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Experimental Study to Improve the Properties of Geopolymer Concrete Using Industrial Waste: A Review

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Abstract:- Recent studies underscore the promise of geopolymer concrete (GPC) and alkali-activated materials (AAMs) as eco-friendly substitutes for conventional Ordinary Portland Cement (OPC). Research has focused on the mechanical characteristics, durability, and environmental advantages of GPC made from materials such as fly ash (FA) and ground granulated blast furnace slag (GGBFS). The application of machine learning techniques, especially Gene Expression Programming (GEP), has proven effective in predicting the compressive strength of GPC, thereby minimizing the necessity for extensive physical testing. Furthermore, investigations into recycled geopolymer cement (RGPC) indicate that integrating up to 60% RGPC into new mixtures preserves mechanical properties, highlighting the material's recyclability. GPC is noted for its enhanced load-bearing capacity, reduced shrinkage, and greater resistance to chemical degradation. The maturity method has also been successfully employed to track strength development in AAMs, while managing sodium hydroxide concentrations can help control alkali-silica reaction (ASR) expansion, thereby improving durability. Ultimately, the implementation of geopolymer concrete and AAMs can significantly lower carbon emissions linked to cement production, offering a practical solution for sustainable construction and effectively addressing environmental issues while preserving or enhancing the mechanical properties of traditional concrete.

Keywords*: Geopolymer, Fly-Ash, Ground Granulated Blast Furnace Slag (GGBFS), Compressive strength, Sustainable construction, Alkali-activated, Durability, Environmental impact.*

Introduction

The construction sector is increasingly confronted with the imperative to integrate sustainable and environmentally responsible materials into its practices, driven by the urgent need to reduce carbon emissions and address the detrimental effects of environmental degradation. In this context, geopolymer concrete has emerged as a promising alternative to traditional Ordinary Portland Cement, utilizing industrial by-products such as fly ash and ground granulated blast furnace slag. This innovative material is recognized for its remarkable mechanical properties, superior durability, and significantly lower environmental impact compared to conventional cement. Geopolymer concrete not only meets the structural demands of modern construction but also aligns with global sustainability goals. This paper aims to delve into the current landscape of research surrounding geopolymer concrete, exploring its mechanical characteristics, durability, and environmental advantages. Additionally, it will discuss the application of advanced machine learning techniques, particularly in predicting the compressive strength of geopolymer concrete, thereby facilitating more efficient and sustainable construction practices. Through this exploration, the potential of geopolymer concrete to revolutionize the construction industry while addressing pressing environmental concerns will be highlighted.

1. Literature Review

Wang, Y., Iqtidar, A., Amin, M. N., Nazar, S., Hassan, A. M., & Ali, M. (2024), A recent study, "Predictive Modelling of Compressive Strength of Fly Ash and Ground Granulated Blast Furnace Slag-Based Geopolymer Concrete Using Machine Learning Techniques", conducted by a team of international researchers, sheds light on the environmental drawbacks of traditional Ordinary Portland Cement (OPC) and proposes Geopolymers (GPs) as a more sustainable option. The research aims to predict the compressive strength of geopolymer concrete (GPC) produced from fly ash (FA) and ground granulated blast furnace slag (GGBFS) using machine learning algorithms. The authors develop three predictive models using Artificial Neural Networks (ANN), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Gene Expression Programming (GEP), with GEP demonstrating the highest accuracy. The study's key takeaways include the potential of AI as a cost-effective and reliable tool for predicting GPC properties, reducing the need for extensive physical testing. Notably, the research highlights the superior performance of GEP, the environmental benefits of using FA and GGBFS in GPC production, and the significant impact of FA, GGBFS, and coarse aggregates on GPC strength.

Naghizadeh, A., Tchadjie, L. N., Ekolu, S. O., & Welman-Purchase, M. (2024), A recent study, "Circular Production of Recycled Binder from Fly Ash-Based Geopolymer Concrete", conducted by a team of researchers from the University of the Free State and Nelson Mandela University in South Africa, explores the possibility of recycling fly ash-based geopolymer concrete to produce a reusable binder. The research involves the crushing and milling of old geopolymer concrete to recover the aluminosilicate material, which can then be reused to create a recycled geopolymer cement (RGPC). The study reveals that incorporating up to 60% RGPC in new concrete mixtures maintains sufficient mechanical properties, although higher percentages of RGPC lead to decreased compressive strength, workability, and increased drying shrinkage. The findings underscore the recyclability of geopolymer concrete, in contrast to traditional Portland cement, and demonstrate its potential to contribute to a more sustainable and circular production process.

