all mixtures. Additionally, RM was introduced as a secondary binder to partially replace OPC, allowing for an investigation into its effects on the workability and mechanical performance of the mixtures. The RM was calcined at 650 °C for 3 hours to enhance reactivity in this study.

2.2 Printer and Print geometries

Several iterations and modifications were implemented throughout this research to develop a 3D printer capable of producing layers that simulate those used in actual construction applications. Fig. 1(a) illustrates the concept behind the printer utilized in the study, originally based on a device used in the construction industry for filling mortar between block gaps. This device, however, underwent extensive adjustments and enhancements to enable it to print larger, continuous layers suited to the demands of 3D printing in construction.

Fig. 1(b) presents a front view of the nozzle fabricated for this study, with dimensions of 5 cm in width and 2 cm in height, specifically designed to replicate the typical size of 3D-printed layers in construction applications. To further ensure stability and precision, a custom setup was fabricated to control both the vertical and horizontal movements of the 3D printing process, as shown in Fig. 2. This setup helped maintain smooth and consistent material deposition, ensuring solid layer adhesion and uniformity during printing. Fig. 2 captures a view of the setup, printer, and nozzle during the printing of the first layer.

(a) (b)

Fig. 1: (a) Mortar filling device; and (b) Front view of the nozzle.

Fig. 2: 3D printing of the first layer using the developed printer.

2.3 Material Proportions

In examining the influence of RM as a partial replacement of OPC in cementitious mixtures, nine compositions, detailed in Table 1, were formulated and systematically evaluated for printability. Mix designs ranged from a control composition with 100% OPC to formulations incorporating up to 40% RM as a cement replacement. The sand was incorporated as 50% by volume of the binder materials across all mixes to maintain structural stability and uniformity.

It's well known that the w/b ratio is a very important indicator during the optimization of 3D printing [8]. Each mix initially utilized a water-to-binder ratio (w/b) of 0.4 as a baseline; however, water content was subsequently adjusted during mixing to ensure optimal flowability for printing. This approach enabled real-time calibration of mix workability, thereby meeting the necessary criteria for extrudability and buildability required in the formation of stable and cohesive printed layers. Table 1 shows the actual w/b values of different mixes.

Table 1: Mix proportions.

No.	Mix ID	OPC (wt.%)	RM (wt.%)	Sand (vol.%)	w/b
1	CR0	100%	0%	50%	0.480
2	CR5	95%	5%	50%	0.456
3	CR10	90%	10%	50%	0.485
4	CR15	85%	15%	50%	0.515
5	CR20	80%	20%	50%	0.515
6	CR25	75%	25%	50%	0.515
7	CR30	70%	30%	50%	0.515
8	CR35	65%	35%	50%	0.550
9	CR40	60%	40%	50%	0.565

2.4 Test Methods

Five tests were employed to assess the printability of the different mortar mixes. The first test involved visual inspection, which was conducted to qualitatively assess the extrudability, buildability, and layer bonding of the printed material. The flow table [9] and mini-slump [10] tests were then used to evaluate the workability of the mixes. The setting time tests [11] were essential to determine the mix's workability window, ensuring it remained printable for a sufficient duration. Finally, the 28-day compressive strength test [12] was conducted on 50 mm cubes to assess the strength of the mixes.

3. Results and Discussion

3.1 Visual inspection

The study began with the mix CR0, composed solely of cement, and extended to CR40, which incorporated 40% RM. The first two mixes, CR0 and CR5, demonstrated poor buildability and were unsuccessful in the printing process. CR10 and CR15 were also not reasonably successful. The failure in these formulations is attributed to inadequate buildability and poor layer adhesion, which prevented proper material deposition and structural integrity during printing. In contrast, the remaining five mixes, with RM content of 20% or higher, exhibited successful printability, though their performance varied based on the specific proportions of RM. Fig. 3 shows the failed mixes (CR0 and CR5), along with some of the passed mixes (e.g., CR25 and CR35).

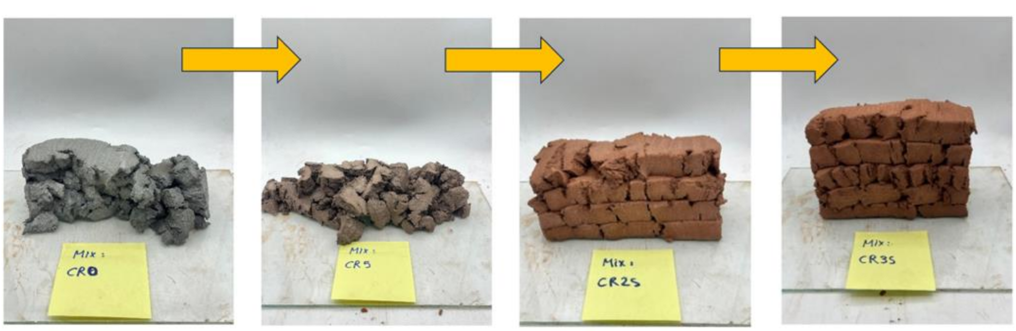

Fig. 3: Failed mixes on the left (CR0 and CR5), and some of the passed mixes on the right (CR25 and CR35).

