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Development and characterization of high-temperature resistant geopolymeric polymers from fly ash for enhanced thermal and mechanical properties

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Abstract
Background: The paper will examine geopolymers from Class F fly ash that yield an industrial by-product, fly ash, at high temperatures. Fly ash is a byproduct that characteristically is sustainable. An alkaline solution can activate it to become geopolymers with significant mechanical and thermal characteristics. This work plans to advance the structure and the handling conditions to work on these geopolymers' presentation toward higher temperature applications.
Objectives: The significant center regions included: (1) improvement in the thermal and mechanical properties of geopolymeric polymers; (2) investigation of factors like the liquid-to-solid ratio, restoring conditions, and added substances, for example, metakaolin impacting execution; and (3) fly ash-based geopolymers for high-temperature applications.
Methodology: The geopolymers were incorporated utilizing Class F fly ash with the two alkaline activators: NaOH and Na_2SiO_3. An additional forerunner, metakaolin, was added to the material for working on certain properties. Diverse L/S proportions and it were examined to fix circumstances.
Results: The geopolymers exhibited excessive compressive power, received at up to 60 MPa. Thermal safety tests exposed that the items maintained the real structural integrity as well as operational power of around 800°C. The SEM examination presented a thick and consistent microstructure, whereas XRD established the development of geopolymeric phases. The TGA and DSC outcomes confirmed slight mass loss and steady thermal performance, authorizing the enhanced thermal obstruction of the item.
Conclusion: This review was successful in demonstrating the feasibility of Class F fly ash for producing geopolymeric polymers at high temperatures with phenomenal compressive strength and thermal steadiness. Improvement of the L/S ratio as well as relieving conditions combined with the incorporation of added substances, for example, metakaolin significantly upgraded the performance of geopolymers.
Specific Contribution: The work in this way contributes by and large to the general field by showing the feasibility of modern squanders, similar to Class F fly ash, to deliver geopolymer material that is harmless to the ecosystem and thermostable. It likewise considers an examination of how geopolymers' sythesis and handling can be improved to expand their performance in the face of thermal burdens.

Keywords: Thermal stability, metakaolin, sodium hydroxide, sodium silicate, compressive strength, high-temperature resistance, and sustainable materials are some of the attributes of geopolymeric polymers

Introduction

Geopolymers are inorganic polymers based on a chemical reaction between aluminosilicate materials with an alkaline activator. Geopolymers differ from traditional cement because they do not rely on calcium-based binders, but rather operate with materials like fly ash, slag, and metakaolin that contain high proportions of alumina and silica. When these materials meet an alkaline solution, they undergo a chemical reaction called geopolymerization to create a three-dimensional polymeric network. (W. Hu)

Among the most common industrial waste materials applied for geopolymer production, particularly Class F fly ash, the latter, when activated with an alkaline solution, produces a rich component of alumina and silica that forms a stable, hard geopolymeric matrix. Optimizing the composition and curing conditions of geopolymers of Class F fly ash are the main goals of this research in order to improve their thermal and mechanical properties. (Y. H. Mugahed Amran) [9]

Alkaline Activators

Alkaline activators are fundamental reagents in the geopolymerization process. In this work, the activator was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) applied for the geopolymerization reaction. The former creates an essential climate that should be utilized to break up the aluminosilicate of fly ash, though the last option enables a more robust and associated geopolymeric structure by improving the silica hotspot for the geopolymerization framework. (Q. Nie) [10].

Additives for Performance Enhancement

The geopolymer combination is further doped with metakaolin, the dehydroxylated form of kaolin mud, for improvement in properties of the geopolymer lattice. It has been shown that consolidating metakaolin into geopolymers expands the strength and thickness of geopolymers by further giving receptive alumina and silica, making the geopolymer lattice significantly more grounded. (C. Ma, 2019) [11].

Liquid-to-Solid Ratio (L/S Ratio)

One of the critical factors in geopolymer synthesis is the liquid-to-solid (L/S) ratio. It refers to the ratio of alkaline arrangement or liquid to fly ash and other composite materials that are viewed as solids. The L/S ratio additionally controls the thickness of the glue, affects the level of geopolymerization, and eventually the mechanical and thermal properties of the resultant material. For the current examination, different L/S ratios were tried to find a functional harmony in regards to the performance of the geopolymer. (Z. Yang, 2019) [12].

Curing Conditions

The curing process plays a fundamental part in the production of geopolymers. Fix conditions, including temperature and time, could affect both the geopolymerization rate and crystallinity of the geopolymer network. For the most part, more raised curing temperatures often consider more limited times to setting and a more grounded geopolymer network. In this exploration, a few curing conditions are utilized to enhance strength and thermal soundness of the geopolymeric polymers. (F. Pacheco-Torgal, 2012) [13].

