

STRENGTH AND DURABILITY BEHAVIOR OF GEO-POLYMER CONCRETE

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Abstract:

The growth in popularity of alkali activated binders as a viable alternative to ordinary Portland cement (OPC) has been driven by their capacity to provide higher technical qualities and increased durability. Geopolymers or alkali-activated cementitious materials are anticipated to emerge as a promising building material in the foreseeable future. These materials possess the potential to provide outstanding performance characteristics while minimising their environmental footprint, all at a fair cost. The aforementioned components have the potential to serve as a substitute for the binder in concrete, hence functioning as a significant component in building projects. Geo-polymer materials refer to inorganic polymers that are composed of alumina and silica units. These materials are created by the synthesis of de-hydroxylated alumina-silicate powders, which are then condensed with alkaline silicate in an environment that is very alkaline. The use of reduced quantities of calcium-based raw materials, lower manufacturing temperatures, and decreased fuel consumption leads to a significant reduction in carbon emissions during the production of geopolymer cement. This reduction ranges from 22% to 72% when compared to the carbon emissions associated with the manufacturing of Portland cement. This research examines the properties, advantages, uses, and assessment of carbon emissions and expenses associated with geopolymer concretes.

Keywords: Geo-polymer concrete, alkali-activated binders, alumina-silicate, and environmentally friendly building materials.

1.0 INTRODUCTION

Concrete is a very resilient building material that is created by the meticulous combination of Portland cement, water, aggregates, and additives in precise proportions. The revision of components and manufacturing methods for conventional concrete is of significant importance due to the substantial usage of concrete as a building material. The extensive use of concrete leads to significant demands for cement manufacturing. Portland cement serves as a binding agent in the manufacturing process of concrete. It is created by combining certain raw ingredients, namely clay and lime, in predetermined proportions. Subsequently, the mixture is subjected to grinding and heating to a temperature of 1500°C. According to Vazinram and Khodaparast (2009), the

production of 1 tonne of cement requires the use of 125 litres of fossil fuel and 118 kilowatt-hours of electricity. Additionally, cement transportation accounts for about 11.9 percent of the traffic on the country's highways. Regrettably, the global production of Portland cement, which serves as a prominent construction material, results in the substantial emission of carbon dioxide (CO₂) into the atmosphere. Specifically, the production of one metric tonne of Ordinary Portland Cement (OPC) releases an equivalent amount of CO₂. This emission of CO₂ is recognised as a significant contributor to the greenhouse effect and the subsequent warming of the planet (Bilodeau and Malhotra, 2000). The primary advantage of geopolymeric cement lies in its ability to mitigate environmental consequences, hence facilitating the transition towards sustainable development. Sustainable development is characterised by the judicious and efficient use of fundamental and natural resources to meet the needs of future generations. This encompasses the reduction of carbon dioxide emissions, improved utilisation of mineral and metal resources, increased incorporation of recycled materials, and the assessment of long-term durability via the examination of mechanical qualities in materials analogous to ancient Roman cement, as researched in the field of archaeology. According to Davidovits (1994), a significant portion exceeding 65% of the Earth's crust is composed of Al-Si minerals. Additionally, the utilisation of calcium-based cement in smaller quantities does not result in the emission of substantial amounts of CO₂. Therefore, it is crucial to comprehend the process by which these minerals transform into cement. In the manufacturing of geo-polymeric cement, temperatures over 750 degrees Celsius are unnecessary. The aforementioned statement indicates that this particular kind of cement manufacture needs just one-third of the fuel required. Hence, geo-polymeric cements do not depend on the calcination of calcium carbonate and do not need the use of high temperature kilns, which use significant amounts of fuel. Consequently, the chemical process and fuel requirements are significantly reduced, resulting in a notable decrease in carbon dioxide emissions during the manufacturing of geo-polymeric cement. Therefore, one effective approach to the production of environmentally friendly concrete involves the reduction of Portland cement content and its substitution with a material characterised by a lower manufacturing temperature, such as geopolymer cement. This study provides a comprehensive examination of the structure, setting and hardening process, technical qualities, assessment of carbon footprint, and cost analysis of geopolymer concrete. Additionally, it briefly discusses a few notable uses of this material.

