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Performance of Geopolymer Concrete with Nano-materials (Nano-Silica / Nano-Alumina) as Additives

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Abstract — Concrete is a major construction material, that is largely made up of cement; however, its high cost and ecological unsustainability has been a source of concern over the years in construction industry. In recent years, innovative cementitious materials that can be used as an alternative for ordinary Portland cement (OPC) with improved performance and emission, are locally source to reduce CO2 emission into the atmosphere during cement production and high cost of cement in concrete production. Therefore, geopolymer is an innovative and environmentally beneficial binder material that was developed to reduce Portland cement ‘s harmful environmental consequences. Geopolymer is one of the trending research areas in composite materials; there are many areas in geopolymer that unexplored still need to be explore. This study investigates the effects of blended metakaolin concrete produced with Sugarcane bagasse ash (SCBA), Rice husk ash (RHA) and alkali solution in concrete production. The optimum percentage of Metakaolin replacement was investigated and the concrete samples were tested for strength, dry shrinkage and elastic modulus. The effectiveness of two materials was examined with Metakaolin in concrete. The -percentage replacement of MK with SCBA and RHA was at 50%, 60% and 70% respectively. The samples of the concrete cubes were cured in ambient temperature and aging period of 7, 14, 28 and 56days were used to cure the samples. The fresh, mechanical properties, shrinkage and modulus of elasticity of geopolymer were investigated. Geopolymer was observed to have medium workability and mechanical properties, showed good results. The optimum mix maximum strength was observed. The target strength from the design is 25N/mm2, though; 88% of its was achieved. The strength is decreasing with increase of MK percentage and also the elastic modulus decrease; whereas the shrinkage increased as the % of MK increases. This study emphasizes, the potential for global adoption, cost saving, environmental friendly and also provide valuable insight for environmentally sustainable development.

Keywords: Geopolymer Concrete, Metakaolin, Sugarcane Bagasse Ash (SCBA), Rice Husk Ash (RHA), Mechanical Properties, Sustainable Construction Materials

I. INTRODUCTION

A. General

The construction industry is under increasing pressure to adopt sustainable practices due to the significant environmental impact of Ordinary Portland Cement (OPC) production[1]. Globally, concrete production requires 2.6 billion tons of cement annually, with one ton of cement emitting one ton of CO2 into the atmosphere. Geopolymer concrete, an innovative and eco-friendly alternative to traditional Portland cement-based concrete, has gained significant attention in recent years due to its superior mechanical properties, reduced carbon footprint, and potential for sustainable construction practices. One way to further enhance the performance of geopolymer concrete is by incorporating Nano materials such as Nano silica and Nano alumina. This integration not only improves the concrete's mechanical strength, durability, and resistance to environmental factors but also contributes to the ongoing effort of sustainable construction.

Nano silica (silicon dioxide particles with a size less than 100 Nanometers) is known for its remarkable pozzolanic reactivity. When added to geopolymer concrete, Nano silica enhances the early-age mechanical properties and accelerates the setting time. This improvement is attributed to the increased surface area of Nanoparticles, which promotes a more efficient reaction between the aluminosilicate source and the alkaline activator. As a result, geopolymer concrete incorporating Nano silica displays enhanced compressive strength, reduced shrinkage, and increased durability.

Geopolymer concrete (GPC) has emerged as a promising, eco-friendly alternative, primarily because it utilizes waste materials and emits approximately 70% less green gas than conventional concrete. GPC is an inorganic alumino-silicate polymer created through the alkaline activation of source materials rich in silicon and aluminum. The studies presented here investigate the enhancement of GPC properties through the incorporation of:

- Rice Husk Ash (RHA): An agricultural waste byproduct of rice milling, RHA possesses high silica content and significant pozzolanic properties.
- Sugarcane Bagasse Ash (SCBA): The fibrous residue remaining after the extraction of sugarcane juice.
- Nano-silica (nS): A highly effective nanomaterial used to restructure matter at the atomic level, which has a key role in improving the microstructural properties of concrete composites.
- Chemical Activators: Common activators include sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). These provide the alkaline environment necessary for the geopolymerization reaction.

B. The Environmental Imperative: The Cost of OPC

The primary driving force behind the research is the urgent need for sustainable construction materials.

