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Application of Industrial Waste to Enhance the Characteristics of Geopolymer Concrete

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ABSTRACT
Geopolymer concrete is an innovative type of concrete that is distinct from traditional Portland cement-based concrete. It is formed by using geopolymers, which are binder materials derived from industrial by-products such as fly ash or slag, activated by alkali solutions. Geopolymer concrete offers several advantages over conventional concrete, including lower carbon emissions due to reduced cement usage, excellent chemical and fire resistance, and potential utilization of waste materials. Geopolymer concrete offers an environmentally friendly alternative to conventional Portland cement-based concrete, and incorporating industrial waste as a source material can further enhance its eco-friendliness and economic viability. By the application of industrial waste in the geopolymer concrete the properties of the geopolymer concrete has been enhanced, which depends up on the alkaline solution used in the concrete. As the alkaline liquid ratio (Na2SiO3/NaOH) is decreased, there is a notable 7.37% enhancement in compressive strength, reaching its highest point at a ratio of 2.0. Similarly, a reduction in the alkaline liquid ratio results in a significant 13.69% elevation in flexural strength. Likewise, a decrease in the alkaline liquid ratio correlates with a substantial 20.26% rise in split tensile strength.
Keywords - Geopolymer Concrete, Industrial Waste, Compressive strength, Flexural strength, Split tensile test.

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I. INTRODUCTION

In the realm of construction, cement's pivotal role as a pozzolanic binder is a widely acknowledged truth. However, the escalating global warming crisis due to greenhouse gas emissions has spurred researchers to shift their focus toward ecologically conscious construction methods powered by renewable energy sources. This shift stems from the fact that cement production is notorious for its intensive energy consumption. Consequently, the quest for alternative construction materials has led researchers to embrace the geopolymer process, drawn by its technological advancements and environmental benefits [1,2]. This shift is particularly urgent considering that manufacturing one ton of cement releases roughly 0.7 tons of CO_2 into the atmosphere [3]. The concept of geopolymers was originally conceived by Prof. Joseph Davidovits in 1978. These are alumino-silicates formed through the reaction of amorphous silica and alumina in a highly alkali-activated chemical medium, all at room temperature. According to Prof. Sir Joseph Davidovits, potent alkalis such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) efficiently catalyze the dissolution reaction for silica (SiO_2) and alumina (Al_2O_3), resulting in the formation of alumino-silicates [4]. This reaction's dynamics are primarily influenced by the inherent properties of the raw materials, the concentration of the activator, and the curing process parameters (such as drying time and temperature). The ready availability of alkalis in the market and the identification of abundant sources of silica and alumina in various industrial residues have piqued the interest of researchers [5]. Industries such as aluminum, steel, power generation, and biomass have conserved these mineral resources within their waste streams. Notable examples include aluminum industry waste like red mud (RM), partially laterite kondalite (PLK), and kaolinitic kondalite (KK), which are mineral-rich and suited for geopolymer production. Steel industry waste, enriched with calcium and silica minerals, is a valuable source for producing diverse calcium silicates and their mineralogical phases [6,7]. Biomass waste from materials like rice husks and bagasse can be transformed into ash, containing about 80-90% amorphous silica, serving as a cost-effective resource for geopolymer processes [8]. Similarly, waste ash from power plants, including fly ash and bottom ash, boasts commendable pozzolanic attributes and can be harnessed for 100% utilization in construction via the geopolymerization route [9]. This holistic approach to harnessing industrial waste has the potential to establish a paradigm for creating construction materials that substantially curtail CO2 emissions.

