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Utilization of Red Mud in Construction: A Review

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Abstract - *Red mud is an industrial by-product produced in the manufacturing of alumina from bauxite ores. Annually, it is estimated that approximately 120 million tons of red mud waste are generated around the world. It is generally insoluble and profoundly alkaline in nature. The dumping of red mud has deleterious effects on land, underground water, and the surrounding areas. At present, the usage of red mud is a crucial issue and a ton of research and formative exercises are going on everywhere all over the world to discover successful and productive methods for its consumption. This article presents an audit of past studies and examinations on the usage of red mud in construction practices, especially in cement and concrete industries.*

***Key Words*: Red Mud, Bauxite, Cement, Concrete, SCC.**

1. INTRODUCTION

Aluminium is the third most copious component present in the crust of the Earth (after oxygen and silicon) and is broadly utilized in transportation, packaging, building, and construction, however, it is hardly available in its uncombined form. Generally, it is found in the form of oxides in minerals such as bauxite and cryolite. Bauxite ores are normally utilized for the extraction of alumina through the Bayer process, which depends on the response with caustic soda (NaOH) under high pressure and heat [1]. However, the processing of bauxite ores by the Bayer's method results in the creation of an enormous amount of a solid mass of waste known as "red mud" or "bauxite residue". The creation of 1t of alumina leads to about 1-1.5t generation of red mud [2] and it is assessed that approximately 120 million tons per year of this industrial waste are generated worldwide [3], which ends up in the stockpiling of red mud at the disposal site as shown in **Figure 1** [4].

The storage and disposal of this copious amount of red mud waste create many environmental issues. The chief red mud disposal methods are lagooning, marine discharge, dry stacking, and dry disposal [3]. Lagooning is the cheapest capital cost land-based removal technique in which the residual sludge from the industrial plants is discharged straight away to the land-based confinements. However, long-term planning and funding are required for the closure and rehabilitation of impoundment structures. Further, there is a range of hazards related to this disposal method such as the risk of human and wildlife exposure to liquor waste and pollution of surface and ground waters. In the marine disposal method, the red mud waste in the form of sludge is directly discharged into the sea through pipelines. The marine disposal method reduces the burden on land resources but it may destroy the marine ecosystem due to the possibility of releasing poisonous metals to the ecosystem. In addition, this disposal method increases the turbidity of seawater and has unknown effects on the food chain of the marine species. The dry disposal method comprises of stacking dewatered and dried red mud in layers at the disposal site. This technique decreases the land stockpiling territory but requires costly establishments and operation of filtration plants capable of handling the entire residue production. The dry disposal method is hard to accomplish in the areas with high precipitation and low net evaporation, and there is likelihood of air pollution in the vicinity of the storage site.

Fig -1: Stockpiles of Red Mud at a Disposal Site[4]

A great deal of research has been done regarding the effective usage of red mud to lessen its deleterious effects on the environment. There are much research works on the usage of red mud, for instance, as pozzolanic pigment [5,6]; as adsorbent, coagulant, and catalyst [7]; for recovery of various metals such as alumina [8], iron [9], and rare earth elements like scandium and uranium [10,11]; for production of bricks and ceramics [12-14]; in wastewater treatment [15,16]. The focus of present research is to study the utilization of red mud in cement mortars or concrete and the impact of its inclusion on their properties.

2. TYPICAL PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF RED MUD

Red mud is the caustic insoluble waste residue created at the alumina industries which uses the Bayer method (digestion of bauxite ores under pressure) for the production of alumina [17]. It has particle size distribution ranging from 0.02µ to 2000µ [18] with texture containing clay (26-80%), silt (9-66%), and sand (0-30%) [19]. It is profoundly alkaline in nature with pH values generally in the range of 8.4 to 12.6 and the electrical conductivities range from 0.7 to 18.2 mS/cm. The surface area of bauxite residue is in the range of 15 to 30 m^2/g [20] and it has a true density of about 3.30 g/cc [21].

