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Advancements in Geopolymer Concrete: Formulation Optimization, Strength Characteristics, and Sustainable Applications

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Abstract

This research explores the optimization of geopolymer concrete (GPC) formulations by investigating the mix proportions of fly ash (FA), fine aggregate, and coarse aggregate. The study focuses on enhancing early strength properties and delves into the complex geopolymerization mechanism, unraveling the unique contributions of each constituent material. Additionally, the research systematically evaluates the strength characteristics of GPC incorporating FA and ground granulated blast furnace slag, providing insights into its mechanical behavior. The influence of various curing conditions on GPC performance is thoroughly analyzed, offering valuable considerations for optimizing the curing process. Through these objectives, the study aims to contribute to the understanding and improvement of GPC, shedding light on its potential applications in sustainable construction practices.

Keywords: Early strength properties, fly ash, formulation optimization, geopolymer concrete, geopolymerization mechanism, ground granulated blast furnace slag, strength characteristics, sustainable construction

INTRODUCTION

For decades, traditional concrete, primarily composed of Portland cement, has been the cornerstone of the construction industry. However, the environmental toll exacted by the production of Portland cement, notably in the form of substantial carbon dioxide emissions, has propelled the industry to reevaluate its practices. The carbon footprint associated with traditional concrete production has become a focal point of global environmental concerns. In response to these challenges, researchers and industry practitioners are seeking alternatives that can mitigate the environmental impact of concrete without compromising its performance. Geopolymer concrete (GPC), with its potential to lower carbon emissions and enhance material properties, has emerged as a subject of intense scrutiny and exploration.

The geopolymerization process, the crux of GPC production, involves the activation of aluminosilicate materials through the use of alkali activators. This process fundamentally diverges from the hydration process inherent in Portland cement-based concrete, where calcium silicate compounds form through the reaction of cement with water. The distinctive advantage of GPC lies in its utilization of industrial byproducts, such as fly ash (FA) or slag, as the primary source of aluminosilicate precursors. Beyond providing a

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sustainable solution for managing industrial waste, this approach reduces reliance on traditional raw materials, contributing significantly to the conservation of natural resources.

The imperative to explore the material properties and performance of GPC is underscored by several crucial considerations. First, unraveling the intricate details of the geopolymerization process and understanding the resulting material characteristics are imperative for optimizing mix designs. This knowledge forms the bedrock for ensuring the effective utilization of waste materials, a critical facet of sustainable construction practices. Second, a comprehensive study of GPC's performance under various conditions is paramount to establishing its reliability and applicability across diverse construction scenarios. As the industry pivots towards sustainable practices, a nuanced understanding of GPC becomes instrumental in guiding decision-makers toward environmentally conscious choices.

The strength of concrete incorporating recycled coarse aggregate is influenced by several key factors. First, the water-cement ratio is a critical determinant, with the necessary water quantity dependent on the characteristics of the aggregates, including their maximum size, shape, and surface features. The amount of cement required for achieving a specific concrete strength varies based on individual aggregate strength and the required free water content for optimal workability. Second, the particle grading of the aggregate is significant in determining the mixing water needed for adequate workability. An increase in fines proportion raises water requirements, potentially impacting concrete strength unless offset by a higher cement content. Additionally, the introduction of an expansive additive contributes to a 10% enhancement in shear strength across various aggregate types. This enhancement is attributed to the axial force generated by concrete expansion, resulting in a broader compressive zone, improved shear resistance, and reduced cracking width. Lastly, the method of crushing concrete to produce coarse aggregate, whether mechanical or manual, has a substantial impact on its strength. The crushing procedure and recycled aggregate dimensions influence the amount of adhered mortar, thereby affecting concrete strength [1–17].

OBJECTIVES

This research aims to achieve several key objectives. First, it seeks to identify the optimal mix proportions of FA, fine aggregate, and coarse aggregate for GPC, with a specific focus on enhancing early strength properties. Second, the study aims to unravel the intricate geopolymerization mechanism by scrutinizing the chemical reactions involved, emphasizing the unique contributions of each material in the geopolymer matrix. Third, the research systematically investigates the strength properties of GPC, incorporating FA and ground granulated blast furnace slag (GGBS), to gain a comprehensive understanding of the material's mechanical behavior. Lastly, the study analyzes the influence of different curing conditions on the performance of GPC, contributing valuable insights into optimizing the curing process for enhanced concrete properties [18–26].