The mechanical attributes of a geopolymer binder are contingent upon factors like binder ratio, waste material type, mineralogical composition, methodology, and mix design [10]. The transformation of the aforementioned industrial residues into geopolymer concrete or cement yields significant positive ramifications for the environment, society, and economy. Essential to this endeavor is the identification of key indicators encompassing environmental, social, and economic dimensions for assessing the sustainability of building materials. Durability of the new materials and the production cost of geopolymer concrete are also imperative considerations. Interestingly, geopolymer concrete derived from fly ash has proven to be around 30% more cost-effective compared to conventional cement concrete. This advancement comes alongside a notable increase in compressive strength, reaching 62 MPa, in contrast to the 21 MPa displayed by OPC-based concrete [11]. Moreover, an energy and cost analysis involving geopolymer brick production has revealed the economic viability of the process, generating a 5% profit margin through the development of slag-based geopolymer bricks [12]. In terms of embodied energy, fly ash-based geopolymer synthesis demands approximately 40% less energy than cement-based concrete. However, it's worth noting that the alkali activator ingredients, particularly sodium hydroxide and sodium silicate, consume 39% and 49% of the energy, respectively. This emphasizes the need for identifying alternative alkali sources, possibly from other liquid waste streams, to bolster the process's economic viability [13]. To this end, efforts are underway to find economical alternatives to alkali activators via industrial liquid waste, with Bayer's liquid waste from alumina extraction emerging as a potentially cost-effective solution due to its content of alumino-silicates, crucial geopolymer precursors [14]. The landscape of geopolymer research holds promise for satisfying the sustainability prerequisites of construction materials. Waste from diverse industrial origins possesses untapped potential to cater to construction material needs through the geopolymer approach. With available raw materials, process outputs, and recent synthesis breakthroughs, the case for adopting the geopolymer process in creating novel sustainable building and construction materials becomes increasingly compelling. Hence, a comprehensive investigation into the mechanical properties, chemical attributes, and the financial and sustainability gains of diverse geopolymer cements, formulated using industrial waste by-products, stands as a pressing research imperative. In essence, this literature review offers a guiding framework for civil engineers and the industrial community to collaborate in the pursuit of developing innovative, sustainable construction materials through the geopolymer route.

II. MATERIALS

Geopolymer concrete is an environmentally friendly alternative to conventional Portland cement-based concrete. It is made by using industrial byproducts like fly ash or slag, along with an alkaline activator solution. Fly Ash or Slag: These industrial byproducts are the primary binder materials in geopolymer concrete. Fly ash is a fine powder obtained from coal combustion, and slag is a byproduct of metal smelting processes. These materials are procured from local vendor, MIDC, Ahmednagar, Maharashtra, India. An alkaline activator solution is a mixture of alkaline chemicals, typically sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). Purpose of this solution is to initiates the geopolymerization reaction that binds the fly ash or slag particles.

III. MATERIALS AND METHODOLOGY

Due to its innovative nature, the conventional procedure for mix design outlined in the Bureau of Indian Standards IS 10262:2009 cannot be directly applied to Geopolymer concrete. In this study, the mix design methodology for Geopolymer concrete was established based on insights from various research papers. This approach closely aligns with the principles of IS: 10262:2009 and is tailored for M40 grade concrete. The testing conventions commonly used for assessing ordinary

Portland cement (OPC) concrete were adopted in this investigation. An optimized mix design was then formulated, taking into account the economic advantages of utilizing locally available materials. While Geopolymer concrete can be manufactured using diverse source materials, the experimental phase exclusively employed low-calcium (ASTM Class F) dry fly ash. Similarly, the aggregate proportions mirrored those observed in OPC, constituting 75-80% of the concrete's overall mass. To mitigate the influence of aggregate properties on the characteristics of fly ash-based Geopolymer, the study exclusively utilized aggregates from a single source.

IV. RESULTS AND DISCUSSIONS

The study revealed that the geopolymer concrete mixture exhibited uniformity, and the maneuverability of freshly mixed geopolymer concrete was assessed using the flow table apparatus, in accordance with the standards IS 5512-1983 and IS 1727-1967. For concrete with extremely high maneuverability, it's recommended to measure this attribute through flow determination, as outlined in clause 7.1.2 of IS 456:2000. The freshly mixed geopolymer concrete displayed elevated viscosity, leading to prolonged water expulsion. This water expulsion contributed to a significant settling of the geopolymer concrete over an extended duration.

Compressive strength

Compressive strength evaluations were performed on 150x150x150mm cubes at intervals of 7, 14, and 28 days. The outcomes are presented in Fig 2. These results indicate that the highest compressive strength was achieved with a silicon dioxide to sodium oxide ratio of 2. Additionally, it was observed that the compressive strength of the 12-molarity mixture surpassed that of the 14-molarity mixture.

