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A Review of Industrial Waste Geopolymer Concrete

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ABSTRACT

Industrial development has led to a significant increase in cement consumption, contributing to approximately 1.35 billion tons of greenhouse gas emissions annually, which accounts for about 7% of total man-made emissions. Simultaneously, thermal power plants produce vast quantities of fly ash, much of which is not properly recycled, posing a substantial challenge for solid waste management. Geopolymer technology offers a promising solution to these issues by utilizing fly ash activated with alkaline activators to create a viable alternative to ordinary Portland cement (OPC). This approach can significantly reduce the carbon footprint of concrete and enhance the recycling of fly ash. This paper reviews the status of fly ash-based geopolymer paste and concrete, critically analyzes significant research findings from the past two decades, and identifies key factors for improving the performance of geopolymer concrete (GPC) under various conditions.

Key words : Geopolymer concrete (GPC), Comprehensive foundation, Carbon footprint, thermal power plants

Introduction

The production of cement is a significant contributor to carbon dioxide (CO_2) emissions, which exacerbate the greenhouse effect. This environmental impact has spurred researchers to explore alternatives that reduce cement usage while maintaining concrete's structural integrity. One promising solution is the development of Geo polymer Concrete (GPC), which utilizes industrial by-products like fly ash instead of traditional cement. When combined with alkaline solutions, this mixture forms a strong, durable material known as Geo polymer concrete. A specific variant of this innovation is Self-Compacting Geo polymer Concrete (SCGC). Unlike conventional concrete, SCGC does not require mechanical compaction to settle into place, highly flow able nature. This attribute not only simplifies the construction process but also improves the quality of the finished structure by minimizing voids and enhancing uniformity. The increasing environmental concerns associated with fly ash waste disposal and high cement consumption necessitate the effective promotion of geopolymer Concrete (GPC). This paper outlines a specific mix design procedure aimed at developing GPC with a focus on achieving better compressive strength economically, using varying proportions of alkaline solutions to binder. The cement industry is a major contributor to global greenhouse gas emissions, with an estimated annual production of 1.35 billion tons of CO2, accounting for approximately 7% of total anthropogenic emissions. Additionally, the growing industrialization has led to an increase in thermal power generation, producing large quantities of fly ash. The improper recycling of fly ash creates significant challenges for solid waste management.

Geopolymer Technology

Geopolymer technology, which uses fly ash activated by alkaline solutions, presents a sustainable alternative to traditional Portland cement. This technology not only reduces CO2 emissions but also enhances the utilization of industrial by-products like fly ash, thereby addressing both environmental and waste management issues.

Nomenclature: Geopolymers are known by various names, such as geocements, alkali-activated cements, hydroceramics, alkali-bonded ceramics, and inorganic polymers. These names refer to materials synthesized through similar chemical processes.

Geopolymerization Process: This involves a rapid chemical reaction under highly alkaline conditions between alumino-silicate oxides and silicates, resulting in the formation of a polymeric structure.

Fly ash

The cement production required to meet the current demand of the global construction industry significantly contributes to greenhouse gas emissions, accounting for approximately 7% of the total man-made emissions. This poses a serious environmental issue. An emerging solution to mitigate this impact is the development of geopolymers, which are influenced by various factors including the nature of the source material, type and concentration of alkaline solution, curing temperature and method, period of heat curing, water content, and rest period. Additionally, the presence of calcium-containing compounds such as Portland cement (PC), calcium hydroxide (CH), and calcium oxide (CaO) significantly influences the setting time, workability, and compressive strength development of geopolymers. Notably, geopolymers made with Class C fly ash (C-FA), which has a higher calcium content, exhibit faster setting times compared to those made with Class F fly ash (F-FA), due to the larger proportion of calcium in the glassy phases.

In summary, optimizing these factors is essential for developing high-performance geopolymers that can serve as sustainable alternatives to traditional Portland cement, thus reducing the carbon footprint of the construction industry.