- Carbon Footprint: Ordinary Portland Cement (OPC) is the most widely used material in the world, with global production exceeding 4 billion tones annually. Its manufacture is a highly energy-intensive process that involves calcining limestone ($CaCO_3$) at extremely high temperatures. This process releases massive amounts of carbon dioxide in two ways:
  - Calcination: The chemical decomposition of limestone releases CO2. This accounts for approximately 50–60% of total emissions.

  - Fuel Combustion: Burning fossil fuels to heat the kiln accounts for the remaining 40–50% of emissions.
- Scale of Impact: Cement production is responsible for an estimated 7–8% of global anthropogenic CO2 emissions, making it one of the largest industrial sources of greenhouse gases.

C. Geopolymer Concrete (GPC): The Green Alternative

Geopolymer technology offers a revolutionary way to create binder materials without relying on OPC.

- Definition: GPC is an inorganic polymer formed by the reaction of an alumino-silicate source material (like fly ash or metakaolin) with a highly alkaline activating solution (typically a combination of Sodium Hydroxide and Sodium Silicate.
- The Geopolymerization Process: The reaction, known as geopolymerization, involves the dissolution of the Si and Al components in the alkaline solution, followed by the reorganization and poly-condensation of the dissolved species into a stable, three-dimensional, amorphous alumino-silicate structure. This structure is often referred to as N-A-S-H (Sodium Alumino-Silicate Hydrate) gel.
- Reduced CO2 Emissions: Because GPC uses industrial or agricultural wastes and requires significantly less heat and energy during its production, it can achieve a CO2 reduction of up to 70-80% compared to OPC-based concrete.

D. Source Materials and Enhancement Strategies

The reviewed studies focus on optimizing GPC by utilizing readily available waste resources and advanced materials:

- Fly Ash (FA): This is the most common precursor material for GPC, an industrial byproduct from coal-fired power plants.
- Supplementary Cementitious Materials (SCMs): The studies specifically investigate using agricultural waste ashes (Rice Husk Ash and Sugarcane Bagasse Ash) as partial replacements for FA. These materials act as SCMs, adding valuable silica to the mix, which further enhances the sustainability and performance of the GPC, particularly its strength and durability.
- Nanomaterial Modification: The introduction of Nano-silica (nS) is an advanced technique. The ultra-fine particles of nS are highly reactive and fill the microscopic pores within the concrete matrix. This densifies the microstructure, leading to higher compressive strength and reduced permeability.

E. The Practical Challenge and Research Focus

While GPC offers environmental benefits, it faces practical barriers that the research aims to address:

- Curing Requirement: Many GPC mixes require high-temperature thermal curing to achieve sufficient early-age strength. This requirement is a major constraint for on-site construction and large-scale applications.
- The Research Goal: The overall goal of the research is thus to develop robust, high-performance, and genuinely viable GPC mixes that are:
  1) Sustainable (using waste SCMs).
  2) Economical (reducing energy and material costs).
  3) Practical (achieving strength at ambient curing temperatures).

II. LITERATURE STUDY

A. Aprilia, Taufiq Saidi, Teuku Budi Aulia, and Agung Efriyo Hadi Polymers 2021:

Nano silica produced from physically-processed white rice husk ash agricultural waste can be incorporated into geopolymer cement-based materials to improve the mechanical and micro performance. This study aimed to investigate the effect of natural Nano silica on the mechanical properties and microstructure of geopolymer cement. It examined the mechanical behaviour of geopolymer paste reinforced with 2, 3, and 4% Nano silica. The tests of compressive strength, direct tensile strength, three bending tests, Scanning Electron Microscope Energy Dispersive X-ray (SEM/EDX), X-ray Diffraction (XRD), and Fourier-transform Infrared Spectroscopy (FTIR) were undertaken to evaluate the effect of Nano silica addition to the geopolymer paste. The addition of 2% Nano silica in the geopolymer paste increased the compressive strength by 22%, flexural strength by 82%, and fracture toughness by 82% but decreased the direct tensile strength by 31%. The microstructure analysis using SEM, XRD, and FTIR showed the formation of calcium alumina-silicate hydrate (C–A–S–H) gel. The SEM images also revealed a compact and cohesive geopolymer matrix, indicating that the mechanical properties of geopolymers with 2% Nano silica were improved. Thus, it is feasible for Nano silica to be used as a binder.