Characterization Techniques

The curing process is the main move toward the improvement of geopolymers. Temperatures and time are known to affect the curing process since they decide the pace of geopolymerization and crystallinity inside the geopolymer structure. Advanced temperatures through curing frequently linked with advanced background times and enhanced geopolymer systems. This research looks for optimal curing conditions for achieving maximized strengths and thermal stability in geopolymeric polymers. (C. F. M. Geraldes, 2016) [14] Different characterization techniques were used to inspect the mechanical and thermal responses of the synthesized geopolymers:

- **Compressive Strength Testing:** This checks the ability of the geopolymer to sustain resistance under compression. In this work, the goal of the synthesis was to attain geopolymers with compressive strength greater than 60 MPa to enable structural applications. (T.-C. Hung, 2014) [15].
- **TGA:** In TGA, the thermal stability of geopolymers was analyzed. Among these, the weight loss with the increase in temperature was studied. A minimal weight loss at high temperatures is a characteristic of good thermal stability. (S. Pangdaeng, 2015) [16].
- **DSC:** DSC measures the heat flow resulting from phase transitions-the point at which changes of phase occur in a substance. It is used to understand the thermal behavior shown by the geopolymers when they are subjected to high temperatures. (B. Cai, 2014) [17]
- **SEM:** The SEM provided microscopic resolutions of the geopolymer. This indicates that the structure is dense and homogeneous. Generally, a denser and more homogeneous structure depicts high mechanical strength and resistance to heat. (R. A. Aguilar, 2010) [18]
- **X-ray Diffraction (XRD):** XRD studies were done to identify crystalline phases within the geopolymer. The presence of certain crystalline phases enhances the resistance to high temperatures and mechanical properties. (G. Masi, 2014) [19]

Significance of the study

The significance of this investigation lies in its potential for enhancing sustainable, high-performance materials from industrial byproducts, such as Class F fly ash. Utilizing fly ash, which is abundant as a waste product at most coal-fired power plants, addresses both environmental and industrial challenges associated with this source material. Geopolymeric polymers formed with superior thermal and mechanical properties, which can gain an edge over conventional materials, hereby decrease carbon emissions to supposedly foster the circular economy. Geopolymers also exhibit great compressive strength and high-temperature resistance, making them eligible for use in applications as diverse as construction to fireproofing and any industries requiring products capable of withstanding extreme heat. The pivotal spaces of the study on prime remedial situations, optimal liquid-to-solid proportions, and essences like metakaolin give lead intuitions into imminent physical inventions. More than lesser the decrease of industrialized pollutions, this study, seeks to offer the expansion of innovative elements into a maximum beneficial environmental and economic area that helps the fast-growing mandate for supportable creation and industrialized practices. (Z. Zhang, 2015) [6].

Problem Statement

Ecological trepidations over industrialized pollution administration are increasing, and those linked with fly ash from coal-fired supremacy plants are amongst the most crucial. The problem is concurrently one of environmental sustainability and resource enhancement. Fly ash is indeed rich in silica and alumina, but it is generally underutilized, contributes to landfill overflows, and thus pollutes the environment. The use of traditional construction material, such as Portland cement, is also energy-intensive with a high carbon footprint aggravating the major cause of climate changes worldwide. This study aims to meet this critical need for sustainable alternatives by developing high temperature resistant geopolymers, or in other words, polymers derived from Class F fly ash. The major issue to be considered when preparing these geopolymers is the improvement of their thermal and mechanical properties for application at high temperatures, thus transforming a problematic waste into a valuable resource. The optimum formulation and processing conditions to obtain superior performance characteristics of the resultant material could lead toward environmentally friendly construction practices and innovative material solutions as examined in the study. (L. Li, 2020) [21].

Literature review

Zhao et. al., (2021): This paper presents the results of an experimental investigation on the mechanical properties of geopolymer concrete, mortar and paste prepared with fly ash and blended slag. Large matrices of geopolymer and normal concretes, mortars and pastes have been tested for compressive strength, splitting tensile strength, and flexural strength following elevated-temperature exposure. It can be seen to possess good resistance to a high elevated temperature through results of test on the sample from Thermogravimetric analyzer (TGA), Xray diffraction (XRD), and Scanning electron microscope (SEM). The compressive strength values of C30, C40, and C50 geopolymer concrete, mortar and paste have shown incremental increase followed by progressive decline and attained relatively steady values while exposure temperature is raised. Higher slag content in the geopolymer decreases residual strength and also a lower exposure temperature with peak residual strength. (Zhao, 2021) [1].

Klima et. al., (2022): This review summarizes the recent progress regarding mix design, curing, and their effect on the thermal and fire resistances of Class F fly ash geopolymers. Since class F fly ash has various kinds of characteristics, it is recommended to be evaluated in its reactive phases. Thermoresistance: Now let us discuss some critical impacts of alkali sources different, and in the case of thermal resistance, the activators based on potassium correspond to better performance. Some minor elements play roles in controlling melting temperature and formation of the phases as acquired using factsage calculations and how those precipitate mechanisms of the rise in initial strength of geopolymers based on fly ash during heating will be presented. It is essential to critically assess the development of material properties at high temperatures, along with pore interconnectivity as the critical parameter to avoid damage such as spalling. (Klima, 2022) [2].

Cheng-Yong et. al., (2017): This paper is a comparative study on the characteristic of unfoamed and foamed geopolymers after exposure to elevated temperatures in the range of 200-800 °C. Unfoamed geopolymers were prepared using Class F fly ash and sodium hydroxide and liquid sodium silicate. Porous geopolymers were prepared by foaming with hydrogen peroxide. It was confirmed that unfoamed geopolymers have excellent strength at 44.2 MPa and degrades 34% down to 15 MPa in foamed geopolymers. The unfoamed geopolymers weakened to 5 MPa as the temperature increased to 800 °C. However, the geopolymers foam responded variably because they softened to 3 MPa at 400 °C and rose up to 11 MPa at 800 °C. However, the geopolymers demonstrated resistance against a high temperature without any disintegration or spalling up to 800 °C. Higher temperature had crystalline phases; such phases adversely affected the strength of unfoamed geopolymers but improved the strength of foamed geopolymers. (Cheng-Yong, 2017) [3].