Kudva, L., Nayak, G., Shetty, K. K., & Sugandhini, H. K. (2024), A recent study, "Assessment of Flexural Response of RC Beams and Unrestrained Shrinkage of Fiber-Reinforced High-Volume Fly Ash-Based No-Aggregate Concrete and Self-Compacting Concrete", conducted by a team of researchers, evaluates the mechanical properties, flexural behavior, and shrinkage characteristics of reinforced concrete (RC) beams fabricated from fiber-reinforced no-aggregate concrete (NAC) and high-volume fly ash self-compacting concrete (HVFASCC). The investigation focuses on the influence of varying polypropylene fiber (PF) contents in NAC on the structural performance of RC beams, specifically examining deflection, crack formation, and shrinkage over a 220-day period. The research findings indicate that the incorporation of fibers improves the load-carrying capacity, ductility, and flexural performance of NAC beams, although fibers have a limited impact on controlling shrinkage. Notably, HVFASCC exhibits the lowest shrinkage and demonstrates superior performance in certain mechanical aspects.

A research team led by **Archanaah Nadarajah, Noor Azline Mohd Nasir, Nabilah Abu Bakar, and Nor Azizi Safiee** explored the early engineering properties of geopolymer mortar produced by combining fly ash and ground granulated blast furnace slag at ambient temperatures. The main objective was to create a sustainable binder alternative to ordinary Portland cement by treating the mixture with an alkaline solution. The researchers examined the compressive strength, water absorption, and drying shrinkage of different binder ratios. The study found that geopolymer mortar with a higher proportion of ground granulated blast furnace slag exhibited rapid strength development, achieving significant compressive strength within three days, especially when metakaolin was present. Furthermore, increasing the ground granulated blast furnace slag content led to reduced water absorption, resulting in denser matrices, while higher fly ash content contributed to decreased drying shrinkage. The addition of metakaolin also improved shrinkage behavior. The study concludes that fly ash-ground granulated blast furnace slag geopolymer mortar is a viable option for applications requiring early strength and offers a sustainable alternative to traditional construction materials.

A recent study conducted by **Firas Abed Turkey, Salmia Bt. Beddu, Ali Najah Ahmed, and Suhair Kadhem Al-Hubboubi**, investigated the behavior of lightweight geopolymer concrete (LWGC) when subjected to high temperatures. The researchers developed a sustainable concrete mixture by utilizing fly ash as a binder, partially substituting it with 10% glass powder, and combining it with lightweight aggregates such as Leca and recycled brick. The concrete samples were exposed to temperatures ranging from 200°C to 800°C to examine their thermal resistance. The results showed that as the temperature increased, the concrete underwent significant degradation, with noticeable damage occurring at 550°C due to dehydration, resulting in a substantial loss of compressive strength. Although the two lightweight aggregates exhibited slightly different performances, both demonstrated a significant decline in strength, with residual compressive strengths ranging from 55.6% to 52.6% at 800°C. Additionally, the study observed reductions in water absorption and density, indicating the adverse effects of high heat. Notably, the replacement of 10% fly ash with glass powder yielded the best results in terms of maintaining strength and stability at lower temperatures, but the material began to deteriorate beyond 400°C. Overall, while LWGC shows promise as an eco-friendly alternative, its structural integrity is significantly compromised when exposed to extremely high temperatures. The study provides valuable insights into optimizing geopolymer concrete for use in high-heat environments.