B. E.P. Ayswarya, Ajalesh B. Nair et al., (2021):

In this research, the reinforcement effects of nano silica (NS), modified rice husk ash (MRHA), and epoxy resin are studied, including the mechanical, dynamic mechanical, and thermal properties of composites. Smaller size and more fillers are needed to improve the characteristics. The mechanical and impact properties of composite are improved by the addition of fillers and an increase in specific surface area. Silica makes up roughly 90% of RHA. As a result, it can be used as a source for making nano silica. In relation to filler loading, density and specific gravity exhibit an ascending trend. This is because adding fillers with nanoparticle sizes gives the composites a high density. Reduced particle size is what gives NS filled composites their increased tensile strength. Flexural modulus of polymer composites is dependent on filler nature, and aspect ratio of the filler particles. Enhancement of thermal stability of RHA, MRHA and NS composites is due to the organic/inorganic interaction between the polymer and filler where inorganic filler delays the volatilization of the products generated at the temperature of carbon–carbon bond scission of the polymer matrix.

C. Bharat Bhushan Jindal, Rahul Sharma 2020:

Nanomaterials, owing to their extraordinary properties are known to improve the microstructure of concrete, enhances the fresh and hardened properties of cement concrete, are widely used in cementitious materials. Many studies have been conducted so far to understand the effects of inclusion of Nanomaterials on the geo polymerization reaction, fresh and hardened state properties, microstructure, and durability of geopolymer composites. The current paper summarizes these studies mainly focusing on the effects of various Nanomaterials such as Nano-SiO2, Nano-Al2O3, Nano-TiO2, carbon Nanotubes and Nano-clay on geopolymer paste, mortar and concrete derived from various industrial by-products as sources of aluminosilicates. Most of the geopolymer products revealed that Nanomaterials enhance the fresh and hardened state properties if used in a controlled quantity. Nano-silica and Nano clay inclusion up to 2% by weight significantly enhances the rate of geo-polymerization reaction, reduces the setting times and improves the hardened state properties. Carbon Nanotubes and Nano-TiO2 enhances geo-polymerization by offering additional nucleation sites. Nano-alumina more prominently reduces the porosity but lesser effective in geo polymerization. X-ray diffraction studies report the increase in XRD peaks indicating the formation of additional hydration products that comply with SEM studies. Investigation of SEM and FTIR reveals that the inclusion of Nanomaterials densifies the microstructure of geopolymer composites and produce high mechanical strength. Durability studies reveal that enhanced geo-polymerization with Nanomaterials also prevents interconnectivity of micropores due to the formation of a denser matrix of geopolymer gel.

D. RattaponSomna, TeeraponSaowapunet al., (2022):

This work discusses the use of rice husk ash (RHA) to create hollow geopolymer blocks based on NaOH activation using both rice husk ash and fly ash (FA). For 15, 30, 60, and 90 minutes, RHA was grounded. Using 14 molar sodium hydroxide, the RHA to FA ratios of 10:90, 20:80, 30:70, 40:60, and 50:50 by weight were applied. At 7, 28, and 60 days, the compressive strengths of geopolymer paste were evaluated. The geopolymer blocks' compressive strengths and water absorption rates were evaluated after 7 and 28 days. The findings demonstrated that the geopolymer's compressive strength rose as RHA content did. Amorphous silica was present in the RHA, which also improved strength and the SiO2/Al2O3 ratio. With an increase in RHA fineness, geopolymer's compressive strength rose. The carbon footprint of a geopolymer hollow block made of rice husk ash and fly ash was roughly two thirds that of a Portland cement system. The outcome demonstrates that the rice husk ash and fly ash geopolymer hollow block could be employed while maintaining standard compressive strength and water absorption. Geopolymer hollow blocks manufactured from rice husk and fly ash have a lower carbon footprint than cement-based ones. As a result, the community and environment benefit from this product's use of environmentally friendly materials.