Literature review

Jamdade P.K et.al (2014) promoted the use of industrial waste fly ash as the replacement for cement. Researchers done experiments on curing time, curing temperature of geopolymer concrete. The compressive strength rises from12 hrs to 24 hrs at 60°c. The compressive strength is considerably achieved but for the polymerization the temperature is not sufficient. The study shows that, for polymerisation the temperature 90°c is quite sufficient. Geopolymer concrete gives more strength than normal concrete in minimum period of curing. Geopolymer concrete has larger compressive strength with higher curing temperature. Increase in the curing temperature beyond 60° c did not increase the compressive strength substantially. As the curing time is increased, it will improve the polymerization and increase the compressive strength.

Krishnan L et.al (2014) conducted studies and concluded that the geopolymer technology is suitable for application in concrete industry as an alternative binder to the Portland cement. Geopolymer binder is prepared using fly ash and GGBS(ground granulated blast furnace slag) with alkaline liquids sodium hydroxide and sodium silicate. A 12 Molarity solution was taken to prepare the mix. The objective of this research work was to produce a carbon dioxide emission free cementious material. Geopolymer concrete is such a material that avoids such harmful effects. The emission of carbon dioxide during the production of ordinary Portland cement is very much high. The production of one ton of Portland cement emits approximately one ton of CO_2 into the atmosphere.

Ali A. Aliabdo et.al (2016) used an innovative industrial waste fly ash as a replacement of cement and the effect of little addition of cement with fly ash are described in this work. Objective of the study is to find out the compressive strength, split tensile strength characteristics of fly ash based geopolymer and also with some addition of cement. This paper also intends to find out the alkaline solution resting time, curing period and curing temperature on fly ash based geopolymer concrete. The study results show that, generally adding cement improves all fly ash based geopolymer properties but it does not improve workability. The increase of fly ash content improves geopolymer concrete properties. Using 30 min resting solution has a significant effect on geopolymer properties compared with using 24 h resting solution.

Hardijito et.al (2008) observed that higher concentration of sodium hydroxide resulted higher compressive strength. Higher compressive strength of geopolymer concrete is also shown when the ratio of sodium silicate-to- sodium hydroxide liquid ratio by mass is higher. There is an increase in compressive strength with the increase in curing temperature in the range of 30 to 90 °C. Longer curing time also increased the compressive strength.

Rashida A jhumarwala et.al (2013) conducted an experimental investigation on Self compacting geopolymer concrete (SCGC). SCGC were synthesized from low calcium fly ash and it is activated by combination of sodium hydroxide and sodium silicate solution. Incorporation of super plasticizer is done for self-compatibility. In this study it is observed that maximum compressive strength of SCGC is achieved at higher temperature cured concrete. It is also observed that, as molarity increases the strength goes on decreasing.

Sashidhar C et.al (2015) conducted study on Fresh and Strength Properties of Self compacting Geopolymer Concrete Using Manufactured Sand. In this study, SCGC mixes were manufactured using class F fly ash and ground granulated blast furnace slag (GGBS) with proportion of 50:50 and with 100% manufactured sand (MS). This investigation is mainly focused on the fresh and compressive strength properties of SCGC. It is done by varying the molarity of sodium hydroxide. During all curing periods at ambient temperature, the contribution of GGBS helps the SCGC mixes to attain significant compressive strength development.

Ushaa T G et.al (2015) investigated the performance of self compacting geopolymer concrete containing different mineral admixtures. In this study, fly ash was replaced by different mineral admixtures. The use of such materials reduces the cost of self compacting geopolymer concrete. It occurs especially if the mineral admixtures used are waste or industrial by-product. From the study it was found that all the self compacting geopolymer concrete mixes had a satisfactory performance in the fresh state. Good workability is found for blast furnace slag series compared to silica fume series among the mineral admixtures considered.