The main oxides present in red mud are aluminium oxide (Al_2O_3), sodium oxide (Na_2O), ferric oxide (Fe_2O_3), silicon dioxide (SiO_2), calcium oxide (CaO), and titanium oxide (TiO_2), and a large variety of minor elements such as Ga, V, P, Cr, Cu, Mn, Ni, Cd, Pb, Zn, Zr, Mg, Hf, Zr, U, Nb, Sr, K, B, Th, rare earth elements, etc. [22]. The mineralogical composition of red mud consists of minerals such as sodalite, goethite, quartz, hematite, anatase, gibbsite, calcite, and boehmite. In addition, other minerals including halite, muscovite, gypsum, rutile, feldspar, halite, and tricalcium aluminate occur in some red muds [20]. The presence of iron oxide or ferric oxide imparts red color to red mud [23] and iron oxide exists in two mineral phases, which are goethite (FeOOH) and hematite (Fe_2O_3) [24]. Another research study found the presence of mineral compounds such as gismondine, epistilbite, and goosecrekite [25]. It should be noted that the variations in the chemical and mineralogical composition of bauxite residue are mainly due to their different origin and the processing methods of the bauxite ores to produce alumina. The chemical composition range (in percentage) of the main constituents of red mud in different alumina enterprises worldwide is as shown in Table 1 [21].

Table -1: Chemical Composition of Main Constituents of Red Mud

Constituents	Chemical Composition (wt%)
Fe_2O_3	20-60%
Al_2O_3	10-30%
SiO_2	2-20%
Na_2O	2-10%
CaO	2-8%
TiO_2	Traces - 28%

3. MICROSTRUCTURAL ANALYSIS OF RED MUD

Scanning electron microscope (SEM) analyses of red mud revealed the presence of 'pits' and 'folds' on the surface of gel material in red mud as shown in **Figure 2** [26]. The free water, which adds to the flowability of the mortar blends, could be consumed by these 'pits' and 'folds' present in red mud. Thus, decrease in flowability can be linked to the increase in substitution level of red mud in cement and concrete mortars [26].

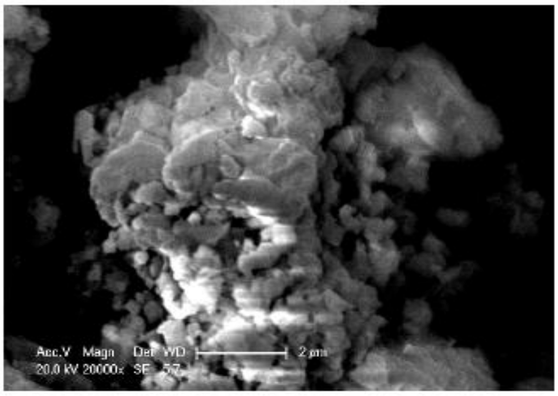

Fig -2: SEM Image of Red Mud[26]

Manfroi studied the XRD pattern for dry red mud at 105⁰C. **Figure 3** shows the results of XRD analysis of the red mud sample. The chief phases identified in dry red mud were gibbsite, chantalite, quartz, hematite, calcite, and cancrinite [27].

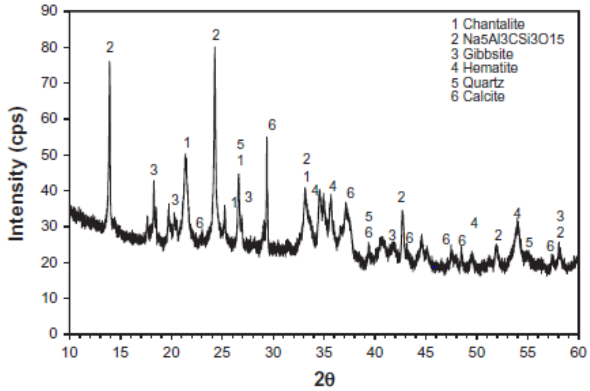

Fig -3: XRD Analysis of Dry Red Mud[27]

According to the XRD examination conducted by Liu and Poon [25], gismondine, goosecerkite, and epistilbite were found to be present in red mud. These three mineral compounds, have a 3-D structure, which is compromised of Al-O tetrahedroids and Si-O tetrahedroids, belong to the group of zeolites, which has been shown to improve the concrete properties according to the past examinations [28,29].