It was noticed that as the RM content increased, an improvement in extrudability and buildability was observed, which led to smoother extrusion and enhanced layer cohesion. This is consistent with findings in the literature, where the incorporation of fine particles, such as RM, has been shown to improve the rheological properties of cement-based mixtures in favour of printability [13, 14]. The presence of RM contributed to better particle packing, which reduced material segregation and enhanced flowability. The improved packing density allows for a more consistent extrusion process and better layer bonding, which is crucial for successful 3D printing [13, 14].

Particle packing theory supports these observations, indicating that finer particles fill the voids between coarser particles, resulting in a denser and more cohesive material. In the context of cement-based 3D printing materials, this effect leads to better material flow and structural stability during the printing process. Additionally, the increased RM content enhanced the cohesion between printed layers, a critical factor in ensuring the mechanical integrity of the final printed object [15].

3.2 Flow table and Slump Results

The flow table and slump tests are essential for assessing the flowability and workability of cementitious materials. Fig. 4 presents the outcomes of these tests, which illustrate the impact of varying water content on the performance of each mixture. Multiple adjustments to water content were made across different mixtures in successive trials to achieve optimal smoothness and extrudability, both critical requirements for successful 3D printing. This iterative process—where the water content in each mix was adjusted and printability assessed, indicates that a slump range of 6.5 to 11.5 mm and a flow table spread of 165 to 190 mm are appropriate parameters for achieving consistent print quality.

Interestingly, for mixes CR15, CR20, CR25, and CR30, all formulated with a water-to-binder ratio of 0.515, even though all of those mixes were printable with different performance, a slight decrease in flow table and slump values was observed as evident in the literature [13, 16]. This trend suggests that the partial replacement of cement with RM, a finely particulate material, necessitates increased water content to achieve sufficient flowability. However, increasing the water content in RM-based mixtures may lead to a reduction in compressive strength, a point which will be elaborated upon in the subsequent section. Thus, careful calibration of water content is crucial to balancing the conflicting requirements of flowability and structural integrity in 3D-printed constructions.