Fig. 1. Compressive tests on Geopolymer concrete

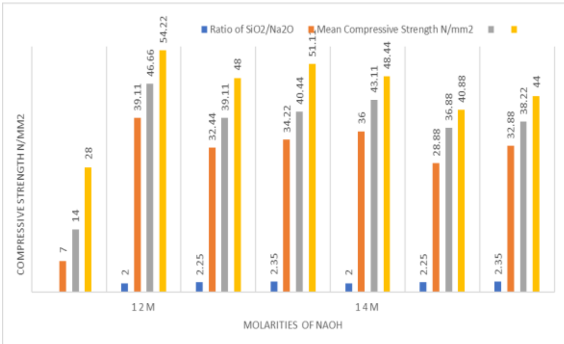

Fig. 2. Compressive strength results for alkaline solution having ratio 2

Flexural strength

Three beam sections, each measuring 100x100x500 mm, were cast and subjected to a curing period of 28 days. These beams underwent two-point loading tests using a Universal Testing Machine. Following a one-day rest period, the beams were subjected to further curing at a temperature of 60°C for 24 hours. The testing setup for the beam sections is illustrated in Fig.3. The beams were symmetrically supported over a 400mm span within the machine. Load was incrementally applied until the specimens failed, and the corresponding failure loads were recorded. The results indicate that the highest flexural strength was achieved with a silicon dioxide to sodium oxide ratio of 2. The flexural strengths were determined in accordance with the guidelines stipulated in IS 516 and IS 5816, respectively. In situations where the designer intends to estimate the flexural strength based on the compressive strength, reference can be made to IS 456:2000, clause 6.2.2.

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Fig. 4. The testing setup for the beam sections

In order to examine the impact of varying silicon dioxide to sodium oxide ratios, graphs depicting the relationship between flexural strength and this ratio were generated. The data derived from Figure 5 illustrates that the highest flexural strength is achieved when the silicon dioxide to sodium oxide ratio is 2, along with a molarity of 12, yielding a value of 13.875 N/mm². As the ratio of silicon dioxide to sodium oxide increases, there is a reduction in flexural strength. It's notable that a higher percentage decrease in silicon dioxide content and a corresponding increase in sodium oxide content result in an augmented flexural strength.

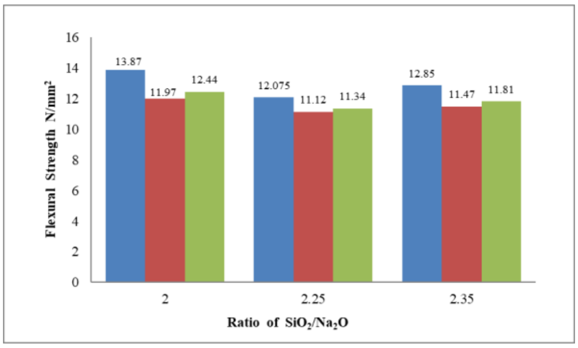

Fig. 5. Effect of varying ratio of Silicon Dioxide to Sodium Oxide on flexural Strength at 28 days for 12 molarity of Geopolymer Concrete

Split tensile test

The split tensile test is a commonly used indirect method to ascertain the tensile strength of concrete. For this study, three cylindrical sections with a diameter of 150 mm and a length of 300 mm were cast and underwent a 28-day curing process. Each cylinder was then allowed a one-day rest period before being subjected to an additional curing phase at a temperature of 60°C for 24 hours. The testing configuration for the cylinder sections is depicted in Figure 6. The outcomes demonstrate that the highest split tensile strength is achieved when the silicon dioxide to sodium oxide ratio is 2. The load was uniformly applied until the specimen fractured along a vertical diameter. In cases where a designer seeks to estimate the tensile strength based on the compressive strength, reference can be made to IS 456:2000, clause 6.2.2.

