Change in Fresh and Rheological Properties of Mortar and Concrete prepared using Red Mud - A Review

Manasa Putrevu1, T. Jothi Saravanan1, Kunal Bishit and K. I. Syed Ahmed Kabeer3

1School of Infrastructure, Indian Institute of Technology Bhubaneswar, Odisha, India
2Department of Civil Engineering, KIET Group of Institutions, Delhi NCR, India
3School of Architecture and Interior Design, SRM Institute of Science and Technology, Tamil Nadu, India
Email: pm27@iitbbs.ac.in

Abstract. The construction industry produces 5-7% of all CO₂ emissions and is the second-highest emitter of all industrial carbon dioxide. Reusing industrial waste and by-products in cementitious materials has found to enhance properties and reduce the carbon footprint. Red mud is one such byproduct generated in large quantities during the manufacturing of alumina. Red mud's utilization in the construction industry can also address the challenge of increasing red mud reserves, posing a threat to the environment. The studies carried out by various authors suggest that red mud could successfully be incorporated in concrete and mortar. The extent of incorporation of red mud in the material can be decided based on the required application and properties. This paper presents a comprehensive review of red mud's effect on the rheological and fresh properties of concrete and mortar which are crucial for their constructability.

Keywords: red mud; cement; concrete; mortar; rheological properties; fresh properties; pozzolanic activity

1. Introduction

Aluminum is the second most abundant metal produced in the world. Around 60 million tons of aluminium was produced globally from bauxite ore in 2015 [1]. The commonly used processes to produce alumina are the Bayer and sintering methods. Red mud which is a by-product of alumina is generated on a large scale in these two processes. Different disposal methods are used for this vast amount of red mud produced. In the Shanxi Aluminium Plant, China, red mud is stored in a dam which not only occupies a large area of land but also costs around 8 million dollars for its maintenance. Approximately 5 million tons of red mud produced here is pipelined to the dam every year [2]. In Seydisehir Aluminium plant (Turkey) also red mud is dumped annually into specially constructed dams around the plant [3]. There has been more than 22 million tons of red mud waste accumulated at Shandong Aluminium Plant since the plant was set up in 1954 [4]. In Iran, significant quantities of red mud are stored in areas adjoining the alumina plants [5]. One of the factory industrial dump of red mud in Hungary brought about an ecological disaster in October 2010. A wave of red mud flooded the nearest city, caused the death of nine people, polluted 40 km² of land and poured into the Danube river [6]. Considering the significant adverse environmental effects of red mud disposal into open lands and water bodies, many studies are devoted to the utilization of this residue.

1.1 Utilization of red mud

Several applications have been identified for red mud utilization according to its physical and chemical properties. Some of them include recovery of various rare earth metals like Ga, Sc, Nb, Li, V, Rb, Ti and Zr, and high iron, sodium and aluminium content in red mud, utilization as a filling material, remediation of contaminated sites and treatment of contaminated liquid waste after adequate neutralization. Red mud can also be an excellent alternative to commercial catalysts due to benefits like low cost, high surface area,
sintering resistance and resistance to poisoning and it can be utilized for building materials production such as cement, bricks, glass-ceramics, clay-based products and geopolymers [7]. Apart from these, researchers have also proposed numerous other methods of utilization of red mud. Still, the production of construction materials using red mud was found to be an efficient approach as it enables bulk usage and provides a potential opportunity to minimize its environmental threat.

Different review studies in the past addressed the utilization of red mud. A number of authors [8,9,10,11,12] studied the applications of red mud. A few authors [13,14] reviewed red mud usage in road base materials. Some other review studies [15] addressed the status of red mud utilization in India and its usage as a construction material. However, this study is specific to the usage of red mud in concrete and mortar and its effect on the fresh and rheological properties of the resulting mix.

2. Materials and methods
In this article, the impact of the addition of red mud on various rheological and fresh properties of the formulated mixes from different papers is assessed highlighting the versatility of red mud as a sustainable material. Depending on the material of study, fly ash and cement were replaced with red mud in varying proportions, to understand the possible extent of utilization of red mud such that the materials possess acceptable values of properties. Experiments were performed in India, South America, China, Iran, Brazil and Spain using different types of red mud. Various experiments were performed in different studies on the samples to determine the optimum red mud content in different construction materials.