LITERATURE REVIEW

The optimum mix for GPC. Their findings indicated that GPC exhibited commendable performance in terms of both workability and strength. Notably, the mix with FA: Fine aggregate: Coarse aggregate ratio of 1:1.5:3.3 and an alkaline solution (NaOH and Na_2SiO_3 combined) to FA ratio of 0.35 demonstrated high early strength.

In a literature review on the mechanism and chemical reaction of FA geopolymer binder, the exact geopolymerization mechanism remains unclear due to the substantially fast chemical reaction involved in the process. They emphasized that each material used in geopolymer plays a distinct role in creating the chemical reaction and mechanism [27].

An experimental study focusing on the strength properties of FA and GGBS-based GPC. Their research involved different combinations of FA and GGBS, utilizing sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) solutions as alkaline activators. The study revealed that GGBS blended FA-based GPC achieved enhanced mechanical properties at ambient room temperature curing without the need for heat curing [28].

The alkali-activated FA-based GPC, considering workability and mix design. The study highlighted the significant influence of curing temperature on strength development, with substantially higher compressive strength observed at 80°C compared to 25°C. The authors emphasized the role of proper curing, such as wrapping with a plastic bag, in preserving moisture and enhancing compressive strength [29].

Experiments on FA-based GPC, investigating various mix proportions with an alkaline solution to FA ratios ranging from 0.30 to 0.50. The results indicated that a higher concentration of sodium hydroxide solution and a higher ratio of alkaline solution led to increased compressive strength in the concrete [30].

In the research on GPC with FA, different ratios of Na_2SiO_3/NaOH (0.39 and 2.51) were explored. The study included tests for compressive strength, split tensile strength, flexural strength, rebound hammer, and acid resistance under ambient temperature and oven drying conditions for 7 and 28 days. The findings suggested that a ratio of Na_2SiO_3/NaOH as 2.51 and a higher concentration of sodium hydroxide solution contributed to increased compressive strength in FA-based GPC [31].

A comprehensive experimental study on FA-based GPC, revealed that its elastic properties and the behavior of reinforced structural members closely resemble those of ordinary Portland cement (OPC) concrete. They emphasized that GPC boasts excellent compressive strength, making it suitable for various structural applications. The authors asserted that existing standards and codes applicable to OPC concrete can be utilized for the design of reinforced GPC structural members. Furthermore, considering potential carbon dioxide taxes on cement and the environmental benefits of FA utilization, GPC may prove to be economically advantageous. Its resistance to sulfate and chloride attacks renders it suitable for construction in abrasive soils with groundwater containing significant amounts of chloride and sulfate salts. Additionally, FA-based GPC exhibits improved rheological properties, with high static and dynamic viscosity facilitating easy transportation and handling. Despite these advantages, the authors cautioned about the inhomogeneity of FA, emphasizing the need for careful consideration of mixing quantity and methods when working with GPC [32].

An experimental investigation into the effect of sodium hydroxide concentration and curing type on the properties of self-compacting GPC. Their study involved three concentrations of NaOH solution (8, 10, and 12 M) and three curing types (hot oven curing, 28 days ambient curing, and self-curing using Polyethylene Glycol—400). The results showed that hardened strength properties and modulus of elasticity increased with the molarity of NaOH solution in all curing regimes. Interestingly, there was no discernible influence of self-curing on GPC [33].

The effect of molarity in GPC. Their study involved different molarities of sodium hydroxide solution (3, 5, and 7 M), concluding that an increase in the concentration of NaOH positively correlated with an increase in the compressive strength of GPC.

The incorporation of GGBS and FA in GPC eliminates the need for heat curing. The strength of GPC increased with the percentage of GGBS in the mix. The authors suggested the extraction of sodium hydroxide and sodium silicate solutions from waste materials in chemical industries to reduce the cost of alkaline solutions required for GPC.