4. UTILIZATION OF RED MUD

4.1 For Preparation of Cement

Singh et al. explored the possibility of preparing cement of 28 days compressive strength comparable to those acquired utilizing ordinary Portland cement by using various mixes of crude blends of bauxite, red mud, lime, fly ash, and gypsum. They also studied the influence of firing temperature on the properties of cement produced using these raw mixes. The raw mixes containing fly ash were unsuccessful to deliver cements having strengths comparable to that of OPC. The test results concluded the optimal proportions to be 15-20% bauxite + 30-35% red mud + 45-50% lime + 7.5-10% gypsum depending on the desired type of cement. Also, the firing temperature of about 1250^{0}C for 1.0-1.5 hours gives the best outcomes for producing different types of cement with desired characteristics [22].

Tsakirdis et al. conducted XRD analysis on Portland cement clinker with red mud (3.5%) obtained from Aluminium de Greece and compared it with Portland cement clinker without red mud as shown in **Figure 4**. As it can be seen, the inclusion of red mud to the Portland cement clinker hardly affected its mineralogical composition. The key mineralogical phases (C_2S, C_3A, C_3A, and C_4AF) were found to be well formed in both types of cement clinkers. They studied the influence of incorporation of red mud on the various characteristics of cement mortars in terms of consistency, setting time, and compressive strength. The test results revealed that the inclusion of red mud only slightly affected the consistency and setting times. However, the compressive strength of mortar containing red mud was found to be relatively higher than the reference samples, especially at 28 and 90 days, which confirmed the possibility of utilizing red mud for the production of cement [30].

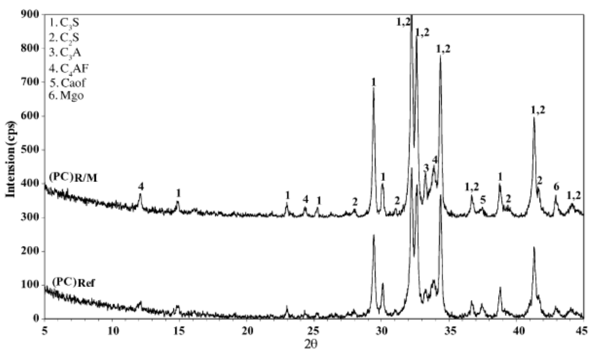

Fig -4: XRD pattern of Portland cement clinkers with and without red mud residue[30]

Vangelatos et al. examined the feasibility of using red mud in the manufacturing process of OPC. Ferroalumina (FA), a filtrand obtained after the dewatering of red mud was utilized as a raw material for cement production. The results indicated that up to 5% of FA can be successfully used in the production of OPC according to the chemical composition of the other raw materials [31].

Meanwhile, Zhang et al. prepared a silica-alumina based cementitious material by utilizing red mud and coal gangue as raw materials. The red mud and coal gangue were blended at a ratio of 3:2 and then shaped into small spheres with water to solid ratio of 0.30 and afterward calcined for two hours at a temperature of 600 ^{0}C. The strength values of designed cementitious material were found to be remarkably higher as compared to the reference OPC. Thus, the results demonstrated the feasibility to utilize red mud and coal gangue together to supplant 50% of the crude materials required for the manufacturing of the cementitious materials [32].

Yao et al. utilized red mud and coal industry by-products as raw materials for the generation of new cementitious materials. The mechanical strength of these red mud-coal industry by-products based cementitious materials were found to be higher than the control group, especially at later ages (180 and 360 days) [33].