2.1 Properties of red mud
The chemical composition of the red mud varies with the origin of bauxite ore and the production process of alumina used [16]. Irrespective of the production process red mud mainly consists of silicon, aluminium, iron, calcium, titanium and sodium oxides [7]. Red mud particles are fine (<10μm) and have a high specific surface area (13cm²/g). Due to its composition, red mud also produces highly alkaline slurries when it reacts with water contributing to its hazardous nature [17]. The chemical composition and physical properties of red mud used in the papers reviewed are tabulated in Table 1 and Table 2, respectively.
### Table 1. Chemical composition of RM used in various studies

| Material | Na$_2$O | MgO | Al$_2$O$_3$ | CaO | TiO$_2$ | SiO$_2$ | Fe$_2$O$_3$ | SO$_3$ | K$_2$O | P$_2$O$_5$ | LOI | MnO | Reference |
|----------|---------|-----|------------|-----|---------|---------|------------|--------|--------|-----------|------|-----|-----------|
| Mortar   | 6.84    | -   | 18.8       | 3.27| 11.2    | 5.54    | 51.8       | 0.23   | 0.08   | 0.16      | 0.04 | 0.02 | [16]      |
|          | 6.84    | -   | 18.76      | 3.27| 11.2    | 5.54    | 51.8       | 0.23   | 0.08   | 0.16      | 0.04 | 0.02 | [17]      |
|          | 0       | 0   | 40.69      | 4.98| 2.03    | 45.76   | 2.85       | 2.15   | 0.45   | 8.14      | -    | -    | [18]      |
| Concrete | 3.13    | 0.91| 23.92      | 18.6| 0       | 2.79    | 15.21      | 18.58  | -      | 0.92      | -    | 9.10 | [4]       |
|          | 8.31    | -   | 17.58      | 4.38| 5.55    | 16.94   | 37.26      | -      | -      | -         | 7.17 | -    | [19]      |
|          | -       | 1.19| 7.11       | 38.3| 18.92   | 12.55   | 0.49       | -      | -      | 15.44     | -    | -    | [20]      |
| Concrete | 5.4     | 1.7 | 17.7       | 14.7| 7.2     | 14.8    | 27.6       | 0.1    | -      | -         | -    | -    | [5]       |
|          | 10.83   | -   | 28.24      | 2.90| 7.50    | 17.90   | 23.79      | 2.49   | -      | 5.96      | -    | -    | [21]      |
|          | 4.90    | -   | 26.24      | 4.90| 7.50    | 17.90   | 23.79      | -      | -      | 5.96      | -    | -    | [22]      |
|          | 5.86    | 0.25| 14.85      | 3.00| 7.00    | 8.39    | 52.85      | -      | -      | -         | -    | -    | [23]      |
|          | 9.41    | 1.61| 23.53      | 1.83| 6.84    | 14.88   | 36.48      | -      | -      | -         | 14.88| -    | [24]      |
| SCC      | 4.37    | 1.75| 16.63      | 18.2| 5.21    | 13.36   | 23.68      | 0.46   | 0.48   | 0.143     | 14.89| -    | [25]      |

### Table 2. Physical properties of RM used in various studies

| Density(kg/m$^3$) | Specific area(cm$^2$/g) | Average grain size(μm) | Reference |
|-------------------|--------------------------|-------------------------|-----------|
| -                 | 20×10$^4$                | 0.78                    | [16,17]   |
| 2187              | -                        | -                       | [18]      |
| 2187              | -                        | -                       | [2]       |
| -                 | 14.2×10$^4$              | -                       | [26]      |
| 3150              | -                        | -                       | [5]       |
| 2420              | 13×10$^4$                | <10                     | [22]      |
| 2420              | 22×10$^4$                | -                       | [21]      |
| 2950              | -                        | 2.86                    | [27]      |
| 3200              | -                        | -                       | [25]      |
3. Performance of cement and mortar containing red mud

3.1 Rheological properties
For a better characterization of mortars in the fresh state, rheometer was used to detect differences between set of samples showing closer values of workability [16]. Mixing of fine particles like red mud in mortars can alter their behaviour significantly. Therefore, rheological property tests can be used to describe the effect of different deformation rates which is not possible in the case of flow tests [17].

