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Sustainable Concrete Development using Biomass-Derived and Industrial Waste Materials: A Review of Current Trends and Future Directions

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ABSTRACT: The objective of this research was to investigate the potential use of alternative materials derived from biomass and various forms of industrial waste to substitute up to 10% of the cement content (as cement replacement materials in M20 concrete) and how they affect the properties of the concrete when tested for compressive strength at various curing times (3, 7 and 28 days) compared to that of standard M20 concrete (reference concrete). The use of these industrial wastes and biomass materials to replace cement not only reduces the amount of cement used in concrete but also potentially reduces the overall carbon footprint associated with the production of conventional concrete. The results obtained from testing the concrete mixes made with BFS and FA revealed that they produced superior long-term strengths than both reference concrete and the remaining biomass materials tested, while all industrial waste-based concrete mixes tested produced at least equivalent long-term compressive strengths to that of reference concrete. Measurements of the long-term compressive strength of the different biomass materials showed that they produced slightly lower strengths at all curing times than reference concrete but provided means of reducing the environmental burden of construction activities (by reducing landfill waste) and of managing the agricultural waste of biomass from producing these agricultural products. Overall, this investigation demonstrated that all of the industrial waste materials tested in this research are suitable for use in strength-oriented applications; furthermore, it demonstrated that all of the industrial waste materials tested are viable alternatives to cement in the production of sustainable and environmentally friendly concrete.

KEYWORDS: Sustainable Concrete, Industrial Waste, Compressive Strength, Biomass Ash, Cement Replacement, Fly Ash, BFS

I. INTRODUCTION

Numerous studies have demonstrated that you can use waste materials to partially substitute for aggregates and cements in concrete. For instance, one of these waste materials is known as bagasse ash, which can be an effective substitute for conventional cement in that; concrete produced with bagasse ash has exhibited compressive strengths comparable to (or even greater than) conventional concrete [1]. Similarly, foundry sand may be used as a substitute for fine aggregate from waste produced by foundries; and, demolition waste may also be an effective substitute for coarse aggregates [2]. The use of agricultural and industrial waste in concrete facilitates the conservation of natural resources and environmental impact remediation [3]. Additionally, many recycled materials (crushed concrete, bottom ash, crushed bricks and waste tires) can be successfully incorporated as raw materials for concrete production [4]. These alternative materials are less expensive than typical concrete raw materials; thus, they can promote improved waste management practices [5].

The incorporation of slag and fly ash are widely accepted method for enhancing the properties of concrete [6]. Ground granulated blast furnace (GGBF) slag can serve as a partial alternative binder for concrete applications [7]. Additionally, palm oil clinkers and palm oil shells have been used in geopolymer concrete [8]. The addition of fly ash and slag improves concrete workability and increases strength and durability in addition to reducing carbon emissions during production [9]. Many industrial by-products, including fly ash, slag, metakaolin, rice husk ash, and palm oil fuel ashes (PFAs) can be substituted in place of some or all of the cement in concrete [10]. Fly ash and slag contribute to increased resistance to chemical attack by lowering the heat generated from the hydration of the cement. Mortars and

concrete made with fly ash-based geopolymer binders have similar characteristics and properties as ordinary cement concrete [11].

Presently, an increasing number of industrial by-products including silica fume, ground granulated blast furnace slag, and fly ash are being used in construction, receiving much attention [12]. A new class of concrete being developed using these types of industrial waste products is called geopolymer concrete. Geopolymer concrete is unique in that it does not use any Portland cement; therefore, it provides a sustainable and environmentally friendly alternative to traditional concrete using cement [13]. The physical performance characteristics of geopolymer concrete are comparable to those of regular concrete and it is produced via a chemical interaction between aluminium, silicon and an alkaline solution — resulting in a highly durable binder material [14].