A comprehensive review conducted by **Noor Fifinatasha Shahedan, Tony Hadibarata, Mohd Mustafa Al Bakri Abdullah, Muhammad Noor Hazwan Jusoh, Shayfull Zamree Abd Rahim, Ismallianto Isia, Ana Armada Bras, Aissa Bouaissi, and Filbert Hilman Juwono**, examines the use of fly ash-based geopolymer concrete in the restoration and retrofitting of marine infrastructure. The research tackles the problem of corrosion in marine structures, primarily caused by chloride ions present in seawater, which lead to the degradation of reinforced concrete. Fly ash, which is high in silica and alumina, creates a strong geopolymer binder when activated, offering resistance to chloride penetration and corrosion. This review emphasizes the advantages of fly ash geopolymer concrete, such as its improved mechanical properties, reduced permeability, and greater resistance to chloride-induced corrosion compared to conventional concrete. It also explores various mechanisms that lead to concrete deterioration in marine settings and underscores the importance of enhancing concrete durability for these applications. The study highlights how geopolymer concrete combats these damaging processes, noting its lower chloride migration coefficients and enhanced durability. Furthermore, it addresses challenges like the variability in fly ash characteristics and the careful handling required for alkaline activators. Despite these hurdles, the authors advocate for further research to refine fly ash geopolymer concrete for marine infrastructure, given its potential environmental benefits and durability.

A recent study by **Mohammed Ali M. Rihan, Richard Ocharo Onchiri, Naftary Gathimba, and Bernadette Sabuni,** explores the effects of partially replacing fly ash (FA) with sugarcane bagasse ash (SCBA) in geopolymer concrete (GPC) on its mechanical properties and microstructure. The researchers investigate a sustainable alternative by examining the performance of FA-SCBA-based GPC cured at ambient temperatures, addressing the limitations of high-temperature curing typically required for GPC. The study substitutes SCBA for FA in proportions ranging from 5% to 20% and analyzes the impact on workability, compressive strength, tensile strength, flexural strength, and microstructure using techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD). The results show that increasing SCBA content reduces workability and compressive strength, but even with 20% SCBA replacement, the concrete achieves satisfactory structural-grade strength exceeding 40 MPa after 28 days of ambient curing. The study also finds that curing temperature significantly influences the concrete's strength, with 80°C being the optimal curing temperature for improved compressive strength. Microstructural analysis reveals that SCBA enhances the overall matrix of the GPC by filling voids and improving durability. This research highlights the potential of SCBA as a sustainable material in geopolymer concrete, offering environmental and energy-saving benefits while maintaining adequate mechanical performance for construction applications.

Rihan, M. A. M., Onchiri, R. O., Gathimba, N., & Sabuni, B. (2024), Assessing the Durability Performance of Geopolymer Concrete Utilizing Fly Ash and Sugarcane Bagasse Ash as Sustainable Binders. This research examines the durability performance of geopolymer concrete (GPC) produced using fly ash (FA) and sugarcane bagasse ash (SCBA) as sustainable binders. The study aims to assess the mechanical properties and durability of GPC under various conditions, including high temperatures and sulfuric acid exposure. The results indicate that GPC exhibits superior water resistance and lower water absorption compared to traditional ordinary Portland cement (OPC) concrete. The study also reveals that GPC maintains its structural integrity at lower temperatures, but undergoes cracking and color changes at elevated temperatures. Furthermore, GPC demonstrates higher resistance to sulfuric acid-induced degradation than OPC concrete, with a lower percentage of weight loss and compressive strength loss. The findings suggest that GPC has potential as a durable construction material for applications in environments prone to chemical attack. Overall, the study highlights the benefits of utilizing FA and SCBA as sustainable binders in GPC, which can contribute to reducing the environmental impact of the construction industry.

This research, conducted by **Biruk Hailu Tekle, Ludwig Hertwig, and Klaus Holschemacher**, explores the use of ultrasonic testing to monitor the setting time and strength development of alkali-activated cement (AAC), which presents a more eco-friendly alternative to ordinary Portland cement (OPC). The authors compare the outcomes from ultrasonic testing with traditional evaluation methods, including the Vicat needle test and compressive strength assessments. The results indicate a strong relationship between ultrasonic velocity and setting time, showing that both initial and final setting times align with specific phases of the velocity curve. Furthermore, the study investigates how variations in binder content and material ratios affect setting time and strength, utilizing the Taguchi experimental design approach. The findings suggest that ultrasonic testing offers continuous, non-destructive insights into the setting process and strength evolution of AAC, highlighting its utility as a real-time evaluation tool for these materials. Notably, factors like the alkaline solid-to-binder ratio have a significant influence on setting time, while the water-to-solid ratio predominantly impacts strength. Overall, the results emphasize the potential of ultrasonic testing to aid in the development of AAC with improved performance attributes.