Shankar.H.Sanni et.al (2013) conducted experimental investigation on the variation of alkaline solution on mechanical properties of geopolymer concrete based on fly ash. The grades chosen for the investigation were M-30, M-40, M-50, M-60 and the mixes were designed for 8 molarity. The alkaline solution used for the study was the combination of sodium silicate and sodium hydroxide solution and the varying ratio taken are 2, 2.50, 3 and 3.50. The test specimens were 150x150x150 mm cubes and 100x200 mm cylinders. Specimens were heat-cured at 60°C in an oven. The freshly prepared geopolymer mixes were cohesive. Increase in the ratio of alkaline solution increases the workability. The strength of geopolymer concrete can be improved by decreasing the water/binding and also aggregate/binding ratios. The curing period improves the polymerization process resulting in higher compressive strength. The obtained compressive strength is in the range of 20.64 – 60 N/mm^2 and split tensile strength is in the range of 3 – 4.9 N/mm^2. The optimum dosage for alkaline solution can be considered as 2.5 and because for this ratio, the strength is maximum for GPC specimens of any grade in compression and tension.

Faiz uddin ahmed sheikh (2016) in his paper, presents mechanical and durability properties of geopolymer concrete that contains recycled coarse aggregate (RCA). The RCA is collected from local construction and demolition (C&D) waste in Perth, Australia. The RCA is used as a partial replacement of natural coarse aggregate (NCA) in geopolymer concrete. Replacement at 15%, 30% and 50% by weight which is corresponding to series two, three and four, respectively, whereas the geopolymer concrete containing 100% NCA is control and is considered as the first series. The effects of RCA on the measured mechanical and durability properties of geopolymer concrete follow similar trend in cement concrete. Observations are done in very good correlations of compressive strength with volume of permeable voids and water absorption of geopolymer concrete containing RCA, whereas the correlation between the compressive strength and the sorptivity is not that strong. This paper presents preliminary study on the effect of recycled coarse aggregates (RCA) mainly on the mechanical and durability properties of fly ash based geopolymer concrete. The mechanical properties are measured at 7 days and 28 days whereas the durability properties are measured at 28 days.

Sabina kramar et.al (2015) in her study, deals with the mechanical and microstructural characterization of geopolymers synthesized from locally available fly ash. Sodium silicate solution is used for activating low calcium fly ash. Characterization of samples were done by means of flexural and compressive tests, X-ray powder diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy and scanning electron microscopy (SEM). Mercury intrusion porosimetry and gas sorption were used to identify porosity and pore size distributions. The compressive strength of the geopolymers, which is in the range of 1.6 to 53.3 N/mm^2, is strongly related to the water content and also with the SiO_2 / Na_2O mass ratio of an alkali activator. The compressive strength significantly increased with decrease in the water content and also with the increased silicon concentration used for the synthesis of geopolymers.

Emad Benhelal et.al (2013) investigated that cement industry has been always among the largest CO_2 emission sources. Almost 5-7% of global CO_2 emissions are caused by cement plants, while 900 kg of CO_2 is emitted to the atmosphere for the production of one ton of cement. In this particular work, discussions have been done on global strategies and potentials toward mitigation of CO_2 emissions in cement plant and the most promising approaches have been introduced. More over the barriers against worldwide deployment of such strategies are identified and comprehensively described. Detail review have been done in three strategies of CO_2 reduction including energy saving, carbon separation and storage as well as utilizing alternative materials. The significant industrial CO_2 emissions released impose an immeasurable impact on the environment. Its atmospheric concentration was substantially enlarged over the past decades from 1.1% per year for 1990-1999, to 3.5% per year for 2000-2007 and eventually reached to 394.35 ppm in May 2011. With the increase in the CO_2 emissions to the environment for the past decades that contribute to the global warming phenomenon, more research was done to overcome this problem. Beside that these emissions strictly forced governments around the world to discuss promising approaches toward emission control and mitigation that could be applied by all industries that facing the same CO_2 emission problem especially for the cement industry. Cement plant has been always among industries which generate plenty of CO_2 aside from other sectors such as electricity and heat generation sector and transportation sector. In addition to CO_2 generation due to fossil fuels combustion in the cement production, carbon dioxide is also produced as by-product during decomposition reactions. Moreover in conventional plants various near optimal design and operation lead to extra and undesired emissions of CO_2 into the environment. Therefore, this analysis was done with objectives to clearly review all the factors that need to be taken into consideration in implementing the strategic approaches on reducing the CO_2 emission to the environment by the cement industries.