II. LITERATURE REVIEW

Class C fly ash can be used in Geopolymer concrete, where different ratios have been studied with simple Portland cement concrete [15]. The use of industrial waste materials instead of normal Portland cement becomes important in terms of environmental and economic considerations [16]. In addition, by using a combination of fly ash and ground granular blast furnace slags, geopolymer can improve the compressive power of concrete even at ambient temperatures [17]. Therefore, optimising the use of local waste materials as a thread mixture in polymer concrete enhances effective waste management [18]. Research efforts are directed to discover the use of industrial waste as complementary cement materials, such as lime mud and fly ash, to improve the strength of concrete [19]. In fact, fly ash has been used as a supplement cement material, at least, due to the ability to reduce the consumption of Portland cement and reduce alkali-calcium reactions in concrete [20]. Two main components of geopolymers binders include alumino-cyclinder elements, solid parts and alkaline activators, liquid part [21]. When the fly ash comes in contact with an alkali solution, it starts dissolving silicates [22]. This process leads to the formation of a gel that binds the loose material together [23]. Fly ash, from burning coal in thermal power plants, can cause industrial solid waste, environmental problems [24]. Changing cement with fly ash helps to relieve environmental concerns, especially the global warming problem due to the greenhouse effect [25]. Using fly ash as a source material and starting polymerisation are the basic elements required to create an alkaline solution polymer. The parameters should be adapted in terms of solvent types, sources, mixture ratio and treatment status to synthesise the metacolin-based geopolymer, as these causatives significantly affect the characteristics of the synthesised geopolymer [26].

III. RESEARCH OBJECTIVES

1. To formulate and produce M20 grade concrete mix with 10% of cement replaced by each of the selected materials.
2. To evaluate the compressive strength of concrete cubes at 3, 7, and 28 days according to IS 516:1959.
3. To evaluate the performance of waste-based concrete mixes in comparison to conventional cement concrete.
4. To assess the environmental and economic benefits of employing biomass-derived and industrial waste as aggregate in concrete production.
5. To recommend sustainable concrete development using agricultural and industrial by-products.

IV. MATERIALS AND METHODOLOGY

Concrete samples were prepared from several material types; Ordinary Portland Cement (OPC), fine aggregate (e.g., sand), coarse aggregate, various types of ash material, and water. A total weight of 20 kg of Ordinary Portland Cement was used in the concrete mix as a primary binder. The amount of fine aggregate added to the mix was 30kg and the amount of coarse aggregate that was used was 60 kg; both were included to provide strength and stability to the concrete mix. In addition to using these materials, various types of industrial and agricultural waste were incorporated into the mix as partial replacements for some of the Ordinary Portland Cement. The types of waste materials that were incorporated as partial substitution for OPC included fly ash (6 kg), CSA (6 kg), BSA (6kg), BFS (6 kg) and RHA (6 kg) and 15 Litre water (only for sample preparation).

Mixing Process of Materials

This research took advantage of agricultural and industrial waste materials to make samples. Fifteen concrete cubes were made using M20 grade concrete with a water cement ratio of 0.5. The concrete cubes involved used varied

cementitious product recipes, where cement was displaced by just 10%. All of the samples were cured in normal water for 3, 7, and 28 days.

V. EXPERIMENTAL OBSERVATION

This experimental study was intended to look at how partial substitutes for OPC would change the way M20-grade concrete performs. The mix design for this project was created according to IS 10262:2009 and IS 456:2000. In this experiment, 10% of the OPC was substituted out for an equal amount of BFS, FA, RHA, CSA, and BSA. All of these different materials were mixed together in 150mm x 150mm x 150mm cubes with a water/cement ratio of 0.5. All of the fine and coarse aggregates were tested prior to being poured into the forms, using the correct IS codes, to make sure that they were appropriate for use when creating cement.

Casting was achieved through mixing the various materials to achieve a uniform consistency. The new concrete was placed in the forms in layers, with each layer being compacted in accordance with established practice. After 24 hours, the samples were removed from the form and cured in potable water for 3, 7, and 28 days. Curing was conducted under normal conditions to ensure that the cement is properly hydrated and that the SCMs had a pozzolanic reaction. The curing of the samples was significant in helping increase the strength for both control and modified mixtures.

We followed IS 516:1959 for compressive strength testing, using a CTM. Each cube sat right in the centre, and we slowly increased the load until it broke. After that, we noted the highest load and worked out the compressive strength. For each curing period, we tested three cubes and took the average—this gave us results we could trust. With this approach, it was easy to compare regular concrete with mixes containing different SCMs.