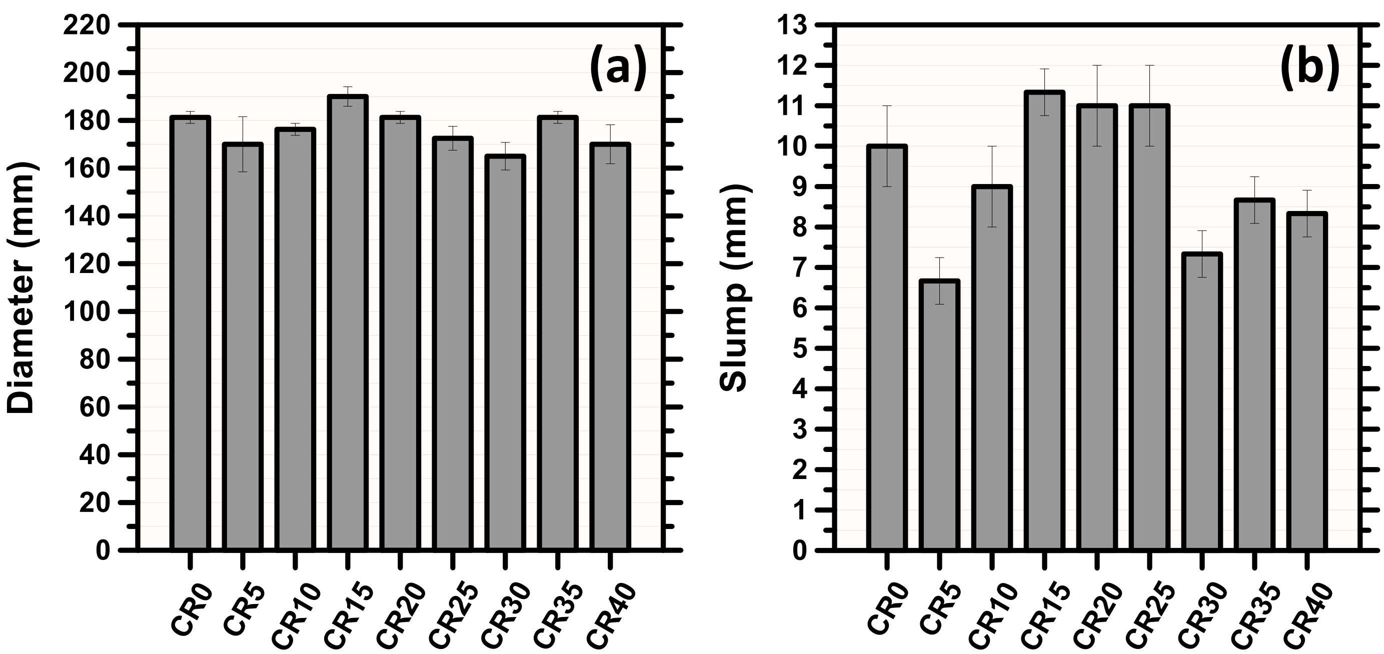

Fig. 4: (a) Flow table test results; (b) Slump test results.

3.3 Setting time

Fig. 5 shows the initial and final setting times for the various mixes. The data reveal a slight increase in the initial setting time as RM is incorporated through the partial replacement of cement. Importantly, the final setting time is not almost affected.

The observed increase in initial setting time can be attributed to the fine particle size and absorptive nature of RM. RM's high surface area results in increased water demand within the mix to maintain workable consistency. This rise in the w/b ratio delays the hydration process, leading to a prolonged initial setting time, as hydration reactions are sensitive to water content and the presence of non-cementitious materials.

The disparity between the initial and final setting times can be explained by red mud's limited chemical reactivity within the mix. Unlike cement, RM does not contribute directly to the hydration process but rather functions as an inert filler. During the early stages, this filler effect disrupts the formation of critical hydration bonds needed for setting, resulting in a noticeable extension of the initial setting time. Over time, however, the hydration reactions proceed, and the final set occurs without significant delay, as the cement content ultimately governs the mix's hardening.

In summary, the addition of RM increases the setting times, with a particularly noticeable effect on the initial setting. This phenomenon underscores the need for careful water content adjustment and monitoring of setting times in mixes with RM replacement to ensure consistency in application and performance.

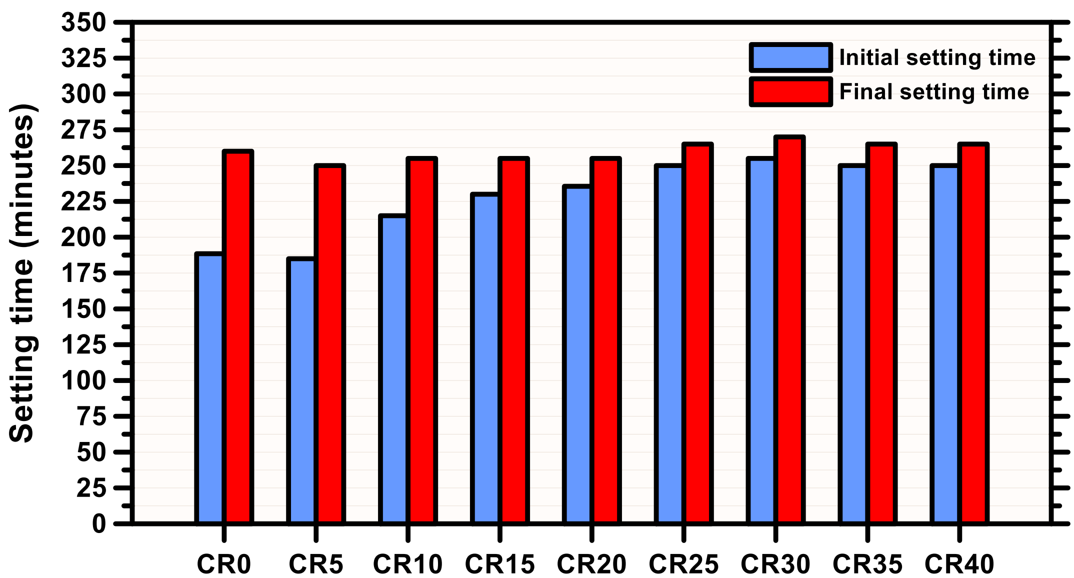

Fig. 5: Initial and final setting times.

