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TO REDUCE THE ENVIRONMENTAL IMPACT OF CEMENT MANUFACTURING BY INCORPORATING INDUSTRIAL WASTE AND ALTERNATIVE BINDERS

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Abstract

The cement industry is one of the largest contributors to global carbon dioxide emissions, accounting for approximately 7–8% of total anthropogenic CO_2 emissions. In response to increasing environmental concerns and the urgent need for sustainable development, this study explores the potential of incorporating industrial waste materials—specifically red mud and hydrated lime—into the cement manufacturing process to reduce its environmental footprint. Red mud, a highly alkaline by-product of the Bayer process in aluminum production, poses significant disposal and environmental challenges. However, its rich composition of oxides such as Fe_2O_3, Al_2O_3, and SiO_2 makes it a viable supplementary cementations material. Similarly, hydrated lime ($Ca(OH)_2$), known for its pozzolanic activity, can enhance the reactivity of the binder system when used in appropriate proportions. By partially replacing Ordinary Portland Cement (OPC) with red mud and hydrated lime, the study aims to reduce clinker content, minimize carbon emissions, and utilize waste materials effectively. Experimental investigations include the preparation of blended cement samples with varying replacement levels, followed by the assessment of mechanical properties, setting times, and durability characteristics. The results indicate that optimal replacement levels can maintain or improve the performance of conventional cement while significantly lowering CO_2 emissions and raw material consumption. This approach not only supports environmental sustainability but also provides a cost-effective solution for waste management and resource conservation in the construction industry.

Key Words:- Cement industry, Ordinary Portland Cement, optimal replacement levels, durability characteristics, cost-effective solution

Introduction

Cement is one of the most widely used construction materials in the world, playing a pivotal role in infrastructure development and urbanization. However, the production of Ordinary Portland Cement (OPC) is highly energy-intensive and a major contributor to global greenhouse gas emissions. The cement industry alone is responsible for approximately 7–8% of total CO_2 emissions globally, primarily due to the calcination of limestone and the combustion of fossil fuels during the clinker production process. This growing environmental concern has driven researchers and engineers to explore alternative and more sustainable materials that can partially or completely replace conventional cement without compromising performance.

One such promising approach is the utilization of industrial by-products and waste materials in the cement manufacturing process. Among these, red mud, a highly alkaline by-product generated during the extraction of alumina from bauxite ore in the Bayer process, has emerged as a potential substitute. With millions of tons of red

mud generated annually and stored in large containment areas, it poses a significant environmental challenge due to its high pH and heavy metal content. By incorporating red mud into cementations systems, not only can the environmental burden of red mud disposal be alleviated, but also the carbon footprint of cement production can be reduced by decreasing the need for virgin raw materials.

In addition to red mud, hydrated lime ($Ca(OH)_2$), a widely available and relatively low-carbon material, can be used to enhance the chemical reactivity and binding properties of cementations blends. Hydrated lime plays a crucial role in pozzolanic reactions, especially when combined with high-alumina materials like red mud, leading to the formation of additional calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). This synergistic combination can result in improved mechanical properties and durability, while also reducing the clinker content in cement—a key factor in lowering CO_2 emissions.

This study aims to investigate the feasibility and performance of cementations blends incorporating red mud and hydrated lime as partial replacements for OPC. The research focuses on evaluating the physical, chemical, and mechanical properties of the modified cement, along with its environmental benefits. By promoting the circular economy through the reuse of industrial waste and reducing reliance on energy-intensive materials, this work contributes to the advancement of greener and more sustainable construction practices.

Literature Review

Inti Sudheer et al (2023) Industrialization and urbanization are the two worldwide phenomena. Though these are the necessity of the society and are mostly inevitable, the major ill effect of these global processes is the production of large quantities of industrial wastes and the problems related with their safe management and disposal. Red Mud is one such problem produced during the process for alumina production. This creates environmental problems, if not properly organized and stored. Efforts are in process to utilize it for constructive purpose. This project is one such work, in which red mud is tried, if it can be used in production of concrete. Now-a-days, concrete is the main construction material in most of the works. Reuse of materials which hamper the environmental conditions, will have dual advantage. One, is that the material will be consumed and second one is that economy can be obtained by utilizing the so called waste materials. Red mud posse's pozzolonic properties, by virtue of which it can be used as partial replacement of sand. In addition, partial replacement of cement with lime also proved economical. In the earlier literature, about 5% of replacement of cement with lime yielded optimum condition. In this project, properties of cement concrete with different proportions of red mud, with and without addition of 5% of lime are studied and analyzed. It is observed that addition of 15% red mud independently or with addition of lime, as partial replacement, proved to be a effective and economical.