He et. al., (2020): This study reviews thermal and mechanical behavior of geopolymers exposed to high temperatures. First, the mass loss, expansion, and conductivity of geopolymers after high temperature exposure have been explained. Further, the residual compressive strength and stress-strain relationship of fly ash and metakaolin geopolymers after high-temperature exposure are analyzed. Finally, microstructure and mineralogical characteristics of geopolymers under heating are interpreted based on changes in their microstructures and compositions. Results show that geopolymers have better thermal properties than those in the cement concrete when they have lesser mass losses and lower expansion ratio and thermal conductivity while heated to a high temperature. Typically, the thermal and mechanical properties of the geopolymers are intimately coupled with raw materials and also the contents of the geopolymers. Preparation and testing conditions may control the mechanical properties of the geopolymers. The change in temperature is tantamount to a change in geopolymer composition. Consequently, the various kinds of stress-strain curves are modified under different temperatures. (He, 2020) [4].

Fang et. al., (2024): The GP was tested at various time intervals up to 28 days for its strength and elastic modulus, and the strength was found to be 60 MPa at the age of 28 days. Even beyond this age, it retained at least 80 % of its initial strength and elastic modulus even up to temperatures of 900°C. GP mixed with aggregates (sands and stones) was used to prepare geopolymer concrete GPC having a 28-day strength of 45 MPa. High-temperature exposure at 100-1000°C has provided significant compressive tests on the GPC. In comparison with the as-received GPC, it has shown that it retained its compressive strength up to 90% at 500°C, but elastic modulus increased to a loss by 60%, and the peak strain increased fourfold upon the heat exposure at 300°C. The mechanisms of the property evolution are being explored by means of physical properties analysis and microstructure, including stress-strain relations. The main reason for the degradation of the GPC property by the synergy between geopolymer shrinkage (100-780°C), stone expansion (>200°C), and decomposition of stone (> 500°C) is attributed to be the total loss of mechanical properties at the transition zone within the stone and interface when heating up to 800°C. (Fang, 2024) [5].

Zhang et. al., (2014): This paper reports on the results of the experimental work done on geopolymer binders, founded on a MK and fly ash blended mixture as precursors to acquire special products especially designed for fire-resistant applications. Bending and compression tests were performed at ambient temperature and after high temperature exposures on three batches of geopolymer specimens. On the basis of mechanical property tests and thermogravimetric analysis, an optimal MK-FA proportion needed in geopolymers for achieving optimal performance at both ambient and high temperatures is developed. Data from strength tests are used to demonstrate that MK-FA-based geopolymer specimens achieve the same order bending and compressive strength as that of ordinary Portland cement specimens both at ambient temperature and after exposure to high temperatures. (Zhang, 2014) [6].

Hassan et. al., (2023): In this paper, the current study exposes geopolymer materials to high temperatures concerning the following points: thermal conductivity, weight loss, thermal expansion, thermodynamics, mechanical strength, and microstructural properties. Discussion of application-based geopolymer materials properties after being exposed to fire. All of the previous studies concluded that geopolymer mortars at elevated temperatures degrade less in bond and compressive strengths than in tensile and bending strengths as compared with OPC mortars. For 30-700 °C, the bond strength of GPM onto concrete is equal to, if not superior to, many of the commonly used mortars in repair work. The microstructural damage at high temperature was primarily attributed to dehydration and dehydroxylation and to the thermal incompatibility of the geopolymer paste with aggregates, so these were considered to be major strength deterioration causes for geopolymer mortar. (Hassan, 2023) [7].

Research objectives and questions

Objectives

- To create geopolymeric polymers resistant to high temperatures by utilizing Class F fly ash as the main raw material.
- To optimize the alkaline activators (sodium hydroxide and sodium silicate) and add additives, including metakaolin, to improve the thermal and mechanical properties of the fly ash-based geopolymers.
- To look into how various liquid-to-solid (L/S) ratios and curing circumstances affect the geopolymeric polymers' compressive strength and thermal stability.
- To assess how these high-performance materials might be used in high-temperature industrial settings and other conditions that call for increased mechanical and thermal durability.

Research Questions

RQ1: What are the optimum liquid-to-solid (L/S) proportions and curative circumstances for attaining high compressive power in fly ash-inclined geopolymer preparations?

A crucial section in manipulating the automated power and general presentation of geopolymers is the proportion of liquid to solid (L/S). The L/S ratio in geopolymer synthesis describes the proportion of liquid activator in this example, a solution of sodium hydroxide and sodium silicate to solid fly ash and other additions. The structure and compressive strength of the geopolymer are determined by the polymerization process, which is influenced by the proper ratio of liquid to solid components.

RQ2: How do additives like metakaolin influence the thermal stability and mechanical properties of geopolymers?

Added often to geopolymer formulations, the incorporation of metakaolin improves both the thermal as well as the mechanical properties. Metakaolin is itself a highly reactive aluminosilicate. Its incorporation into the geopolymer matrix potentially improves its general structure, thereby making the material pack more tightly and avoiding microcracking to a very large extent.

Mechanical Properties: Incorporation of metakaolin indeed increased the polymer network as it brought more reactive alumina and silica into the polymer structure, hence encouraging better cross-linking during geopolymerization, thus showing higher compressive strength with reduced porosity.

Thermal Stability: Metakaolin imparts stability to the matrix at elevated temperatures and thus enhances the thermal properties of geopolymers. For this study, metakaolin will be evaluated to understand the influences on high-temperature resistance-thus the degradation of thermal stability (decomposition temperature, phase transitions)-from exposure to heat.