2.0 GEO-POLYMERS AND MINERAL RESOURCES FOR PRODUCING GEO-POLYMER CEMENT

The concept of geopolymer was first introduced by Davidovits in 1979, when he proposed the synthesis of three-dimensional alumina silicates. This notion was inspired by the enigma surrounding the construction of the Great Pyramids. According to Davidovits, a variety of supplemental cementing materials such as coal and lignite fly ash, rice husk ash, palm oil fuel ash, other ashes, blast furnace and steel slag, silica fume, limestone, metakaolin and natural pozzolan have the potential to generate geopolymers using mineral and metal resources. Despite the global trend towards reducing the reliance on coal-fired power plants, it is worth noting that until the year 2015, a significant quantity of fly ash, approximately 290 million tonnes, accounting for approximately 8% of the global cement market, could potentially be utilised as a valuable mineral

resource for the purpose of geopolymer cement applications (Davidovits, 1994). According to Davidovits (1994), the use of quenched vitreous slag as a metal resource has the potential to provide a significant amount of blast slag, estimated to be between 290 and 560 million tonnes, for cement manufacture in the year 2015. Metakaolin is a pozzolanic substance that is derived from the calcination of China clay at temperatures ranging from 700 to 900 degrees Celsius, as specified by the EN 206/BS 5328 standards. Metakaolin is a deliberately made substance, as opposed to being a by-product, and its production method has resemblance to that of geo-polymers.

3.0 The classifying of Geo-polymer structures

Geopolymers include three distinct categories of inorganic polymers, which are differentiated based on the Si/Al ratio present within their structural compositions.

- 📖 Poly (sialite) (-Si-O-AL-O-)
- 📖 Poly (sialate-siloxo) (-Si-O-Al-O-Si-O-)
- 📖 Poly (sialate-disiloxo) (-Si-O-Al-O-Si-O-Si-O-)

Poly (sialate)

(-Si-O-Al-O-)

Poly (sialate-siloxo)

(-Si-O-Al-O-Si-O-)

Poly (sialate-disiloxo)

(-Si-O-Al-O-Si-O-Si-O-)

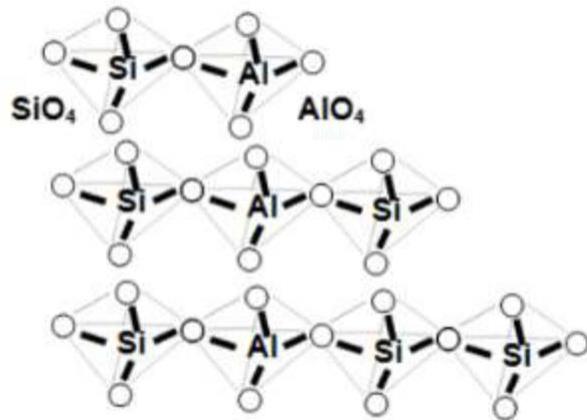


Figure. Basic Structure of Geo-polymer Structure of all type

The chemical and physical qualities of the final product are influenced by the distribution and relative quantities of the various aluminium (Al) and silicon (Si) building pieces.

4.0 GEOPOLYMERIZATION OF PRIMERY MONOMERS

The three main steps in the process of geopolymerisation are:

- 📖 The disintegration of any pozzolanic substance or source of silica and alumina occurs when it is easily dissolved in an alkaline solution. This process leads to the creation of mobile precursors of alumino-silicate oxides via the intricate interaction of hydroxide ions.
- 📖 The partial alignment of mobile precursors, together with the partial internal reorganisation of the alkali poly-sialates.
- 📖 The re-precipitation process involves the particles from the original solid phase undergoing a transformation, resulting in the solidification of the whole system and the formation of an inorganic polymeric structure.

The thereby produced substance, known as poly(sialates), exhibits the following empirical formula: The chemical formula $Mn \{-(SiO_2)_z - AlO_2\}_n \cdot wH_2O$ represents a compound consisting of manganese (Mn) atoms bonded to a repeating unit composed of a combination of silicon dioxide (SiO_2)

In this case, the cation denoted as M may be potassium, sodium, or calcium, while the variable "n" represents the degree of polycondensation. Additionally, the variable "z" can take on the values of 1, 2, or 3. Poly(sialates) are polymers consisting of chains and rings, wherein Si^{4+} and Al^{3+} ions are coordinated with oxygen in a tetrahedral manner (Davidovits, 1991).