Wang et al. prepared sulfoaluminate cement using red mud and desulfurized gypsum (a by-product obtained from wet flue gas desulfurization) as raw materials. The cement produced from this process showed excellent strength in comparison to the Portland cement and this cement preparation technology proved to be an efficient method to utilize both of these industrial solid wastes [34].

4.2 For Production of Concrete

Riberio et al. looked at the possibility of utilizing non-calcined red mud in the construction industries. They observed that the inclusion of red mud stimulated the setting process. However, the pozzolanicity and the strength characteristics were found to decrease with the increase in the substitution level of the bauxite residue. Therefore, the study suggested the usage of non-calcined bauxite residue as a partial cement replacement material in mortars and concretes for non-structural applications [35].

Similarly, Sneff et al. examined the influence of red mud waste on the rheological behavior and hardened properties of cement mortars. They found that the incorporation of red mud up to 20% (by cement weight) did not influence the hydration process, but after this limit, the hydration of cement paste decreases with the increment in the substitution level of red mud. When increasing red mud levels, the hardened samples showed lower compressive strength and higher water absorption [36]. Another study by Sneff et al. assessed the impact of red mud and water-binder (W/B) ratio on the various concrete properties. They prepared samples by supplanting cement by red mud up to 40% (by weight). Two W/B ratios of 0.47 and 0.58 were used to make concrete samples while the workability was kept constant. The outcomes indicated that the porosity, compressive strength, water absorption, and carbonation extents were negatively affected when the W/B ratio was increased from 0.47 to 0.58 for the concrete samples with 20% red mud particles. The compressive strength of mortar with 20% RM + 0.47 W/B dropped to 13% as compared to the reference mortar samples cured at 360 days, while the compressive strength of mortar with 20% of RM + 0.58 W/B dropped by 46% [37].

Rathod et al. evaluated the strength characteristics of hardened concrete samples, in which red mud was utilized to partially supplant Portland cement by up to 40%. Experimental results demonstrated that both compressive strength as well as splitting tensile strength reduced with the increasing levels of red mud. It was reasoned that the optimal percentage of cement replacement by weight was 25% [38].

Shetty et al. studied the strength characteristics of SCC samples by utilizing red mud as a partial cement replacement material and used foundry sand as a fine aggregate (regular sand) replacement material. The results showed that the maximum compressive strength can be obtained for SCC samples containing red mud up to 2% with used foundry sand up to 10%, but when the content of red mud is higher than 2%, the compressive strength for SCC decreased as shown in **Figure 5** [39].

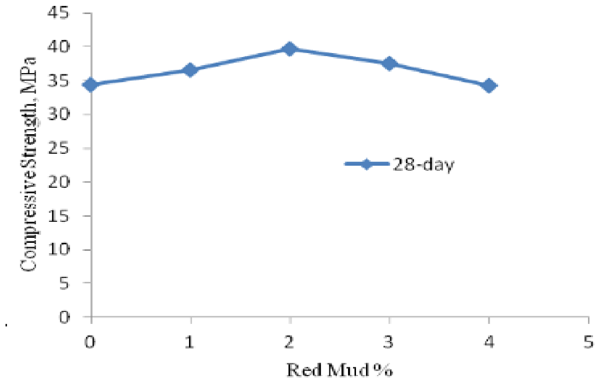

Fig -5: Variations in Compressive Strength of SCC containing Red Mud[39]

Manfroi et al. carried out investigations to examine the compressive strength characteristics of cement mortars containing red mud up to 15%. The red mud used was dry and calcined at temperatures of 600, 700, 800, and 900 ^{0}C. It was recommended to use 5% of dry and calcined red mud at 600-800 ^{0}C for producing cement mortars of strengths comparable to that of the reference mortars [27].