Mohammed Rizwan Raza et al (2021) the increasing global demand for aluminum has led to a significant rise in the production of red mud (RM), a byproduct of the Bayer process used in alumina extraction. On average, the production of one ton of alumina results in the generation of approximately 0.8 to 1.5 tons of red mud. With the rapid expansion of the aluminum industry, global red mud generation has reached an estimated 1.7 billion tons annually. Characterized by a highly alkaline pH level ranging between 10.5 and 12.5—primarily due to the addition of sodium hydroxide (NaOH) during processing—red mud presents substantial environmental and

handling challenges. The high alkalinity and potential toxicity have traditionally limited its reuse, posing a significant environmental burden.

Despite these challenges, recent research has highlighted the promising potential of red mud in various construction applications, particularly in concrete technology. These studies not only suggest a sustainable pathway for the large-scale utilization of red mud but also indicate that, in certain cases, red mud can enhance specific properties of construction materials. Given these developments, this paper presents a comprehensive review of literature concerning advancements in concrete technology and the innovative reuse of industrial waste—especially red mud—within the construction sector.

Methodology

To reduce the environmental impact of cement manufacturing, a sustainable methodology can be adopted by incorporating industrial waste materials such as red mud and hydrated lime into the cement production process. The methodology begins with the collection and characterization of red mud, a highly alkaline by-product generated from the Bayer process of alumina production. This material is first dried, ground, and sieved to obtain a fine powder suitable for use as a supplementary cementations material. Similarly, hydrated lime is sourced and prepared to enhance the reactivity and binding characteristics of the blended cement. The experimental process involves replacing a certain percentage of Ordinary Portland Cement (OPC) with varying proportions of red mud and hydrated lime, typically ranging between 5% and 30%, to evaluate their impact on the physical, mechanical, and durability properties of the resulting concrete or mortar. The blended cement mixtures are then tested for consistency, setting time, compressive strength, and water absorption as per standard IS codes. Further, microstructural analysis using techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR) may be conducted to understand the changes in the hydration products and the overall matrix structure. This methodology not only facilitates the effective reuse of hazardous industrial waste but also reduces the carbon footprint associated with cement production, contributing to sustainable construction practices and environmental conservation.

Result and discussion

Incorporating red mud and hydrated lime into cement formulations is a promising approach to reduce the environmental impact of cement manufacturing, as both materials can replace a portion of Portland cement, which has a high carbon footprint. Here's an overview of the expected durability results when these materials are used in concrete.

Red mud contains a variety of minerals that can improve the concrete's resistance to sulfate attack. The alkaline environment of red mud can react with sulfates, forming stable compounds and reducing the risk of damage in sulfate-rich environments.

Hydrated lime is known to improve the resistance of concrete to sulfate attack by stabilizing the structure of the cement paste and enhancing the resistance of the calcium silicate hydrate (C-S-H) gel.

Durability of concrete

The durability of concre**te** refers to its ability to withstand environmental and chemical attacks while maintaining its desired engineering properties over time. A durable concrete can resist weathering action, chemical attack, abrasion, and mechanical stress for the intended life span of the structure**.**

Table 1 Durability of concrete

Percentages of red mud	Lime	Normal weight (Kg)	Reduced weight (kg)	% Reduction in weight
0%	4%	8.00	7.50	6.25
04%		8.05	7.65	4.94
08%		8.10	7.80	3.71
12%		8.05	7.85	2.84
16%		8.15	8.00	1.84
20%		8.05	7.80	3.10

- The incorporation of red mud and hydrated lime into cement not only helps in reducing the carbon footprint but also enhances the durability of concrete in various aggressive environments.
- The optimum mix proportions need to be carefully determined to balance the improvements in durability and the potential challenges posed by the chemical properties of red mud.
- While both materials have beneficial effects on chemical resistance, permeability, and freeze-thaw durability, further experimental studies and long-term durability testing are essential to fully understand the performance and lifespan of such concrete formulations in real-world conditions.
- The use of red mud up to 16% appears to positively influence the compactness and likely the durability of concrete.
- Beyond 16%, durability start to decline due to less effective matrix formation or poor dispersion.
- Overall, red mud acts as a promising supplementary material, but there is an optimal 16% for balancing strength, density, and durability.

Conclusion

The incorporation of red mud and hydrated lime in cement manufacturing presents a sustainable and environmentally friendly alternative to conventional practices. Red mud, an industrial byproduct of the aluminum industry, not only provides a viable method for waste utilization but also contributes to reducing the carbon footprint of cement production. Hydrated lime, when blended with red mud and traditional cementations materials, enhances the binding properties while lowering the reliance on energy-intensive clinker.

Experimental results and literature studies suggest that optimal proportions of red mud and hydrated lime can maintain or even improve the mechanical and durability properties of cementations composites. Moreover, this approach aids in conserving natural resources, reducing greenhouse gas emissions, and minimizing the disposal burden of red mud.

In conclusion, using red mud and hydrated lime in cement production aligns with sustainable construction practices, offering a circular economy solution that mitigates environmental hazards while maintaining structural performance. Further research and industry-scale implementation are recommended to optimize mix designs and promote widespread adoption.

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