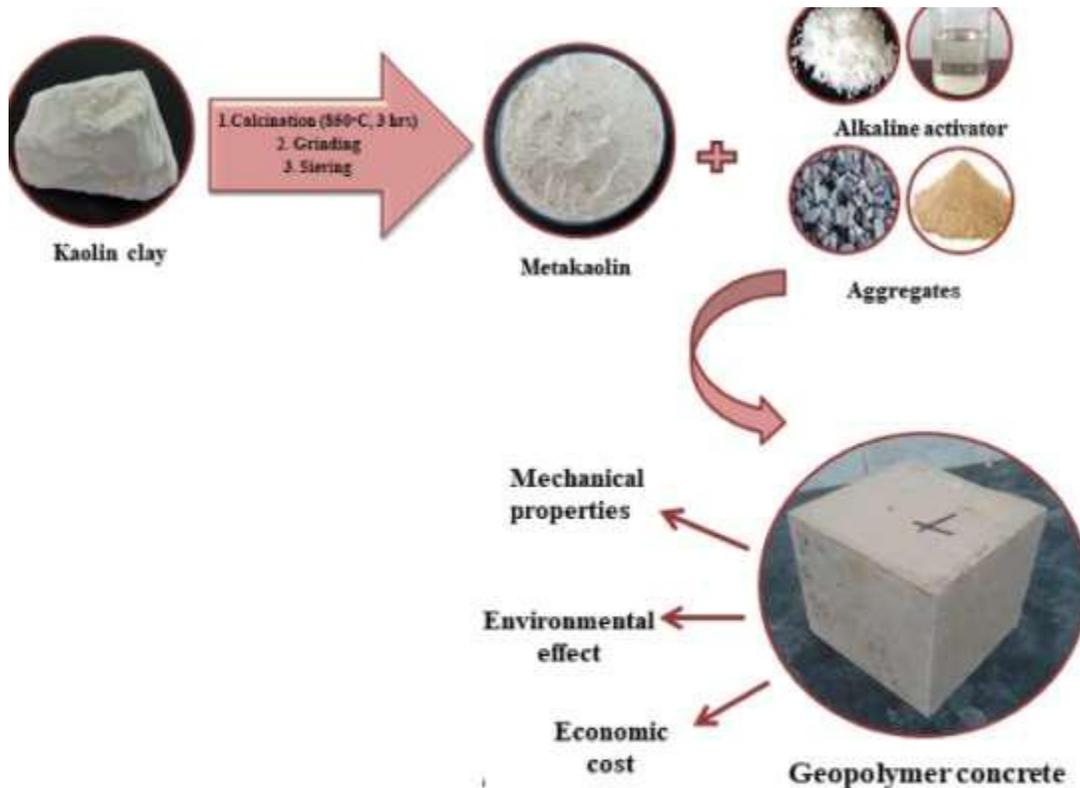
5. SETTING AND HARDENING MECHANISM FOR GEOPOLYMERIZATION Geopolymeric substances are produced by the process of activating alumina silicate materials with alkaline silicates or hydroxides at temperatures ranging from ambient to a maximum of 120°C . Geopolymers possess morphologies that range from amorphous to semi-crystalline, characterised by nano-sized particles, which vary depending on the temperatures at which the curing process takes place. Aluminosilicates, such as kaolin, metakaolin, fly ash, and metallurgical slag (e.g., blast furnace slag), are often used in the synthesis of geopolymers. The activators utilised in this process consist of sodium and potassium silicates, which may be combined with sodium and potassium hydroxides. The process of dissolution and precipitation of aluminium (Al) and silicon (Si) complexes starts when alumina silicate resources are in close proximity to alkali solutions. The dissolving process is influenced by factors such as the consistency of the alkaline solution, the kind of alkaline cation present, the speed at which stirring occurs, and the specific structures and chemical compositions of the alumina silicate material. The specification of alumina silicate source material and the condensation of alkaline solution are identified as the primary elements in this context. Following the dissolution of alumina silicate particles from their surfaces, the precipitation of a gel commences, followed by the infiltration of aluminium and silicon complexes into the gel phase. Consequently, the density of aluminium (Al) and silicon (Si) complexes decreases on the surface of alumina silicate particles, resulting in an enhanced dissolution of Al and Si. The length and intensity of stirring have a crucial role in directing the penetration process. In contrast to the relatively lower activation energy required for the synthesis of Al-O-Si, the polymerization process of Al and Si complexes takes place prior to the creation of Si-O-Si. Consequently, the condensation of aluminium (Al) and silicon (Si) complexes derived from alumina silicate sources will coincide with their dissolution and penetration processes. There are many parameters that influence the process of condensation, including temperature, pH, and cation size. The rate of condensation process is accelerated by elevated temperatures, increased pH levels (resulting in greater condensation of alkaline solution), and the presence of alkaline cations with larger atomic sizes.