The assessment of rheological properties for mortar mixes by [16] showed that the yield stress increased with time. In contrast, the plastic viscosity was nearly constant over time, indicating yield stress to be a better parameter for observation of rheological behaviour. Superplasticizer exhibited better control of rheological behaviour compared to varying water to binder ratio. They prepared mortar mixes with varying red mud and water to binder ratio (W/B) and observed, 20% of cement replaced with red mud and W/B of 0.47 (medium replacement of cement and low W/B ratio) to exhibit the highest plastic viscosity. The formation of long polycarboxylate chains that interacted with other particles in solution, in this case, was responsible for the increased viscosity. The viscosity of the mixes also increased with red mud addition [16].

Results from a study [17] showed that the red mud addition increased the torque value. But the torque is more affected by the reduction of water content than by the addition of red mud. As red mud particles are very fine (specific area of 20m²/g and an average particle size of 0.78μm) they tend to agglomerate and hinder the flow of the mix increasing the torque required. The vertical variation on the torque line also gradually increased in each stop time. Intense structure formation takes place during this period, and the maximum torque required to turn back the mix is higher in each successive period. Therefore, the addition of red mud resulted in a substantial change in rheological properties over time with changing superplasticizer amounts and water content.

3.2 Pozzolanic activity
The red mud used in different papers was observed to have different pozzolanic activity depending on the production process of red mud used. A study has [18] used the strength activity index (SAI) to evaluate the pozzolanic activity of the red mud and fly ash. As shown in Table 3, the value of the SAI of red mud was similar to that of fly ash. The similarity was due to the similar chemical components which were responsible for the pozzolanic activity like Al₂O₃, SiO₂ and Fe₂O₃ present in both red mud and fly ash. Whereas another study [17] observed the concentrations of calcium and hydroxyl ions in the solution contacting with red mud containing mortar samples to be 1.7 mmol/L and 141.2 mmol/L, respectively. This indicates that the red mud could not sufficiently fix calcium ions and hence exhibited low pozzolanic activity as opposing to the previous case.

The differences in pozzolanic activity were also responsible for varying trends observed in other experiments as performed by various authors.

| Table 3. Pozzolanic activity [18] |
|-------------------------------|
| Strength Activity Index (%)    |
| 7 days                        |
| 28 days                       |
| Reference                     |
| Control mix                   | -          | -   | [18]   |
| Fly ash -mix                  | 79.95      | 88.05 | [18]   |
| Red mud-mix                   | 79.6       | 88.46 | [18]   |
3.3 Fresh concrete properties

3.3.1 Slump flow test

The flowability of the mixes decreased with increasing red mud content for all cases. The high surface area and porous nature of red mud increased water demand and reduced the slump flow of the mixes [25]. However, this was compensated by adding extra superplasticizer content. [18] noted that this superplasticizer content required to meet the workability of 600-750mm for self-compacting concrete mixes increased with increasing red mud content as seen in Fig. 3.2. Apart from increasing superplasticizer content excess water was also required for mortar mixes [16], as the combined impact of red mud and water was also significant. The rest of the mixes assessed by different authors showed decreasing slump flow with increasing red mud content whose values are illustrated in figure 1. However, a few authors [24, 28] noted the results after the superplasticizer addition and, therefore observed an upward trend.

The relation between slump (mm) and the replacement ratio of cement, filler, and fly ash in the several mixes is plotted in figure 1.

**Figure 1.** Slump flow values for the concrete and mortar mixes (the dotted line represents mortar mix, a solid line represents concrete mix, and dashed line represents controlled low strength material) [4, 18, 22, 24, 25, 27, 28, 29, 30]
3.3.2 J-ring and T500 tests

The results of the J-ring test showed decreasing passing ability of the mixes with increasing red mud content [18,24,28]. The viscosity of the mixes after red mud addition was assessed by the T500 test (Table 4). The results observed [25,18,28] exhibited a downward trend with increasing red mud content. The extra superplasticizer content added to compensate the loss of flowability might have influenced the results observed [28].