This study, led by **Arkamitra Kar**, examines alkali-activated binders (AAB) as a sustainable substitute for Portland cement. The research develops and assesses 30 distinct AAB mixtures that utilize fly ash and slag, activated with sodium hydroxide and sodium silicate, while evaluating their properties from the microstructural level to the specimen level. The findings reveal that a precursor-activator ratio (Ms modulus) of 1.4 results in the highest compressive strengths at curing temperatures of 23°C, 40°C, and 60°C, with strength values ranging from 20.9 MPa to 85.0 MPa. Significantly, completely substituting fly ash with slag improves strength by 126%. Microstructural investigations using techniques such as X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDS), and isothermal calorimetry indicate that sodium aluminosilicate hydrate gel is the primary phase responsible for strength, while the inclusion of slag accelerates reaction rates by forming calcium silicate hydrate. The study also shows that ultrasonic pulse velocity can effectively estimate key properties like dynamic modulus of elasticity and compressive strength. Additionally, a nonlinear regression model was created to predict compressive strength based on microstructural data and ultrasonic velocity, demonstrating a strong correlation with experimental findings. Overall, the research highlights the potential of AAB for sustainable construction applications.

This research, conducted by **Aziz Hasan Mahmood, Stephen J. Foster, and Arnaud Castel**, investigates the influence of mixing duration on the properties of geopolymer concrete, comprising 65% fly ash and 35% slag. As a sustainable alternative to Portland cement, geopolymer concrete is recognized for its comparable or superior mechanical and durability characteristics. The study specifically explores the effects of brief mixing times (1 minute) versus extended mixing durations (10 minutes) on the workability, setting time, and hardened properties of fresh concrete. The results show that prolonged mixing times significantly improve workability, allowing the concrete to remain usable for up to 120 minutes, whereas shorter mixing durations lead to rapid setting within 15 minutes. Furthermore, extended mixing times enhance mechanical strength due to the increased dissolution of silicate and aluminate species, which promotes better geopolymerization. Key metrics such as compressive strength, splitting tensile strength, and elastic modulus demonstrate notable improvements with a 10-minute mixing time. Microstructural analysis also reveals a more homogeneous binder phase with fewer unreacted particles. These findings highlight the critical importance of adequate mixing in the effective application of geopolymer concrete in construction.

This study, conducted by **Trevor Williamson and Maria C.G. Juenger**, explores the effect of sodium hydroxide (NaOH) solution concentration on the alkali-silica reaction (ASR) in alkali-activated fly ash concrete (AAFA), a sustainable alternative to traditional concrete. Despite its eco-friendly benefits, AAFA's durability, particularly with regards to ASR, remains a pressing concern. The research investigates how varying NaOH concentrations influence the alkalinity of the pore solution and its subsequent impact on ASR when using reactive aggregates. Through a series of experiments involving mortar cubes and concrete prisms, the researchers found that exceeding an optimal NaOH concentration level increases alkalinity, potentially leading to greater ASR expansion. However, even at higher NaOH levels, AAFA exhibited significantly less expansion than conventional Portland cement concrete. This reduced expansion is attributed to the low calcium content in fly ash, which restricts the formation of expansive ASR gel. The findings highlight AAFA's inherent resistance to ASR and suggest that precise control of NaOH concentration can enhance its durability, making it a promising material for sustainable construction.

Yuan, J., Li, L., He, P., Chen, Z., Lao, C., Jia, D., & Zhou, Y. (2021), This study, examines the influence of different alkali-activated ions (Na^+, K^+, and Cs^+) on the geopolymerization process of geopolymer cement pastes. As a more environmentally friendly alternative to traditional Portland cement, geopolymer cement is created by combining aluminosilicate materials, such as metakaolin, with alkali solutions. The research investigates how these alkali ions affect the dissolution of raw materials, the diffusion process, and the polymerization stages involved in geopolymer formation. The geopolymerization process is characterized by two distinct stages: the reacting stage and the curing stage. The findings reveal that the atomic number of the alkali metal ions has a significant impact on the geopolymerization process, with higher atomic numbers resulting in accelerated geopolymerization. This leads to faster reaction rates and an increased degree of polymerization, attributed to the increased basicity of the system, which enhances the dissolution of aluminosilicate materials and expedites the overall reaction. The results highlight the potential to control the geopolymerization process through the selection of alkali ions, thereby optimizing material properties for various applications.