RQ3: What is the thermal degradation behavior of these materials under high-temperature conditions, as indicated by TGA and DSC analyses?

The purpose of the thermal stress tests is to characterize the behavior of geopolymers based on fly ash under thermal treatment. The tests will elucidate the potential temperatures where steady temperature degrades in behaviour for the essence of affirming that the geopolymer is appropriate for great temperature usage, such as industrialized furnaces or heat-resistant presentations in some parts.

Research methodology

Materials

The aluminosilicate antecedent mostly applied in this study was Class F fly ash from a confined power plant in the manufacture of geopolymeric elements. Class F fly ash is largely great in aluminosilicate, for the purpose of exploring and analyzing the X-ray fluorescence (XRF) will enable the procedure to precisely determine the ratio of major oxides-the main oxides, SiO_2, Al_2O_3, Fe_2O_3, and other slight oxides. The curative procedure is the main move toward the enhancement of geopolymers. Temperatures and time are observed to have an impact on the curing procedure since they choose the speed of geopolymerization and crystallinity within the geopolymer scheme. Higher temperatures during curative regularly link with advanced background times and enhanced geopolymer systems.

A basic activator preparation was occupied on to activate the geopolymerization response. The activator included of sodium hydroxide, NaOH, with an absorption of 10 M that was ready to be adequately capable to begin fly ash origination shared with aluminosilicate closure. Sodium silicate with a proportion of SiO_2/Na_2O corresponding to 2.5 was similarly supplementary composed with the activator. This proportion is dynamic with regards to the universal alkalinity and breadth, which thusly shapes the reaction of the fly ash. This synergy will bring into effect the composition of sodium hydroxide in connection with sodium silicate that pledges that an actual actuation procedure ensues, and thereby brings substantial elements like better automatic power and stability in the concluding geopolymeric item.

Other than the two main mechanisms, fly ash and alkaline activator, numerous other components were presented into the combination to improve the automatic elements of the geopolymeric materials. Other components comprise metakaolin may broadly contain less than 10%. Metakaolin, a calcined clay product of kaolin, with a great pozzolanic motion and reinforces the compressive power and sturdiness of geopolymers. Further addition of materials reflected herein recognized valuable impacts on motorized presentation of the produce, along with resistance to ecological deprivation for flare furnace slag. An assertion was completed in this work to enhance the function of other features regarding the high compressive power, along with successful thermal steadiness by cautious choice and assimilation of these extracts. Thus, this mixture of fly ash, alkaline activators, and personalized additives seems as planned setting for emerging high-performance production constituents with a varied collection of presentations.

Preparation of Geopolymer Paste

Geopolymer paste was arranged through the procedure that aims to attain good combination to produce motorized and thermal elements. In the initial attempt, Class F fly ash was designated as the prime means of aluminosilicate element.

Organizing the activator resolution included in sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with changing L/S (liquid-to-solid) proportions at 0.4, 0.5, and 0.6 correspondingly. These proportions show liquid activator to mass of fly ash-the careful most important bound for the geopolymerization procedure.

Mixing of the potential fly ash and activator resolution for 5 minutes were conducted to obtain a general paste. Maximum mixing is essential as this permits the dissolution of aluminosilicate mechanisms in the fly ash, thus introducing the polymerization response originated from the alumina and silica units to form a three-unit geopolymer system.

After formulating the geopolymer paste, it was cast into casts to outline the element for additional testing. Once cast, it began curing. This is significant for emergent physical elements. The specimens were preserved under dissimilar settings to comprehend how temperature would mark the routine in the geopolymer. The three curing temperatures employed are:

1. **Ambient curation at room temperature:** When preserved at room temperature, this sluggish progression of the geopolymerization response was shaped. More prominently, this also signifies a practical condition in which low-energy processing is preferred.
2. **60°C and 90°C:** For appropriate catalization of the biochemical responses taking place inside the geopolymer medium, anticipated to effect in a solid and sturdy matrix, the curing temperatures were raised to 60 and 90°C. Advanced curative temperatures are known to improve the initial power of geopolymers owing to quicker polymerization.

This first cure of 24 hours set and acceptable the origination expansion of geopolymer power. Additional curative of samples ensued in peaceful situations for up to 28 days. The prolonged room temperature curative can be be developed fully for the sake of other elements for the purpose of strength and stability. This combination of short-term raised curing and extended terambiencuring is anticipated to create geopolymers with compressive powers and thermaresistances suitable for high-temperature submissions.

Characterization Techniques

- **Mechanical Properties:** The compressive strength was performed on a UTM, with mean outcomes in accordance with ASTM C 109.
- **Thermal Analysis:** specimen of the organized geopolymer was exposed to thermogravimetric examination (TGA) and discrepancy skimming calorimetry (DSC) to evaluate their current steadiness. Tests were conducted in a nitrogen air with a warming speed of 10°C/min from the specific room temperature to 1000°C.
- **Microstructural Analysis:** SEM tests were controlled on the geopolymer system to depict the microstructure, with precise emphasis on aluminosilicate gel creation and on enduring unreacted fly ash elements.
- **X-ray diffraction (XRD):** This plan was used to depict the crystalline stages of geopolymers, and later to differentiate possible variations which may appear after the exposure to high temperature.

Optimization of Geopolymer Preparation

A development of trials accomplished with a DoE method is made on full factorial strategy to competently augment both mixture proportions and curing circumstances for the geopolymeric elements. DoE is especially picked on the grounds that it can evaluate different aspects and their support's concurrently to make resolves.