E. T. Meena, S. Priyanka and P. Mounika:

Nanotechnology represents a burgeoning field with the potential to revolutionize various domains of research and development. The definition of Nanotechnology has been a subject of exploration by numerous scientists. In the context of construction materials, Nano-sized materials hold promises for applications in structural repair and rehabilitation. This study specifically investigates the impact of incorporating Nano-silica into conventional concrete at different ratios on key properties such as setting time, workability, compressive strength, splitting tensile strength, and flexural strength. The Nano silica content is systematically varied from 0.0% to 3.0% at intervals of 0.5%. The objective is to assess how these incremental changes influence both the fresh and mechanical properties of the concrete. Results from the experimental investigation reveal that the mechanical strength of the concrete increases proportionally with the higher ingress of Nano-silica. However, this enhancement in strength is accompanied by a reduction in the workability of the concrete.

F. Herwani, Ivindra Pane et al. (2018):

The purpose of this study was to determine the impact of alkaline activator solution (AAS) molarity on the compressive strength of geopolymer concrete made from fly ash with a variable sodium hydroxide (NaOH) solution molarity. As a test variable, sodium hydroxide solution was selected as the activator solution. The sodium hydroxide solution concentrations utilized for ambient curing were 10M, 12M, and 14M. According to test results, raising the content of sodium hydroxide (NaOH) solution increases the compressive strength of geopolymer concrete. Geopolymer concrete's ideal compressive strength was attained at a sodium hydroxide solution (NaOH) concentration of 12M. Geopolymer concretes compressive strength only achieves around 50-60% of the planned. On a 12M molar NaOH solution, geopolymer concrete attained its maximum compressive strength. Only 50–60% of the required compressive strength was really reached. The geopolymer concrete shrank the least when the NaOH solution had a 14M molarity. On a molarity of 12M, the compressive strength increased by 32.56% the most, whereas on a molarity of 14M, it increased by just 8.51%. The geopolymer concrete also demonstrated a high initial compressive strength.

G. Research Gap Identification

1) Incomplete Understanding of RHA Characterization

- There is a lack of systematic investigation into the chemical composition, physical properties, and microstructure of RHA and their collective influence on geopolymerization processes.

2) Environmental and Economic Impacts Underexplored

- The environmental benefits (e.g., CO_2 reduction, waste management potential) and economic feasibility of using RHA-based geopolymer concrete have not been quantified or modelled comprehensively in existing studies

3) Limited Research on SCBA

- While the potential of SCBA to promote ambient curing has been shown, research on this material as a GPC precursor is still limited compared to more common materials like GGBFS.

III. OBJECTIVES AND METHODOLOGY

A. Objectives

- To design and develop novel hybrid Geopolymer Concrete (GPC) mixes by partially replacing the primary aluminosilicate binder (e.g., Fly Ash) with an optimal combination of the two agro-industrial waste materials:

Sugarcane Bagasse Ash (SCBA) and Rice Husk Ash (RHA).

- To investigate the optimal percentage of SCBA and RHA combination that allows for effective ambient temperature curing while achieving high early and final compressive strength.
- To study the effect of incorporating different dosages of Nano-silica (nS) on the workability and mechanical properties (compressive strength tensile strength, and flexural strength of the developed hybrid GPC.
- To perform microstructural characterization using advanced techniques like Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) to understand the synergistic effect and the reaction products of the multi-component binder system (FA-SCBA-RHA-nS) on the geopolymer matrix densification.

B. Methodology

Mix Design and Proportioning The mix design and proportioning of geopolymer concrete involve selecting appropriate materials, determining their proportions, and optimizing the mix to achieve desired properties. Geopolymer concrete typically relies on industrial by-products such as fly ash or slag as source materials.

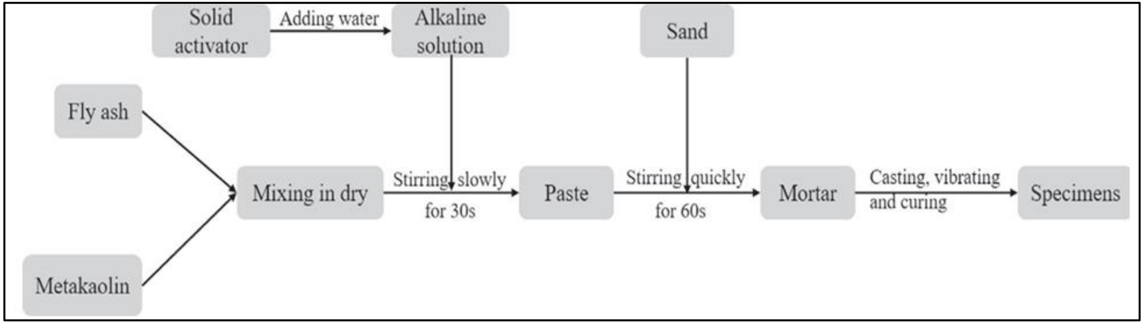

Fig. 3.1: Preparation methods of geopolymers concrete

Here is a general guideline for mix design and proportioning of geopolymer concrete:

1) *Selection of Source Materials:*
   - Aluminosilicate Source: Commonly used materials include fly ash, sugarcane bagasse ash, rice husk ash. These materials contain reactive aluminosilicate compounds that participate in the geopolymerization process.
   - Chemical Activators: Common activators include sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). These provide the alkaline environment necessary for the geopolymerization reaction.

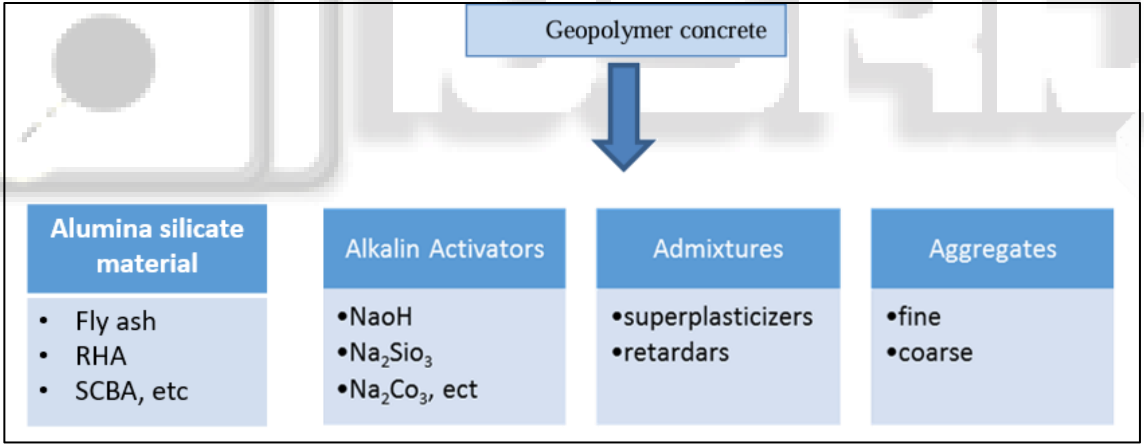

Fig. 3.2: Constituents of geopolymer concrete

2) *Sodium Hydroxide (NaOH)*
   - Type: Alkali Hydroxide Solution (also called Lye or Caustic Soda).
   - Function: NaOH is the primary source of the highly alkaline environment required to dissolve the source materials (Fly Ash, Rice Husk Ash, Sugarcane Bagasse Ash). It provides the necessary OH^- ions that break down the Si-Al bonds in the aluminosilicate precursors, releasing Silicon (Si) and Aluminium (Al) ions.

3) *Sodium Silicate (Na2SiO3) Solution*
   - Type: Alkaline Silicate Solution (also commonly known as waterglass).
   - Function: Na2SiO3 provides soluble silicate, which significantly accelerates the geopolymerization reaction (condensation and polymerization). It acts as a polymerization agent and is crucial for forming the stable, three-dimensional polymeric structure (N-A-S-H gel) that gives geopolymer concrete its strength. It also increases the overall silicon-to-aluminium (Si/Al) ratio in the mix, which is vital for the strength and stability of the final product.