Geopolymer compositions are formulated to exhibit both crystalline and amorphous structures, making them suitable for many industrial uses. Crystalline polystyrene (PS) and polystyrene sulfonate (PSS) are formed as a result of an exothermic reaction, while the geopolymer undergoes an amorphous structural transformation during the curing process at ambient temperature.

6. GEOPOLYMER CONCRETE MIX DESIGN

Geo polymer concrete is a construction material in which aggregates are held together by a binder consisting of two components: alumina silicates and an alkali solution. This binder is often referred to as geopolymer binder. Mix proportioning is a process that involves finding the appropriate proportions of elements that, when combined and properly cured, will provide concrete that is both

workable and capable of attaining the specified level of strength and durability upon hardening. Hence, it is important to take into account many factors, such as the desired workability as assessed by slump, the water to binder ratio, the binder content, and the aggregate proportions, throughout the mix design process. The recommended weight ratio of alkali solution to fly ash in geopolymer concrete is advised to be within the range of 0.3 to 0.45, as shown by Costa et al. (2007). Table 2 provides a useful reference for determining the desired workability and compressive strength.



Compressive Strength (Mpa)	Workability	Mass ratio of water to polymeric material in solid form
60	Very low	0.16
50	Low	0.18
40	Normal	0.70
35	Fluid	0.77
30	Fluid	0.74

7. GEOPOLYMER CONCRETE CASTING AND CURING

The tools and machinery required for the manufacturing of geopolymer concrete is identical to that of ordinary Portland cement (OPC) concrete. In the typical process of casting this particular form of concrete, essential constituents such as fly ash and aggregates are combined, followed by the introduction of an alkaline solution including additives. The use of increased temperature during the

curing process facilitates the response of the paste in geopolymer concrete. The compressive strength of geopolymer concrete is significantly influenced by the curing time and temperature. There are two potential curing circumstances that may be taken into consideration, namely fog and sealed conditions. The research conducted by Bondar et al. (2009 and 2011) demonstrates that specimens cured under sealed conditions exhibit about 15% higher compressive strength compared to those cured under steam conditions.