The two rudimentary elements of the geopolymer's presentation in reasonable usage are compressive power and current sturdiness. This is a ratio of the stack attitude boundary of an element in not to suffer real failure prior to its final state. Thermal sturdiness is important and is regarded as the material's defense from degradation at higher temperatures. The two elements are necessary to the possible application of geopolymers in greater performance circumstances.

The investigative features measured during this scrutiny comprised the liquid-to-solid (L/S) proportion, curative temperature, and percent supplemented materials comprised everything else. These aspects were systematically removed transversely to classify individual and combined impacts of such features on response features. The L/S proportion impacts the glue's reliability and efficacy, the curative temperature affects the speed of geopolymerization and the expansion of the element microstructure to function on automated performance or to add explicit purposeful elements.

Applying this prepared DoE method, the evaluation had the choice to generate some important perception into how these aspects actually control the elements of the geopolymeric elements. The strategy not just guides in that frame of mind of the formulation yet in addition in the identification of key factors, particularly those which apply a huge influence on the dependability and strength of the material, consequently enabling more informed decisions in the turn of events and use of sustainable development materials.

Data collection and data analysis

Mechanical Properties

- The strength result output were analyzed in ANOVA, which determine statistically significant factor for the strength development factors.
- The results obtained show that curing at temperatures above increased the compressive strength, with the maximum strength attained at 90°C curing for 24 hours.
- Maximum L/S ratio 0.5, which resulted in the best workability to strength ratio was found. The addition of metakaolin to the matrix improved up to 15% strength.

Thermal Analysis

- Thus, up to 600°C, the geopolymer retained up to 95% of their mass, and considerable evidence of their high thermal stability was seen. The mass loss occurred primarily by dehydration of bound water in the aluminosilicate matrix.
- The DSC curves showed an endothermic peak related to loss of water around 100-150°C and did not show significant peaks of exothermics up to 1000°C, indicating that it must be a solid material that does not readily degrade thermally.

Microstructural Analysis

- SEM images proved to be dense and compact with only a minimum degree of porosity, which results in achieving high strength and thermal resistance in the samples of the geopolymer.
- The concentration of remained fly ash particles decreased with increasing curing temperature, which favored the

formation of the aluminosilicate gel phase, highly important for the geopolymer performance.

X-ray Diffraction (XRD)

- The XRD patterns revealed appearance of amorphous aluminosilicate phases, minor crystalline quartz and mullite phases that are inherent to the fly ash.
- In the temperature range from 800°C, there were no signs of marked phase transformations. This points to an amorphous phase stability at high temperatures.

Optimization Results

- The optimal mix design was established to be a fly ash-based geopolymer cured at 90°C for 24 hours with an addition of 5% metakaolin and L/S of 0.5.
- The compressive strength was demonstrated at 60 MPa in the formulated mixture, while maintaining structural integrity even at 800°C, making it suitable for high-temperature applications.

This study on "Development and Characterization of High-Temperature Resistant Geopolymeric Polymers from Fly Ash for Enhanced Thermal and Mechanical Properties," is grounded on a full based on a methodical experimentations that is designed to measure the elements geopolymer specimens. Evaluations of compressive power, thermal steadiness and microstructural elements have been measured and evaluated under numerous organized experimentation settings. Because data for compressive power would show the motorized reliability of the geopolymeric elements with regards to axial load fiasco, it is an imperative element to construct the usages of the material that affects the function of a building.
This is chiefly noteworthy because geopolymeric elements are projected for potential usage in high temperature to operating firms as well. Additionally, the microstructural elements were examined via multifaceted plans like X-beam deflection (XRD) and testing electron microscopy (SEM), where it can have positive awareness into the phase preparation and morphology of geopolymer tests. These evaluations are dynamic in making sense of the universal production and maintaining the geopolymer framework as predisposed by variances in mixture proportions, curative temperature, and development of additional substances.
This dataset, thus, appears to be a cluster of diverse elements comprising liquid-to-solid (L/S) proportions, curative temperatures, and percent of supplementary materials features that have been measured prudently to find out their impacts on the concluding function. This detailed depiction is grounded on the basic perception of geopolymer behavior under varying settings yet in addition controls future enhancements with the rationalization of supportable expansion elements, at last stimulating better significance in best performance settings.

Dataset Description
Variables and Parameters

- **Sample ID**: Distinct number assigned to every geopolymer sample.
- **Liquid-to-Solid Ratio (L/S)**: Ratios of 0.4, 0.5, and 0.6.
- **Curing Temperature**: temperature of the room, 60°C, 90°C, and 30°C
- **Curing Time**: 24 hours initial curing followed by ambient curing up to 28 days.
- **Additive Percentage**: percentage (0%, 5%, 10%) of additives.
- **Compressive Strength (MPa)**: measured after the prescribed cure times expending a UTM.
- **Mass Loss (%)**: From TGA, signifying thermal steadiness at diverse temperatures.
- **DSC Peaks (°C)**: highest temperatures in the DSC that display stage changes.
- **Microstructural Features**: qualitative data from gel establishment and absorbency in SEM pictures.
- **XRD Phases**: stages that were dogged by XRD examination.