Metilda et al. evaluated the effect of the inclusion of red mud on the hardened properties of concrete and compared it with the conventional concrete samples. The red mud was introduced as cement replacement material with an increment level of 5% up to 25% (by weight). The strength characteristics were found to enhance up to 15% substitution level, even greater than the conventional samples, but when the substitution level is higher than 15%, these strength characteristics decreased [40].

Liu and Poon [25,26] explored the feasibility of utilizing red mud to supplant fly ash in self-compacting mortars and concrete. When increasing red mud levels, the flowability of mixture samples decreased while the compressive and flexural strengths were enhanced. The results demonstrated that the compressive strength of control samples were about 7.4% and 8.25% lower than the SCC blends containing 30% and 40% (by weight) red mud at 56 days, respectively. In addition, no negative effect was found on the elastic modulus of the SCC blends when the content of red mud was increased from 0 to 30%. Overall, they concluded that the optimal range for supplanting fly ash by red mud in SCC mixtures is 10% to 40% [25].

Tang et al. demonstrated that the red mud contents of 12.5 25, and 505 (by weight) can be used to partially supplant fly ash in self-compacting concrete (SCC). The influence of incorporating red mud on fresh and hardened properties of concrete was also contemplated. They found that super plasticizer was needed to maintain the SCC requirements as the flowability characteristics were found to decrease with the increasing levels of red mud in SCC. However, the slight increment in compressive strength and elastic modulus was noticed in SCC containing red mud. They also studied the micro-structural properties of self-compacting concrete containing red mud and the SEM results revealed that the crystal structure of red mud concrete samples was triclinic in shape for RMC25, as compared to the rod-like structure of the control samples. Minor micro-cracking was found in concrete samples containing 25% and 50% of red mud while several voids were found in the reference samples and concrete samples containing 12.5% of red mud. The results also depicted that the presence of red mud slightly enhanced the interfacial transition zone(ITZ) between aggregates and cement paste for red mud concrete samples as compared to the control samples [41].

Shori and Lamba evaluated the influence of supplanting cement by red mud in concrete. They conducted tests on M25 grade of concrete in which cement was supplanted by red mud up to 20%. About 6% of balast fiber was also used in each test series. The experimental results demonstrated that the maximum strength characteristics can be obtained for concrete containing about 15% of red mud with 6% of balast fiber [42].

Oliveria and Rossi utilized red mud to manufacture coarse aggregates for concrete. About 70-80% of red mud waste was directly utilized to produce new coarse aggregates and several tests were conducted to examine their different properties such as density, elastic modulus, axial compression strength, and hydraulic abrasion strength. The experimental outcomes of their studies were quite motivating to use red mud to produce new red mud aggregates for use in concrete [43].

Molineux et al. explored the possibility of manufacturing lightweight aggregates by replacing pulverized fuel ash (PFA) content of the aggregate mixes with red mud in the percentage ratios of 25, 31, 38, 44, and 50%. The results demonstrated that about 44% of red mud replacement produced the aggregates with the highest density and strength characteristics. Also, the produced aggregates were found to have high water absorption capacity, which made the suitable for use in urban greening applications [44].

5. CONCLUSIONS

The generation of alumina from bauxite ores results in the generation of an insoluble solid waste called red mud. Every year, millions of tons of this industrial by-product re generated and hence, there is a huge need to recycle or reutilize this gigantic amount of red mud. Otherwise, it causes harmful effects on the environment. Several research studies indicate that red mud can be successfully utilized as a raw material to prepare different types of cement. Red mud can be utilized as a cement replacement material in the production of concrete and it can be employed in the production of self-compacting concrete. Some research studied show that the addition of red mud as cement replacement material up to a certain extent can enhance the properties of the concrete. It is notable that most researches have been centered around utilizing red mud as a cement replacement material and very few studies are available in which red mud is utilized in the production of aggregates for concrete. Thus, more research is needed to determine the sound and effective ways of using red mud as aggregates in concrete or as a raw material in the production of aggregates for concrete.

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