For the compressive strength testing of samples containing 10% alternative materials, they all were tested at intervals of 3, 7 and 28 days against a control group that contains no substitution and gave the following results; 12.5 MPa @ 3 days, 18.8 MPa @ 7 days and 26.4 MPa @ 28 days for the Standard Control sample.

When using concrete mixed with Fly Ash at 10%, compressive strength will register as follows with respect to time as well; 10.2MPa @ 3 days, 17.6MPa @ 7 days and 27.3MPa @ 28 days – indicating slight improvement in long term).

Similarly, compressive strength will also measure 11.8 to 28.6 MPa for an equivalent sample made with BFS at 10% substitution rate, while RHA yields 9.4 to 25.1 MPa over the same testing periods. Likewise, 8.65 to 23.8 MPa for the BSA sample through the prescribed elapsed time frames. The results suggest that compressive strength improvements, or otherwise, can be attributed to both the number of days since pour completion and the amount of substitution; with regard to curing periods being less advantageous than longer durations.

VI. RESULT AND DISCUSSION

M20 grade concrete has been tested with (10%) replacement of cement by chemically suitable materials producing visible variations in the strength of concrete over a three-, seven- and 28-day period. The control mix displayed the expected compressive strength for M20 concrete. All of the SCM's have provided resultant 28-day strengths that were higher than the control mix with BFS providing higher than any other SCM or Control Concrete. Fly Ash also demonstrated good performance with regard to strength at the later time period while having lower than expected early time period strength than the control concrete. The results indicate that industrial left-over products such as BFS and FA possess sufficient pozzolanic properties and hydraulic properties to continue producing additional strength due to time. Biomass-derived SCMs like RHA, CSA, and BSA didn't hit the same compressive strength as the control or industrial waste mixes. Still, RHA stood out among the three—it performed better thanks to its high SiO₂ content, which really helps strengthen the concrete's microstructure. CSA and BSA lagged a bit, mostly because they have higher LOI and some unburnt particles left over, which makes them less reactive. Even with their lower strength, all three stayed within the acceptable range for low to medium strength uses. According to this evaluation, BFS and FA can be recommended when higher CS's are needed for structure applications; whereas, RHA, CSA, & BSA will assist in creating sustainable and environmentally friendly structures as they will lower the amount of OPC used, decrease the amount of CO₂ released into the atmosphere, and help establish better WM practices by using SCM's as part of the concrete mix. All of

these factors will provide both structural performance & environmental benefits for the use of SCMs in sustainable concrete mixes.

VII.CONCLUSION

The research shows that both industrial and biomass waste can be used as additional cementitious material in M20 grade concrete. The control mix achieved the prescribed compressive strength values while the industrial waste produced in this research, BFS and FA, performed even better than the control mix and improved its performance in the long term. The biomass waste materials; RHA, BSA, and CSA had strength reduction on the order of the control mix, however, there is a sustainability advantage with those materials because they help solve waste disposal problems and reduce the amount of cement needed in a concrete mixture. In summary, this research shows that BFS and FA can be used for higher strength applications, while RHA, BSA, and CSA are better suited for environmentally friendly low to medium strength applications. This demonstrates a double win for performance and protecting the environment, as well as promoting the use of waste materials for sustainable concrete.

Recommendations for Further Studies

Future research should investigate the burning and processing conditions of biomass ashes to minimize loss on ignition (LOI) and increase their reactivity. Researching blends that contain biomass-derived and industrial wastes may present better overall performance by balancing their chemical and physical properties. Long-term durability research, including resistance to sulfate attack, chloride penetration, and freeze-thaw cycles, would be beneficial to conduct to measure the practical suitability of such blends of biomasses, along with staged trials. It could also be beneficial to investigate higher replacement levels (greater than 10%) and both mechanical and durability aspects to further enhance options for sustainable replacement of cement.

Limitations

This study evaluated compressive strength at 3, 7, and 28 days and did not look at other important mechanical properties such as flexural, tensile strength, or modulus of elasticity. It is possible the wasted material dosage tested of 10% did not show the full potential of the explored materials, as well. Also, durability characteristics, such as shrinkage, permeability, and chemical resistance are beyond the scope of the present study.

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