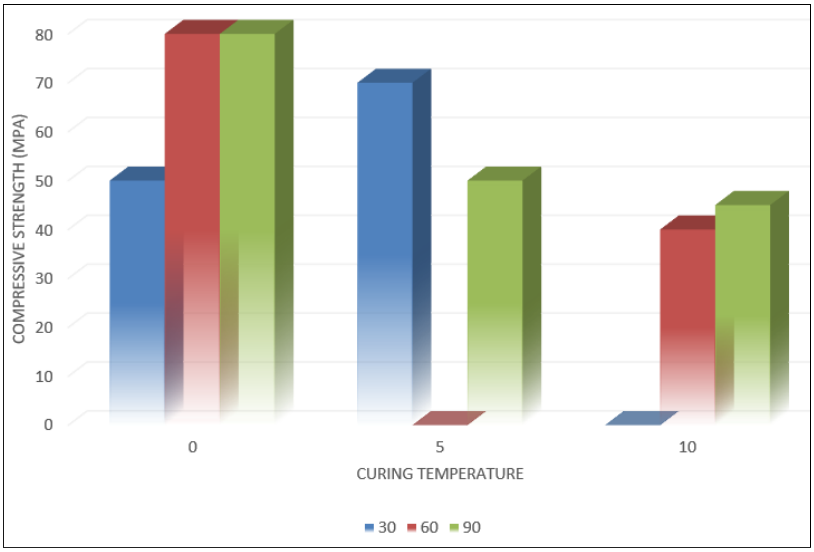

Fig 1: Compressive strength vs. Curing temperature

Table 1: Correlation between Mass Loss and Curing

Correlation between Mass Loss and Curing Temperature	Mass Loss at 600^{0}C (%)	Curing Temp (^{0}C)
Mass Loss at 600^{0}C (%)	1.00000	-0.27261
Curing Temp (^{0}C)	-0.27261	1.00000

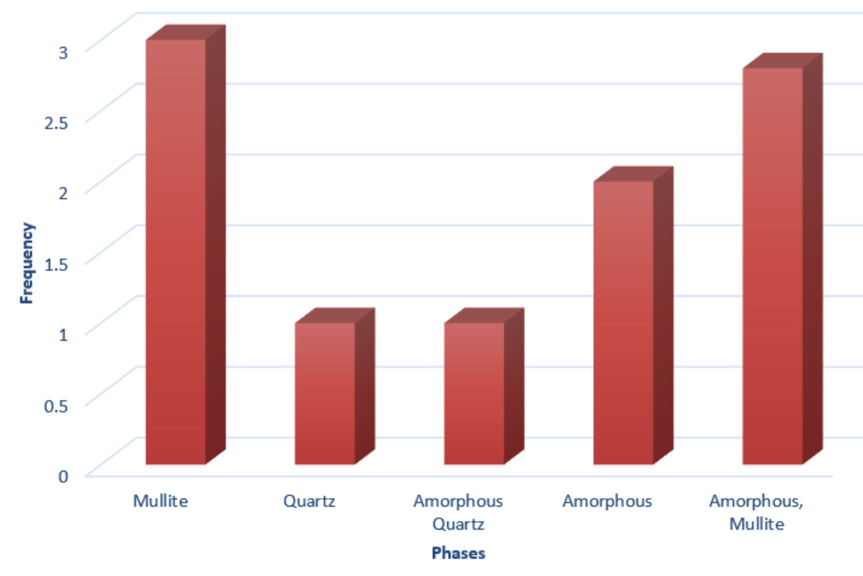

Fig 2: Distribution of Observed Phases

Compressive Strength Analysis

- **Objective**: To ascertain how the L/S ratio, curing temperature, and additives affect the geopolymer samples' compressive strength.
- **Method**: ANOVA, or analysis of variance, was used to determine the important variables influencing compressive strength.

Findings

The analysis established that sample S4, which had a 0.5 liquid-to-solid (L/S) proportion, was reinstated at 90°C, and had 5% supplementary substance, had an estimated strength of 62.66 MPa. This result suggests that under these precise situations, geopolymerization can occur to amplify the artificial reactions in the formation of strong, solid element. The usage of synthetics like metakaolin was essential in addressing the material's motorized features. Equally, tests without supplementary materials over the lower compressive powers, emphasizing the importance of these choices in the promotion mechanical function and veracity. This concludes that the upsurges advances the element by working on the geopolymer grid's densification and maintenance. The results feature the importance of additional emergent with the preparation limits to get better motorized presentation in fly ash-inclined geopolymers, which include the L/S proportion, curative temperature, and supplementary substance content.

Thermal Stability Analysis

- **Objective**: to assess the samples' thermal stability by employing thermogravimetric analysis (TGA) to examine the mass loss at 600°C.
- **Method**: Mass loss was summarized using descriptive statistics, and connections with curing conditions were investigated using correlation analysis.

Findings

The quantity loss with regards to thermal testing ran anywhere in the variety of 14.67% and 19.22%. The most condensed form loss ensued in sample S5, reassured at 30°C with 5% supplementary substance. This suggests that the development of 5% supplementary material worked on the current obstruction of geopolymeric element expressively, with degradation conveyed by heat openness restricted. Additionally, tests reinstated at prolonged temperatures, like 90°C, exhibited lower thermal degradation, and it is assumed that curative at an upraised temperature stimulates higher thermal safety. This could be because of better geopolymerization at elevated temperatures, conveying about an additional grounded and steadier thermal degradation compared with some other feature. Later, curative temperature and supplementary substances undertake a dual part whereas rationalizing the thermal function of fly ash-inclined geopolymers, making them more sensible for high-temperature submissions.

DSC Peak Analysis

- **Objective**: To determine the temperature at which important thermal processes, like dehydration and structural alterations, take place.
- **Method**: To find thermal events that signify stability and phase transitions, the DSC peaks were examined.