3.4 Compressive strength

Fig. 6 presents the 28-day compressive strength results, illustrating a clear trend of decreasing strength as the proportion of RM increases through partial replacement of cement. This decline in compressive strength can be primarily attributed to two interrelated factors: the fine particle size of RM and its high water demand. Due to its fine granularity and absorptive nature, RM requires an increase in water content to ensure adequate workability and flowability within the mix. However, this necessary increase in water content leads to a higher water-to-cement ratio, which, as established in cementitious materials research, generally weakens the overall matrix structure by increasing porosity and reducing the density of the hardened cement paste.

Furthermore, RM mineral composition may also contribute to the observed decrease in strength. Unlike traditional cement particles, RM particles do not undergo the same hydration reactions that contribute to strength development. Instead, Instead, they act as fillers, which, while potentially beneficial for workability, provide limited contributions to strength gain gain over time. As water content increases to accommodate RM fine particles, the dilution of cementitious compounds further

further reduces the available binding capacity, compromising the structural integrity of the mix. Thus, while RM can enhance certain properties like flowability, its inclusion at higher levels necessitates careful management of water content to mitigate its adverse effects on compressive strength. In summary, the increase in RM content, coupled with the resulting water demand, leads to a dual effect: an initial improvement in workability offset by a notable decrease in compressive strength, highlighting the need for precise adjustments to achieve optimal performance in RM-based cementitious formulations.

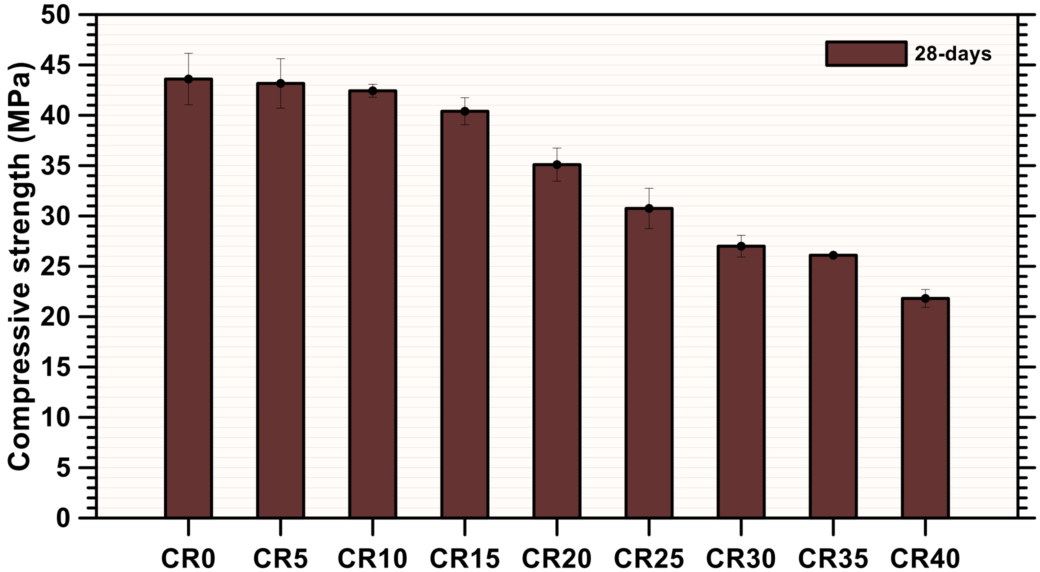

Fig. 6: 28-days compressive strength.

4. Conclusions

This study evaluated the potential of RM as a partial cement replacement in 3D-printable cementitious mixtures, examining its effects on workability, setting time, and compressive strength. Results from flow table and slump tests indicated that RM can improve flowability and extrudability within a specific water content range, with optimal slump values of 6.5 to 11.5 mm and flow table diameters between 165 and 190 mm. These parameters were identified as essential for achieving consistency in 3D-printed layers, supporting reliable deposition and cohesion.

However, the addition of RM was found to delay setting times, particularly the initial set, due to RM's high water demand and its fine particle structure. This trend underscores the need for controlled water adjustments to balance early hydration rates and printing timelines. Furthermore, compressive strength tests revealed that as RM content increased, there was a notable reduction in the 28-day compressive strength of the samples. This strength reduction is attributed to both the increased water content required to accommodate RM and the inert nature of RM, which does not actively contribute to cementitious hydration.

The findings suggest that while RM can improve certain aspects of workability and reduce reliance on traditional cement, it necessitates careful calibration of water content and mix proportions to offset its effects on setting time and strength. Future studies may explore admixtures or additives that could enhance the binding potential of RM-based mixtures, potentially addressing the observed trade-off between workability and compressive strength. Overall, this research contributes valuable insights into sustainable cement formulations, demonstrating the feasibility of using RM in 3D-printable mixes while emphasizing the need for adjustments to achieve optimal performance.

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