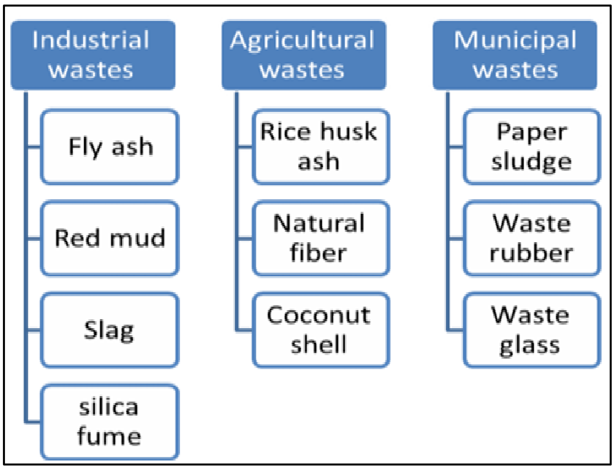

Fig. 3.3: Solid wastes that used in geopolymers concrete

(a) SCBA and FA (b) Coarse aggregates (c) Fine Aggregates

(d) Sodium hydroxide (e) Sodium silicate

Fig. 3.4: Raw Materials Used

4) *Mix Design Parameters:*
   - Target Strength: Define the desired compressive strength and other mechanical properties based on the application requirements.
   - Workability: Determine the required workability based on the construction methods (e.g., pumping, casting) and limitations of the specific application.
   - Durability Requirements: Consider factors such as resistance to chemical attack, freeze-thaw cycles, and abrasion based on the exposure conditions.
5) *Proportioning:*
   - Binder Content: Adjust the ratio of aluminosilicate source to activators to achieve the desired strength and workability. Typically, the binder content is expressed as a percentage of the total mass of the geopolymer mix.
   - Water-to-Binder (W/B) Ratio: Control the W/B ratio to achieve the desired workability while minimizing excess water, which can lead to reduced strength and durability.
6) *Mix Components:*
   - Fine Aggregate: Include fine aggregates such as sand to improve workability and contribute to the overall strength of the geopolymer concrete.
   - Coarse Aggregate: Depending on the application, include coarse aggregates that meet the desired size and gradation requirements.
   - Superplasticizer: Use superplasticizers to enhance workability without increasing water content excessively.
7) *Mixing Procedure:*
   - Activation: Mix the aluminosilicate source with activators thoroughly. This process initiates the geo polymerization reaction.
   - Aggregates: Gradually add aggregates to the mix while continuing to blend. Ensure uniform distribution of all components.
8) *Curing:*
   - Temperature and Duration: Geopolymer concrete typically benefits from elevated curing temperatures (e.g., 60-80°C) for an initial period, followed by

ambient curing. Determine the curing duration based on the specific mix and environmental conditions.

9) *Testing of Fresh and Hardened Properties*

The GPC mixtures were subjected to standard civil engineering tests to evaluate their workability and final performance.

a) Fresh Properties:
- Slump Flow Test (Workability): Performed immediately after mixing according to standards (e.g., ASTM C143) to assess the fluidity and handleability of the fresh concrete.
- Setting Time: Measured to understand the influence of SCMs and nS on the geopolymerization kinetics.

b) Mechanical Properties (Hardened Concrete):
- Compressive Strength (CS): Tested on standard cubic specimens (e.g., 100mm cubes) at multiple curing ages (e.g., 7, 14, 28, and 56 days), following standards like BS, EN12390-03. This is the primary indicator of overall concrete quality.
- Splitting Tensile Strength (STS): Tested on cylindrical specimens to evaluate resistance to fracture under tension.
- Flexural Strength (FS): Tested on prism specimens using the four-point loading test to measure resistance to bending.

c) Durability Tests (Selected Mixes):
- Water Absorption and Sorptivity: To quantify porosity and the material's resistance to water ingress.
- Resistance to Chemical Attack: Specimens exposed to aggressive solutions (e.g., acid or sulfate solutions) to assess long-term chemical durability.

C. *Quality Control Measures*

Quality control measures are essential in ensuring the consistency, reliability, and performance of geopolymer concrete. Here are key quality control measures to implement throughout the production process:

1) Raw Material Testing: Conduct thorough testing of raw materials such as fly ash, slag, activators (sodium hydroxide, sodium silicate), aggregates, and any additives to ensure they meet specified standards and are consistent.
2) Mix Design Verification: Verify the mix design through trial mixes and testing to confirm that it meets the required specifications for strength, workability, and durability.
3) Batching Accuracy: Implement precise batching procedures for all components to ensure accurate proportions. Use calibrated measuring equipment and regularly check the accuracy of batching systems. 4. Mixing Process Control: Monitor and control the mixing process to ensure uniform dispersion of materials. Adequate mixing time and proper equipment maintenance are crucial for achieving homogeneity.