Findings

Thermal examination at important highpoints displays that they fundamentally occur anywhere in the variety of 110°C and 130°C, which recounts to the loss of water and slight alteration in the geopolymeric lattice. It recounts to an authentic bound water vaporization slightly than important decline because of slight microstructure variation. The deficit of momentous tops past this range discovers the substance's veracity and excessive current reliability. These outcomes show that fly ash-based geopolymeric polymers, with upgraded added substances and curing conditions, are robust against debasement at high temperatures. This further justifies their application in a high-temperature application where thermal strength is a basic prerequisite.

Microstructural and Phase Analysis (XRD)

Objective: To ascertain the phases that exist and their impact on the qualities.

Findings

The fly ash-based geopolymers' X-beam diffraction (XRD) study showed the presence of quartz and mullite, as well as nebulous phases, which meant quite a bit to the material's general qualities. The nebulous phases work on the holding and cohesiveness between the particles, which is fundamental for mechanical performance and adds to the strength and solidness of the geopolymer framework. Since quartz is a crystalline material, it expands the geopolymers' unbending nature and compressive strength. Eminently, the presence of mullite is particularly profitable due to its high liquefying point and protection from thermal shock, which offer exceptional thermal steadiness. These phases cooperate to strengthen the geopolymer's structural integrity and assurance its efficacy at high temperatures, which makes it proper for a scope of high-temperature applications in materials designing and development.

Results

ANOVA Test for Compressive Strength

Objective: To determine whether samples with various L/S ratios (0.4, 0.5, and 0.6) differ in compressive strength in a way that is statistically significant.

ANOVA Result

- **F-statistic**: The ANOVA test yielded an approximate F-statistic of 0.086.
- **P-value**: The p-value is roughly equivalent to 0.918.

Interpretation

As apparent from the examination of compressive power with regards to L/S proportions, a high p-value (>0.05) was found and, subsequently, no numerical variations were established at least with the intentional L/S proportion values (0.4, 0.5, and 0.6), the variation in the proportion do not virtually have a substantial connotation for compressive power of geopolymeric elements. From the outcomes, it can be resolved that curative temperature and the use of extracts have a greater impact than the L/S proportion on the automatic elements of geopolymers. This can really allow the enhancement of the formation and processing circumstances for geopolymer elements since it denotes that practitioners can focus on the other sort of variable to attain power features without much apprehension over minor differences in L/S proportion within the verified strictures.

6.2. Compressive Power vs. Curative Temperature Analysis

Objective: To observe how additives and curing temperature affect compressive strength.

Findings

An examination of the compressive power bar plot for the geopolymeric specimen makes some tendency reliant on curative temperature and extracts. It is seen that specimens cured at advanced temperatures, predominantly 90°C, have the uppermost compressive power as likened to those cured at moderately small temperatures. This means that curative at higher temperatures underwrites to better processes in geopolymerization at relative additives of 5% and 10% absorptions. In the geopolymerization response, maybe through improvement of connecting power as well as the operational veracity. The illustrations displayed the highest compressive power worth at 28 days in those specimens that shaped an L/S proportion of 0.5, which were preserved at 90°C, as 5% additive was supplementary and was thus applied efficiently to show that optimal curing settings and additives through a creative interaction to attain very high-performance geopolymerics. The possible application, apart from the heftiness in offering motorized power, of these geopolymers in aggressive settings is also advocated.

Relationship Examination between Mass Loss at 600°C and Curative Temperature

- **Objective**: To determine the association between curative temperature and thermal steadiness (mass loss).
- **Correlation Coefficient**: About -0.272 is the connection coefficient between bulk loss at 600°C and curative temperature.

Interpretation

That is, there is negative relationship between curative temperature and figure loss, meaning that the advanced curative temperatures may lead to less thermal dilapidation of geopolymeric elements. The improved thermal steadiness can be due to augmented chemical responses at advanced temperatures, supporting thicker cross-connecting of the geopolymeric system. This tendency backs the claim that enhancement of curative circumstances will not only lead to enhanced powered strength but also produces a much-enhanced thermal function of the element, which is now better suitable for maximum-temperature usage where sturdiness plays a major function. This underscores the necessity for use of the suitable curing plan with emerging high-function geopolymeric elements.

Distribution of Observed Phases (XRD)

Objective: To determine the frequency of various phases that were detected in the samples using X-ray diffraction (XRD).

Findings

Examination of count plot displays that the core stages that are described in geopolymeric specimens comprise amorphous, mullite, and quartz, whereas greatest of the specimens display mixtures like "Amorphous, Quartz." This occurrence of those precise stages is particularly very important to define thermal resistance with mechanical properties. Mullite is the constituent of the geopolymer that indicates great thermal steadiness and power, mostly underwriting the high power of the geopolymer at raised temperatures. Furthermore, the shapeless stage attends as a bonding and physical part of the geopolymeric matrix. The relationship of stage conformation with compressive power outcomes strengthens the impression that a well-balanced occurrence of these stages can enhance the geopolymeric elements. This discovery underscores the prominence of stage description for better indulgence and improvement of fly ash geopolymers' material elements which lead to their application in high-temperature resistance and physical usage.

Summary

It has been verified that curative temperature as well as positive percentages of extracts' accumulation are constructive aspects for augmentation in compressive power and thermal steadiness of geopolymeric polymers resultant from fly ash.

- Such minor differences between diverse L/S proportions show that curative temperature and extracts play crucial function for enhancing the elements of geopolymer.
- Correlation analysis, and the stage dissemination itself, offers an additional feature in how the curative conditions effect the steadiness and presentation of these geopolymers.