Ferreira, L., Branco, F. G., Costa, H. S., Julio, E., & Maranha, P. (2015), This study explores the use of the maturity method in alkali-activated binders, presenting them as a sustainable and efficient alternative to traditional cement. Alkali-activated mortars are produced by replacing ordinary Portland cement with industrial by-products, such as fly ash, and incorporating alkaline solutions. The research examines the impact of temperature and curing conditions on the compressive strength of these mortars. Through experimental testing, the authors establish a correlation between strength and maturity, demonstrating the effectiveness of the maturity method in predicting strength development in alkali-activated mortars. The findings reveal that the addition of sodium silicate to the alkaline activator significantly improves strength, particularly at lower curing temperatures and shorter durations. Additionally, the research shows that higher curing temperatures and the combination of ordinary Portland cement with alkali-activated mixtures result in increased compressive strength. Overall, this study highlights the eco-friendly and efficient nature of alkali-activated mortars, suggesting their potential applications in the precast industry.

This research, conducted by **Susan A. Bernal and John L. Provis**, delves into the progress and challenges surrounding alkali-activated materials (AAMs), which are considered a more environmentally friendly alternative to traditional Portland cement. The study assesses the durability of AAMs when exposed to aggressive environments, including high levels of CO_2, sulfates, and chlorides. While AAMs offer benefits such as lower CO_2 emissions and performance comparable to conventional cements, concerns regarding their long-term durability persist, particularly with respect to carbonation, sulfate attack, and chloride penetration. The authors further investigate the microstructural and chemical factors influencing AAM performance, highlighting the significance of precursor materials, activator chemistry, and the pore structure of the binding gels. Although AAMs demonstrate considerable potential, the research suggests that further studies are necessary to gain a comprehensive understanding of their durability in real-world applications and to develop testing methods that can accurately predict their long-term performance.

This study, conducted by **Sandeep Thapa, Suman Debnath, Suhasini Kulkarni, Hardik Solanki, and Snehansu Nath**, examines the environmental implications of cement production and explores geopolymer concrete as a more sustainable option. Geopolymer concrete, produced using alumina- and silica-rich materials such as fly ash and GGBS, offers comparable strength to traditional concrete while significantly reducing carbon emissions. The researchers investigated various mix ratios and curing conditions, achieving a maximum compressive strength of 43.6 N/mm² with a 16M NaOH concentration and steel fibers. The results showed that higher molar concentrations of NaOH and curing temperatures improved strength, particularly at 100°C. The study emphasizes the importance of optimizing binder content and mix proportions to achieve desired mechanical properties, recommending mechanized mixing and heat curing. The findings indicate that geopolymer concrete is a promising, eco-friendly material that can substantially reduce carbon emissions in the construction industry. Further research is suggested to refine its formulation for enhanced performance and sustainability.

2. Conclusion

In conclusion, geopolymer concrete stands as a transformative innovation in the pursuit of sustainable construction materials, providing a robust alternative to conventional Ordinary Portland Cement. By utilizing industrial by-products such as fly ash and ground granulated blast furnace slag, geopolymer concrete not only addresses the pressing issue of waste management but also significantly reduces the carbon emissions associated with traditional cement production. The comprehensive body of research examining its mechanical properties, durability, and environmental advantages highlights its capability to fulfill the structural requirements of contemporary construction while simultaneously promoting ecological sustainability. Moreover, the incorporation of advanced machine learning methodologies to predict the compressive strength of geopolymer concrete represents a significant leap forward in material science, enabling more precise and efficient material testing. This integration supports better decision-making processes in construction, ultimately leading to more sustainable practices. As the construction industry adapts to the challenges posed by climate change and resource scarcity, the widespread adoption of geopolymer concrete could play a crucial role in enhancing sustainability and fostering responsible resource management, paving the way for a more environmentally friendly future in the built environment.

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