D. *Mechanical Property Testing*

1) *Compressive Strength Testing*

Compressive strength testing is a crucial procedure in the quality control and performance evaluation of geopolymer concrete. Compressive strength is a key indicator of the material's ability to withstand axial loads and is a fundamental parameter in assessing the structural integrity and durability of concrete. The testing process involves subjecting cylindrical or cubical specimens of geopolymer concrete to gradually applied axial loads until failure occurs, allowing for the determination of the maximum load bearing capacity.

2) *Procedure:*

a) Specimen Preparation:
- Mold Filling: Geopolymer concrete specimens are typically cast in cylindrical or cube molds using the same mix design and procedures as the actual structural elements.
- Compaction: The fresh concrete is compacted to ensure uniform density and minimize voids. Careful compaction is crucial to achieving accurate and reliable compressive strength results.

b) Curing:
- Standard Curing Conditions: The specimens are cured under controlled conditions, typically at specified temperatures and humidity levels. The curing duration follows the project specifications and may include periods such as 7, 14, or 28 days.

c) Specimen Removal:
- Demolding: After the designated curing period, the specimens are carefully demolded. Special care is taken to avoid damaging the specimens during the demolding process.

d) Surface Preparation:
- Grinding and Smoothing: The surfaces of the specimens may be ground or smoothed to ensure uniform loading during the compressive strength test. This step helps minimize any irregularities that could affect the test results.

e) Testing Machine Setup:
- Load Application: The prepared specimens are placed in a compression testing machine. The machine is calibrated to ensure accuracy, and the specimen is aligned to receive an axial load along its longitudinal axis.

f) Loading:
- Gradual Loading: The axial load is applied gradually at a constant rate until the specimen fails. The loading rate is typically within the range specified by relevant standards.

g) Failure Mode Identification:
- Observation: During the test, the behavior of the specimen is closely observed. The failure mode, whether it is a sudden and brittle failure or a more ductile behavior, can provide additional insights into the concrete's characteristics.

h) Recording Results:
- Maximum Load: The maximum load sustained by the specimen before failure is recorded. This load is used to calculate the compressive strength of the geopolymer concrete.
- Failure Stress: The stress at the point of failure is calculated by dividing the maximum load by the cross-sectional area of the specimen.

i) Calculation of Compressive Strength:
  - Compressive Strength Formula: The compressive strength of geopolymer concrete is calculated using the formula: Compressive Strength=Maximum Load Cross-sectional Area Compressive Strength=Cross sectional Area Maximum Load

j) Analysis and Interpretation:
  - Comparison: The calculated compressive strength is compared to the specified design strength or project requirements. Deviations from expected results may prompt further investigation and adjustments in the mix design or curing conditions.

IV. EXPECTED OUTCOMES

The successful completion of this project is anticipated to yield several significant outcomes:

- Sustainable and High-Performance Material: Development of an optimized, environmentally friendly hybrid GPC mix proportion that maximizes the utilization of two prominent agro-industrial waste materials, SCBA and RHA, as cementitious replacements.
- Enhanced Ambient Curing Feasibility: The formulated hybrid GPC is expected to achieve target compressive strengths (e.g., meeting structural grade requirements) when cured at ambient temperatures, effectively overcoming a major commercialization hurdle for GPC.
- Superior Mechanical Properties: The synergistic inclusion of Nano-silica is expected to result in hybrid GPC with significantly enhanced mechanical properties (CS, TS, FS) compared to control mixes, owing to the finer particle and catalytic effects of the nanoparticles.
- RHA Performance: RHA has been affirmed as a strong candidate for fostering greater sustainability in construction practices.
- Reduced Water Absorption: The incorporation of RHA improves the density of the GPC, leading to better durability properties. An addition of 20% RHA reduced the water absorption of GPC by 14%.
- SCBA Performance: SCBA proves to be a suitable substitute for fly ash in GPC, with FA-SCBA mixtures achieving high compressive strength even with ambient curing, which minimizes energy usage and environmental effects.
- Nano-silica Performance: The addition of nano-silica may consistently improves the compressive strength of geopolymer concrete.

Optimal Compressive Strength at Specific Dosage: The maximum compressive strength is expected to be achieved when the dosage of nano-silica is optimized, with one study showing strength improvement by over 20% when the dosage was increased up to 3%.

Nucleation and Pore Refinement: Nano-silica is expected to act as a nucleation site, accelerating the geopolymerization reaction and filling micro-pores, leading to a denser and more homogenous matrix structure.

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