Discussion

Table 2: Comparison with Existing Literature

Study (Authors' Names)	Focus/Objective	Control Methods Analyzed	Key Findings	Comparison with Current Study
Xiao *et al.* (2020)	Investigate how L/S ratios affect the characteristics of geopolymers.	Various L/S ratios	It was discovered that although L/S ratios have an effect on workability, compressive strength is not greatly impacted by them.	confirms the current study's conclusion that there are no appreciable variations in compressive strength between L/S ratios.
Palomo *et al.* (2014)	Evaluate how the curing conditions affect the geopolymerization process.	varying temperatures for curing	The mechanical characteristics and strength of geopolymers are enhanced by elevated curing temperatures.	corresponds with the current research, which shows that at higher curing temperatures, compressive strength increases significantly.
Gao *et al.* (2018)	Analyze how additives can improve the performance of geopolymers.	Additive concentrations	It was discovered that some additions greatly enhanced the mechanical characteristics of geopolymers.	In line with recent research showing that additives at concentrations of 5% and 10% improve compressive strength.
Kumar *et al.* (2019)	Examine the geopolymers' thermal stability at different curing temperatures.	Mass loss at high temperatures	found that the curing temperature and heat deterioration had a negative connection.	confirms the finding of this investigation that a higher curing temperature reduces mass loss.
Sharma *et al.* (2021)	Examine the impact of phase distribution in geopolymers.	Analysis of phase composition using XRD	identified the crucial phases—mullite and amorphous—that improve the stability and strength of geopolymers.	confirms the results of the present investigation about the significance of phase composition for mechanical and thermal properties.

Overall Implications

Such findings deeply have impact on the applications of geopolymers, particularly fly ash-inclined geopolymers, subsequently no numerically essential variations at a varied L/S proportions. The potential practitioner can focus on the curative temperature and extracts to enhance power-driven elements of geopolymers. An upsurge in curative temperature was revealed to intensify the compressive power of these geopolymers and advance thermal steadiness. The temperatures of curative are adjusted to optimize the elements of such high-function elements through intense conditions. Conversely, the approved impacts of particular extracts denote that geopolymeric preparation can be guided appropriately for anticipated performance characteristics. The stage examination outcomes additionally enhance the concept of a balanced constituents of stages to become critical for enhancement in power and resistance to thermal dilapidation. This work conveys to forefront curing settings and additive choice during geopolymeric element preparation, therefore, to better use in erection and other applications at maximum temperatures.

Contribution to the Field

This study essentially contributes to the existing body of knowledge with regards to geopolymeric elements for the powered and thermal elements of fly ash-inclined geopolymers. The study stresses on inspiring classical conventions that the L/S proportions do not numerically show compressive power variances. It guides the effort in the direction of improving curative circumstances and the usage of explicit extracts. Such appreciative drives scientists and specialists to place superior stress on these features through substantial plan and processing, thus conceivable usage of geopolymers in creation and the industrialized segments. Additionally, the correlation scrutiny of huge loss with curative temperatures evidently specify an imperative correlation between thermal steadiness and powered performance, stressing the inevitability of planned curative procedures in training of high-performance geopolymers. Stage classification can provide balance between nebulous and crystalline stages may advance the decisive pliability and usability of geopolymers in high-temperature usage. In a cooperative sense, these influences advance the state-of-the-art for geopolymer science as it views today and launch a groundwork that unlocks the doors to imminent study and revolution into maintainable building elements. Eventually, they introduce a move in the direction of more ecologically subtle production practices.

Conclusion and recommendations

Conclusion

The study was successfully demonstrate the possibility of applying fly ash-inclined geopolymeric polymers as maximum-temperature sturdy elements with improved thermal elements. Based on methodical experiments, it had recognized the circumstances that physical, including a 90°C curing temperature, liquid-to-solid (L/S) proportion at 0.5, can be used with 5% additives such as metakaolin. The themes seen in these findings can be seen as the viability of applying industrial by-products including Class F fly ash, a plentifully obtainable waste material, in the creation of justifiable and environment-friendly replacements to predictable creation elements. It is not only supportive in decreasing ecological pollutant but can be used to produce high-performance items that can maintain high thermal situations, as such maximum temperatures can fit them seamlessly for intractable linings, thermal protection, and fire-resistant configurations. Consequently, if such effective optimization of geopolymeric schemes exists, then that would mark a hopeful stage for supportable materials science.

Recommendations

Further investigation is required on the sustainable durability of these geopolymeric materials to appreciate their performance under cyclic thermal loading and ecological differences. Critical data on their real-world submissions as well as consistency in practical situations would be required if the resistance of these constituents towards repetitive thermal stresses and over long periods of ecological variations is assumed. The lifecycles and sturdiness of geopolymers and thus direct their usage in construction developments and structures linked with great settings.

The procedure of geopolymerization is impacted by numerous extracts that may improve the bond of the features and material steadiness. The wide-ranging investigation of numerous kinds of extracts could shield even wider areas of usage of these green resources with more tailor-made solutions in areas such as construction, motorized, and aerospace firms where higher performance element is desirable.

The results thus underwrite to the optimization of the geopolymeric schemes, offering crucial perceptions into curative and additive plans targeted at the attainment of well-formed elements of this type. This means, the detection of the optimum circumstances for the process of these materials is fundamentally a standard for additional researches and real-world works. General, such wide-ranging research will improve the performance of geopolymeric resources besides hurrying expansion in the more effective and environment-friendly construction practices at last by soliciting the sustenance of the creation sector for movement advancing toward eco-friendly clarifications.

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