Table 4. J-ring and T500 test results [5,11,23,24]

| Percentage of red mud used to replace | J –Ring displacement (mm) | T500 (s) | Replacement type | Reference |
|--------------------------------------|---------------------------|----------|------------------|-----------|
| 0                                    | 549                       | 5.15     | Fly ash replaced with red mud in self-compacting concrete mixes | [24,28] |
| 12.5                                 | 505                       | 2.8      |                  |           |
| 25                                   | 550                       | 3        |                  |           |
| 50                                   | 560                       | 2.9      |                  |           |
| 75                                   | 580                       |          |                  |           |
| 100                                  | 570                       |          |                  |           |
| 0                                    | 735                       | 3.7      | Fly ash replaced with red mud in self-compacting concrete mixes | [18] |
| 10                                   | 690                       | 4        |                  |           |
| 20                                   | 700                       | 3.6      |                  |           |
| 30                                   | 685                       | 4.9      |                  |           |
| 40                                   | 650                       | 6.6      |                  |           |
| 0                                    | -                         | 5.4      | Cement replaced with red mud |           |
| 2.5                                  | -                         | 5.5      | in self-compacting concrete mixes incorporating lime stone powder filler | [25] |
| 5                                    | -                         | 6.1      | in self-compacting concrete mixes incorporating granite powder filler |           |
| 10                                   | -                         | 7.1      |                  |           |
| 2.5                                  | -                         | 7.1      | Cement replaced with red mud in self-compacting concrete mixes incorporating marble powder filler |           |
| 5                                    | -                         | 7.9      | in self-compacting concrete mixes incorporating granite powder filler |           |
| 7.5                                  | -                         | 8.4      | in self-compacting concrete mixes incorporating marble powder filler |           |
| 10                                   | -                         | 8.9      | in self-compacting concrete mixes incorporating marble powder filler |           |
| 2.5                                  | -                         | 3.0      | Cement replaced with red mud in self-compacting concrete mixes incorporating marble powder filler |           |
| 5                                    | -                         | 3.2      | in self-compacting concrete mixes incorporating marble powder filler |           |
| 7.5                                  | -                         | 4.5      | in self-compacting concrete mixes incorporating marble powder filler |           |
| 10                                   | -                         | 4.9      | in self-compacting concrete mixes incorporating marble powder filler |           |

3.3.3 V-funnel and L-box ratio tests

The V-funnel and L-box tests are indicators of viscosity and as expected increasing red mud content increased V-funnel time and reduced L-box ratio. Studies [2,4] have also reported an increase in V-funnel time with increasing red mud content for mortar mixes. These observations were attributed to the fine particle nature of red mud which contributed to the increase in viscosity. The addition of red mud also enhanced the surface area and volume of paste for fixed water content in the mixes and increased the
viscosity [25]. A study [25] assessed mixes with varying filler amounts and noted different trends depending on the type of filler (marble waste, lime waste and granite powder). Granite powder increased the viscosity and V-funnel time. But marble powder addition was seen to reduce the viscosity which was ascribed to its fine particle size distribution. The results of these tests are presented in figure 2 and figure 3 for varying proportions of red mud.

**Figure 2.** V-funnel test values for concrete and mortar mixes (solid line represents concrete and dotted line represents mortar) [4,18,25,27]

**Figure 3.** L-box test values for concrete mixes [25,27]
3.3.4 Segregation and bleeding
Increased red mud content reduced the segregation percentage for fly ash replacement series of self-compacting concrete mixes [18]. The reason was attributed to the increased cohesiveness of the mixes after red mud addition. Red mud addition also decreased the bleeding percentage for the self-compacting mortar mixes assessed [2]. Similar observations were made [29] for controlled low strength materials having red mud as replacement of cement from 0%-30% where the bleeding reduced from 5% to 1.81%. This trend was ascribed due to pits and folds present on red mud surface (also seen in SEM images) which absorbed the excess water.

4. Conclusion
In overall, red mud addition had a positive effect on mortar and concrete mixes as it decreased segregation and bleeding and enhanced viscosity, although it reduced workability. The reduced workability could also be compensated by the addition of superplasticizer and water content. The effect of enhancing viscosity can be suitable in decorative mortars where the red mud could be used as a replacement of viscosity-enhancing admixtures reducing the cost of production of decorative mortars. Further analysis in the microstructural level can be performed to understand the interactive effects of red mud. Cost analysis of incorporating red mud in the mixes can also be performed appraising its incorporation in concrete and mortar mixes. The study reveals a promising opportunity for the usage of red mud in concrete and mortar as it enhances properties and simultaneously contributes to the reduction of carbon footprint.

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