Daniel L Y (2010) in his paper, presents a study on geopolymers and geopolymer/aggregate composites made with class F flyash. Samples were heated up to 800° C to evaluate strength loss due to thermal damage. There is 53% of strength increase for geopolymer after temperature exposure. The tests show that the aggregates steadily expanded with temperature with an expansion of about 1.5–2.5% at 800°C. Correspondingly, the geopolymer matrix undergoes contraction of about 1% between 200°C and 300°C and also a further contraction of 0.6% between 700°C and 800°C. This apparent incompatibility is concluded to be the cause of the observed strength loss. 15 different geopolymer combinations and four different aggregates are presented in this study.

Kunchapusuresh et al (2021) mechanical properties of geopolymer concrete and OPC concrete after exposure to elevated temperature (280c to 600 ^{0}c) were studied and compared to each other. In the present study, at 400°C temperature, the decreases of compressive strength of OPC concrete while air-cooled is 4% and 19% for water-cooled. For the geopolymer concrete is around 26% and 31%. Compare with air-cooled OPC specimen, despite the fact that there is a higher rate of strength decrease for GP concrete up to a temperature exposure of 200°C. After200°C, the strength loss decreases in geopolymer concrete when compared to OPC concrete up to 400°C.The strength loss is more at 400°C for OPC concrete, but in geopolymer concrete, the strength loss is less at 400°C, at 400°C the residual strength is nearly equivalent for both OPC concrete and geopolymer concrete. It might additionally be noticed that, while the rate of strength loss is nearly the equivalent for both the kinds of concrete between 400 °C and 600 °C. The geopolymer concrete when compared with OPC concrete there is a higher strength loss for geopolymer concrete at an early stage of temperature raise (200°C) in this research.At a temperature exposure above 400 ℃, the un-reacted crystalline materials in geopolymer concrete get changed into shapeless state and experience polymerization. Accordingly, there is no further strength loss (compressive strength, tensile strength, flexural strength) in geopolymer concrete, OPC concrete keeps on losing its strength properties at a quicker rate past a temperature presentation of 600°C.

Mohd Mustafa Al Bakri Abdullah et al (2022) was examined the consumption of Ordinary Portland Cement (OPC) caused pollution to the environment due to the emission of CO 2 . As such, alternative material had been introduced to replace OPC in the concrete. Fly ash is a by-product from the coal industry, which is widely available in the world. Moreover, the use of fly ash is more environmental friendly and save cost compared to OPC. Fly ash isrich in silicate and alumina, hence it reacts with alkaline solution to produce aluminosilicate gel that binds the aggregate to produce a good concrete. The compressive strength increases with the increasing of fly ash fineness and thus the reduction in porosity can be obtained. Fly ash based geopolymer also provided better resistance against aggressive environment and elevated temperature compared to normal concrete. As a conclusion, the properties of fly ash-based geopolymer are enhanced with few factors that influence its performance.

Conclusion

Geopolymer technology offers a viable solution to reduce the carbon footprint of the cement industry and improve the utilization of fly ash from thermal power plants. The review highlights the significant potential of GPC in the concrete industry, particularly in applications requiring high durability and thermal resistance. Future research should focus on optimizing mix designs, understanding long-term performance, and scaling up the production process to facilitate wider adoption. The cement production required to meet the current demand of the global construction industry significantly contributes to greenhouse gas emissions, accounting for approximately 7% of the total man-made emissions. This poses a serious environmental issue. An emerging solution to mitigate this impact is the development of geopolymers, which are influenced by various factors including the nature of the source material, type and concentration of alkaline solution, curing temperature and method, period of heat curing, water content, and rest period.

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