8. PROPERTIES OF FRESH GEOPOLYMER CONCRETE

The setting time of a geopolymer mix may be controlled by modifying the composition of the mixture, allowing for either accelerated or delayed setting. The attainment of structural integrity and acceptable strength was seen within a very short duration, sometimes as brief as sixty minutes, depending on the specific synthesis circumstances (Van Jaarsveld et al., 1997). Utilizing granulated blast furnace slag as the primary constituent, supplemented by the inclusion of metakaolinite. The study conducted by Cheng and Chiu (2003) revealed that the setting time of the geopolymer paste was influenced by several factors, including the curing temperature, kind of alkaline activator, and composition of the source material. According to the authors, the observed setting time for the aforementioned geopolymer paste ranged from 15 to 45 minutes when subjected to a temperature of 60°C. The temporal interval that elapses between the completion of the mixing process to the commencement of the casting stage for newly prepared geopolymer concrete has more significance in actual scenarios. Consequently, evaluating the setting time of geopolymer concrete at increased temperatures may not be suitable. According to the laboratory study conducted by Hardjito et al. (2003a), it was observed that the newly prepared geopolymer concrete exhibited a prolonged workability period of at least 120 minutes after the mixing process, without any indications of initial setting or reduction in compressive strength. The observed outcomes were contingent upon the nature of the source material, with larger concentrations of CaO resulting in accelerated setting. The inclusion of constituents other than Al₂O₃ and SiO₂ in the source material may potentially impede the setting process. In materials derived solely from geological sources, such as calcined kaolin, the primary chemical constituents consist only of Al₂O₃ and SiO₂. However, byproduct products like fly ash may include other compounds, such as Fe₂O₃. Hence, it may be inferred from the findings of Hardjito et al. (2004) that geological materials in their pure form exhibit a higher level of reactivity when exposed to alkaline activators, resulting in a decrease in the time required for initial setting. According to Costa et al. (2007), geopolymers made from fly ash exhibited an accelerated initial setting time when exposed to elevated temperatures. The final setting of these mortars was seen to take place about 15 to 25 minutes after the first setting. According to Bondar (2009), the setting time of natural pozzolans is directly influenced by the concentration of silicate. Specifically, a larger concentration of silicate tends to result in a longer setting time. However, it is worth noting that this relationship may not hold true in cases when the silicate source comprises minerals like opal, which exhibit quick reactivity when exposed to an aqueous alkaline solution.

9. PROPERTIES OF HARDENED GEOPOLYMER CONCRETE

There appears a multitude of perspectives about the primary factors that exert influence on the compressive strength and other mechanical characteristics of geopolymer concrete. According to

Palomo et al. (1999), the compressive strength is influenced by many important elements, including the alkaline activator used, the temperature and duration of the curing process (Hardjito et al., 2004a, 2004c). Nevertheless, previous studies have documented that several factors play a crucial role in achieving successful polymerization. These factors include the proportions of Si, Al, K, and Na, the molar ratio of Si to Al in the solution, the ratio of alumina silicate mineral to kaolinite (in the presence of kaolinite), the type of alkaline activator, the water content, and the curing temperature (Xu and Deventer, 2000; Barbosa et al., 2000; Rowles et al., 2003). According to Fernandez-Jimenez et al. (2006), the inclusion of silicate ions in the alkaline solution significantly enhances the mechanical strength and modulus of elasticity values. However, it does have a little negative impact on the otherwise robust matrix/aggregate and matrix/steel bond. The experimental findings indicate that the molar ratio of H₂O/M₂O in the mixture composition has a substantial impact on the compressive strength of geopolymer concrete made from fly ash. Conversely, the effect of the Na₂O/SiO₂ molar ratio is comparatively less significant (Hardjito et al., 2004a, 2004c). The compressive strength of geopolymer is shown to decrease with an increase in the molar ratio of H₂O/M₂O and the water to geopolymer solids ratio, as reported by Hardjito et al. (2004a, 2004c). Furthermore, the study conducted by Van Jaarsveld et al. (2002) revealed that subjecting hardened material to prolonged curing at high temperatures might potentially compromise its structural integrity. According to Palomo et al. (1999b), the study conducted on fly ash-based geopolymer binder has shown that the compressive strength is notably affected by the curing temperature and curing time. However, it is important to note that this relationship may vary depending on the specific aluminosilicate materials being used. According to Hardjito et al. (2004a, 2004c), the compressive strength of fly ash based geopolymer concrete may be enhanced by extending the curing duration and elevating the curing temperature. However, it should be noted that the strength improvement may not be as pronounced when the curing temperature exceeds 60°C or the curing length exceeds 48 hours. Typically, a significant portion of the ultimate compressive strength, around 70%, is attained during the first 4-hour period after the setting process. Due to the rapid polymerization process involved in the chemical reaction of the geopolymer paste, the compressive strength of the concrete exhibits little variation with respect to its age subsequent to a 24-hour curing period. This discovery presents a contrast to the well recognized behavior of ordinary Portland cement (OPC) concrete, whereby the process of hydration occurs gradually over an extended duration, resulting in a progressive rise in strength over time (Hardjito et al., 2004a, 2004c). One notable distinction in terms of kinetics between Portland cement and alkaline activated systems is the presence of a comparatively lower threshold temperature in the former. Beyond this threshold temperature, the process of thermal curing might potentially have a negative impact on both mechanical strength and material durability. In contrast, the selection of an appropriate reaction time and curing temperature for an activated ash can lead to the formation of distinct reaction products while maintaining material durability. This is supported by Fernandez et al. (2006), who observed that higher curing temperatures are associated with reduced Al content in the final product, thereby enhancing mechanical properties. The enhancements observed are consistent with the development of a uniform aluminaosilicate matrix,

as reported by Fernandez-Jimenez et al. (2006). The present study provides a summary of the features shown by geopolymers derived from various alumina silicates.