Fig. 6. Split tensile Test on Geopolymer Concrete

In order to investigate the influence of varying silicon dioxide to sodium oxide ratios, graphical representations were created to illustrate the relationship between split tensile strength and this ratio. The data extracted from Figure 7 demonstrates that the highest split tensile strength is achieved, where the silicon dioxide to sodium oxide ratio is 2, coupled with a molarity of 12, resulting in a value of 8.13 N/mm². With an increasing ratio of silicon dioxide to sodium oxide, there is a corresponding decrease in split tensile strength. It's noteworthy that a higher percentage decrease in silicon dioxide content and a concurrent increase in sodium oxide content lead to an elevated split tensile strength.

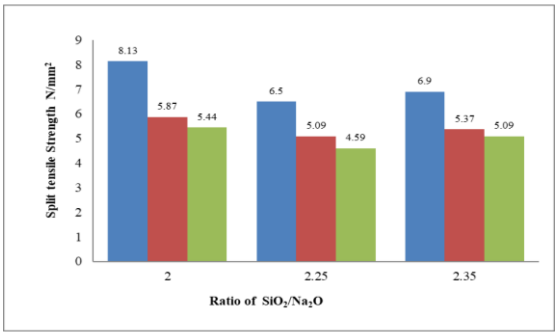

Fig. 7. Effect of varying ratio of Silicon Dioxide to Sodium Oxide on split tensile strength at 28 days for 12 molarity of Geopolymer Concrete

V. CONCLUSION

Initially, the workability of Geopolymer concrete was notably stiff until additional water was introduced. The inclusion of extra water rendered the

Geopolymer concrete mix more workable. This addition of water, however, led to a reduction in the concentration of sodium silicate and sodium hydroxide solutions within the Geopolymer concrete mix. Consequently, the workability of the mix was enhanced. The alkaline solutions, due to their viscous nature, typically offer resistance to flow. The introduction of extra water diminished the viscosity of the Geopolymer concrete mix. As time progressed, the workability of the Geopolymer concrete mix increased, subsequent to the wet mixing of its constituents.

Unlike conventional concrete, which necessitates external curing due to heat generated during the hydration reaction, Geopolymer concrete undergoes a polymerization process that expels water. This intrinsic characteristic obviates the requirement for supplementary curing.

The Geopolymerization process hinges on the pivotal role played by alkaline solutions (sodium silicate and sodium hydroxide) and fly ash. The optimal mechanical properties of concrete are achieved when the sodium silicate to sodium hydroxide ratio is maintained at 2. This ratio promotes the interaction of SiO3 in sodium silicate solution and –O-H- in sodium hydroxide with the chemical constituents of fly ash, resulting in the formation of -Si-O-Al-O- or -Si-O-Al-O-Si-O- bonds. However, as the sodium silicate to sodium hydroxide ratio escalates beyond 2 to 2.5 and subsequently to 3, the content of sodium silicate solution increases. This surplus silicate content, while not participating in the Geopolymerization reaction, weakens the -Si-O-Al-O- bonding, thereby precipitating a decline in the compressive strength, flexural strength, and split tensile strength of Geopolymer concrete.

- With a reduction in the alkaline liquid ratio (Na2SiO3/NaOH), there is a 7.37% increase in compressive strength, peaking at a ratio of 2.0.
- A decrease in the alkaline liquid ratio leads to a 13.69% increase in flexural strength.
- Similarly, a decrease in the alkaline liquid ratio corresponds to a 20.26% increase in split tensile strength.

The molarity of sodium hydroxide stands as a primary parameter influencing the mechanical strength of Geopolymer concrete, yielding the following effects:

- As the molarity increases from 12M to 14M, there is an adverse impact on compressive strength, leading to a decrease of 11.06%.
- Correspondingly, an increase in molarity from 12M to 14M results in a 17.69% reduction in flexural strength.
- Similarly, split tensile strength diminishes by 10.90% as molarity escalates from 12M to 14M.

This decrease in strength parameters is attributed to the heightened solid content that accompanies an increase in molarity. As molarity rises, there is a corresponding augmentation in solid content (i.e. sodium hydroxide flakes), leading to a reduction in water content within the solution. Previous research indicates that the mechanical properties of Geopolymer concrete tend to increase as molarity advances from 8M to 13M, but strength begins to decline beyond 13M. In this study, the strength of the concrete was observed to decline from 12M to 14M.

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