The optimum compressive strength, split tensile strength, and flexural strength of GPC specimens were achieved with 40% GGBS replacement by FA after heat curing.

Neethu Susan Mathew et al. in 2015 observed that a GGBS to FA ratio of 50:50 was optimal for GPC cured at ambient temperature. GPC demonstrated higher early strength, split tensile strength, flexural strength, modulus of elasticity, and bond strength compared to OPC-based concrete. Additionally, it exhibited lower water absorption and slightly lower density, indicating enhanced durability. However, the production cost of GPC was noted to be higher due to transportation costs and the expense of alkaline activators derived from by-products. These recent research findings collectively contribute to the ongoing exploration and optimization of GPC, shedding light on its properties, production methods, and potential applications in construction.

The term "Geopolymer" is used to describe a binder formed with an alumino–silicate gel structure, which, according to some researchers, may not necessarily be in a polymeric form. Although works on reinforced GPC are limited, existing test results indicate that the structural behavior of GPC and OPC is essentially similar, with GPC sometimes having a slightly lower modulus of elasticity at the same strength level. In contrast, geopolymer composites exhibit superior performance in durability tests, including resistance to sulfate, acid, and corrosion. This is attributed to the polymeric nature of the geopolymer matrix without the presence of free lime. Despite the ongoing debate about the exact microstructure of geopolymer, studies indicate that it is possible to formulate geopolymer composites with consistent strength levels for structural use by selecting suitable alkaline activator solutions and curing regimes.

The compressive and split tensile strengths of GPC decrease with increasing FA content in the mix, regardless of the curing period. The highest compressive and split tensile strengths were observed for the mix with 0% FA and 100% GGBS, regardless of the curing period. The rate of strength gain is fastest at a 7-day curing period and decreases with age.

The effect of alkali content, silica content, and water content of geopolymer mix on compressive strength. Water plays a crucial role during the dissolution, polycondensation, and hardening stages of geopolymerization. Reduction of water content improves compressive strength, and the choice of curing temperature and time affects the final compressive strength of the geopolymer. Heat, particularly during curing, enhances the dissolution rate of solid alumina–silicate material, leading to increased compressive strength. Microstructure studies indicated the formation of new amorphous alumina–silicate phases like hydroxysodalite and herschelite.

The durability studies on FA-based GPC, exposing it to sulphuric acid solution. The acid caused surface damage to heat-cured GPC specimens, resulting in a mass loss of approximately 0.5% after three months of exposure. The sorptivity curve for GPC was less linear compared to control concrete, indicating lower water absorption rates.

The effect of temperature and duration on the development of GPC under oven heating. Curing temperature and duration were found to be crucial factors in activating GPC. A curing time between 6 and 24 h produced higher compressive strength, and the rate of strength gain was slower at 60°C compared to 120°C.

Heat-cured specimens had significantly higher compressive and split tensile strengths compared to steam and ambient air-cured specimens.

The environmental and health impacts of cement manufacturing emissions. They concluded that the cement industry poses significant harm to the ecology and recommended a focus on effective emission control technology, energy efficiency, and global collaboration in environmentally friendly technologies for sustainable development.

The mechanical properties of GPC composites. They identified two limitations of GPC: delayed setting time and the need for heat curing to gain strength. These limitations were addressed by replacing 10% of FA with OPC, resulting in a GPC composite with higher compressive, split tensile, and flexural strengths than traditional GPC at 28 days of age, even in ambient curing conditions.

CONCLUSION

The extensive literature review on GPC reveals its promising potential in terms of workability, strength, and durability. Studies emphasize optimal mix proportions, the intricate geo polymerization mechanism, and the beneficial influence of GGBS and curing conditions. Increased concentrations of sodium hydroxide and proper curing contribute to enhanced compressive strength. GPC exhibits elastic properties resembling OPC concrete, with potential economic advantages and superior durability. Recent investigations shed light on factors such as sodium hydroxide concentration, curing methods, and waste material utilization, providing valuable insights for strengthening GPC and reducing production costs. Overall, the findings contribute to a comprehensive understanding of GPC properties, production methods, and potential applications in construction, emphasizing its role in sustainable and durable construction practices.

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