9.1. Alkali activated slag

Alkali-activated slag cements have been recognized in the academic literature for almost forty years. Typically, the activation of these cements requires a sodium oxide (Na_2O) content ranging from 2 to 7 percent or a potassium oxide (K_2O) value ranging from 3 to 10 percent of the slag composition. According to Chatterjee (2003), the observed strength of this particular kind of concrete has shown a gradual increase over time. Specifically, the strength has been measured at 21Mpa after 3 days, 36Mpa after 1 year, and 40Mpa after 6 years. These measurements were obtained from a concrete mixture with a binder content of 350Kg/m³, a binder to aggregate ratio of 1:5.96, a water to binder ratio of 0.46, and a maximum size aggregate (MSA) of 25mm. The compressive strength of alkali-activated slag cement concrete exhibits a continuous increase when subjected to water curing, reaching its maximum value after a period of 365 days. Nevertheless, when the concrete is subjected to a sealed curing environment, its strength ceases to increase after about 90 days. The aforementioned phenomenon may be ascribed to the limited presence of moisture necessary for the process of slag hydration inside the concrete. Concrete that is exposed to air consistently has the lowest level of strength, whereas strength retrogression is shown at ages above 28 days. According to Shi et al. (2006), the strength of the material reaches its peak during a period of 14 to 28 days after hydration, after which it begins to decline. According to Neville (1995), in the context of Portland cement concrete, the impact of insufficient water on strength is more pronounced when the water to cement ratio is larger, resulting in reduced strength development. This effect is further amplified when fly ash or slag are present.

9.2. Alkali activated fly ash

Despite the limited number of studies available on the flexural strength and elastic modulus of alkali activated fly ash (AAFA), the existing evidence suggests that both properties exhibit lower values compared to those seen in Portland cement. In a study conducted by Puertas et al. (2003), it was shown that the flexural strength of alkali activated PFA mortars was measured to be 5.79 MPa, but OPC based mortars exhibited a higher flexural strength of 7.76 MPa. Additionally, it was shown that the elastic modulus of ordinary Portland cement (OPC) mortars was 5.679 GPa, surpassing the values seen for pulverized fuel ash (PFA) mortars activated with 8M sodium hydroxide (NaOH) (4.441 GPa). According to the study conducted by Fernandez-Jimenez et al. (2006), the incorporation of soluble silicates into the alkaline solution resulted in an enhancement in the modulus of elasticity in geopolymer concrete made with pulverized fuel ash (PFA). Nevertheless, despite efforts to enhance its performance, the alkali activated PFA concrete exhibited a static modulus of elasticity that fell far below anticipated levels. The results reported for Ordinary Portland Cement (OPC) concrete exhibited a range of 30.3 to 32.3 gigapascals (GPa), while the values for geopolymer concrete varied from 10.7 GPa (without the presence of silicate) to 18.4 GPa (with the inclusion of silicate). In the study conducted by Hardjito et al. (2004), it was revealed that concrete samples produced under identical circumstances had improved elastic modulus values, ranging from 22.95 to 30.84 GPa. In addition to having shorter setting durations in comparison to

traditional concrete, geopolymers also exhibit greater unconfined compressive strengths and have much less shrinkage during the setting process when compared to ordinary Portland cement (OPC). Specifically, over a period of 7 days, the shrinkage of geopolymers is only 0.2% of that seen in OPC, while for a period of 28 days, it is only 0.5% of OPC's shrinkage (Van Jaarsveld et al., 1997). One potential explanation for this behavior might be attributed to the microstructural properties of the newly introduced binder, which has the ability to generate a zeolite-type phase during the alkali activation process of fly ash. The characteristics and microstructure of zeolites are often understood to remain unchanged despite the loss of water that occurs during their synthesis. This is due to the reversible nature of water loss in most zeolites, as well as their ability to absorb water from the ambient humidity in the environment (Fernandez-Jimenez et al., 2006). The drying shrinkage strains exhibit minimal magnitudes, while the creep factor, defined as the ratio of creep strain to elastic strain, attains a value of 0.30 after about six weeks of loading, starting from the seventh day, with a sustained stress equivalent to 40% of the compressive strength. In subsequent periods, the level of discomfort experienced by individuals exhibited a little, but noticeable, rise (Hardjito et al., 2004). In accordance with BS 5400-4:1990, a recommended value of 1.6 is indicated for the creep factor of ordinary Portland cement (OPC) concrete under typical circumstances. However, it is important to note that this value may vary depending on factors such as ambient conditions, concrete maturation at the time of loading, and its composition. In their study on the loading of self-compacted concrete with ordinary Portland cement (OPC), Kaewmanee and Okamura (2001) obtained a value of 1.35 for the sustained stress applied on the 7th day, which was equivalent to 40% of the compressive strength. Conversely, Tarek and Sanjayan (2008) demonstrated that the rate of creep factor evolution over time for slag mixes is lower compared to OPC mixes, with a value of 1.49 observed at the point of cracking.

9.3. Alkali activated Natural Pozzolan

Geopolymeric mixes of concrete that use activated natural pozzolans have often shown reduced strength and modulus of elasticity compared to mixes including ordinary Portland cement (OPC) during the first stages of curing. However, over an extended period of curing, these geopolymeric mixes achieve comparable or even superior levels of strength and modulus of elasticity when compared to OPC mixes. The findings suggest that the use of an alkali activated natural pozzolan in the production of concrete results in the development of mechanical strength and modulus of elasticity that range from moderate to high. Additionally, this kind of concrete exhibits significantly reduced shrinkage compared to standard OPC. The ultrasonic pulse velocity of geopolymer concrete mixes is consistently seen to be lower compared to ordinary Portland cement (OPC) concrete mixes, despite the former exhibiting greater compressive strengths and lower densities (Bondar, 2009, 2011).

10. EVALUATION OF CARBON FOOTPRINT AND COST FOR GEOPOLYMER CONCRETE

There are two possible benefits associated with the use of alkali activated alumina silicate as a binder in concrete, namely its carbon footprint and cost-effectiveness. The growing need to enhance sustainability within the concrete sector renders these elements more significant. The quantitative

assessment of the relationship between the carbon dioxide (CO₂) footprint and the cost of geopolymer concrete, as well as its compositions, is approximately estimated in comparison to Portland-based cements (Bondar, 2009).

10.1 Supply and cost of activators

The investigation conducted by the author indicates that in order to generate 1m³ of geopolymer concrete, a mixture of 66kg of potassium hydroxide and 46kg of water-glass (assuming a density of 1.35 kg/m³) is required, along with 400kg of pozzolan. The prices of these activators vary across different markets. For instance, industrial potassium hydroxide (25kg KOH Flake UNSD manufactured in Korea) is priced at \$81, while water-glass (11.35 kg water-glass solution sold by Sheffield Pottery in the U.K.) is priced at \$12. In terms of unit cost, potassium hydroxide is estimated to be \$3.2 per kg, whereas water-glass is priced at \$1.1 per kg. Therefore, based on a general guideline, the cost of activators needed to activate 400kg of pozzolans is estimated to be \$266.6. Additionally, it is assumed that the price of 25kg of pozzolan is equivalent to the price of 25kg bags of OPC. Consequently, the cost of the necessary activators would amount to \$17 per 25kg (Bondar, 2009).

11. CONCLUSION

Geo-polymer concretes exhibit a significant increase in mechanical strength, characterized by a high modulus of elasticity, and demonstrate a much reduced level of shrinkage compared to ordinary Portland cement (OPC). The manufacturing of geo-polymer concrete has the potential to significantly decrease carbon dioxide (CO₂) emissions, ranging from 22.5% to 72.5% in comparison to the production of ordinary Portland cement (OPC). Geo-polymer concrete has similar qualities to ordinary Portland cement (OPC) concrete and may be manufactured at a comparable cost.

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