RESEARCH ARTICLE

RSP Science Hub

International Research Journal on Advanced Science Hub
2582-4376
Vol. 04, Issue 05 May
www.rspsciencehub.com

Check for updates

http://dx.doi.org/10.47392/irjash.2022.031

Construction and Demolition Waste-based Geopolymer Concrete: A Brief Review

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Article History

Received: 22 January 2022
Accepted: 5 May 2022

Keywords:
C & D Waste;
geopolymer;
rheology;
SCMs;
recycled aggregate

Abstract

Cement concrete and other cement-based composites find wide application in the construction industry. The manufacturing of cement releases a large amount of CO2, so the use of cement has become a major area of environmental concern. Attempts have been made to minimize the quantity of cement in concrete by replacing it with supplementary cementitious materials. Geopolymer concrete is one of those potential candidates for alternative cementitious materials. In today's world, the production of Construction and Demolition (C&D) wastes has been increased worldwide which finds no suitable disposal and cannot be used in ordinary concrete due to potential deterioration of concrete quality. However, C&D waste can be safely used with geopolymer concrete with and without the usage of Supplementary Cementitious Materials (SCMs) and play a major role in improving the strength and durability properties of concrete.

1. Introduction

Cement, sand, and coarse aggregate are one of the most widely used construction materials used in civil engineering projects for the production of concrete. In the past decades, the construction industry consumed a huge amount of ordinary Portland cement. The manufacturing of this cement requires tonnes of energy and is considered a major cause of CO2 emission into the atmosphere. Almost 7% of the greenhouse gas emission (by weight) is contributed by the cement industry (Ali, Saidur, and Hossain). To solve this issue, attempts have been made to minimize the quantity of cement in concrete by substituting it with supplementary cementitious materials. Moreover, to decrease the use of Portland cement, alternative cementing materials are in use. Attempts made in the past suggested the replacement of Portland cement in concrete with geopolymer cement, to control the release of CO2 into the atmosphere. Geopolymers (inorganic polymers) can be formed by low-temperature polymerization of aluminosilicate materials and alkalis, resulting in Si-O-Al bonding (Lolli et al.). Source materials and alkali solutions are two key ingredients in geopolymer cementing. Aluminium (Al) and silicon (Si) from geological sources or by-products should be rich in raw materials. In solutions based on sodium or potassium, alkali solutions are widely used. The composites of mortar and concrete prepared with these geopolymer binders indicate similar strength and appearance as those of traditional cement binders. Moreover, geopolymers are well known to exhibit outstanding acid resistance, fire resistance, and mechanical properties (Bassani et al. Mohammadinia et al.). A typical geopolymer's carbon footprint is considerably lower compared to Portland cement. Ouellet-Plamondon et al. (2014) demonstrated that only 'one-part geopolymer' exhibits much lower levels of a carbon footprint than Portland cement-based mixtures (Ouellet-Plamondon and Habert). Every year, the production of construction and demolition waste (C&D waste) is increasing, causing the waste to dispose of at landfills or dumped illegally. It is a major environmental and social issue to remove these waste materials. The recycling of these wastes as aggregates (in a new product) will improve solid waste utilization and help conserve natural resources. In recent years, demolition wastes have been used as recycled aggregates for the production of new concrete. In addition, the use of recycled aggregate is demanding because of rising landfill costs and the scarcity of natural resources. Several researchers have suggested that recycled aggregates are environmentally friendly as well as cost-effective for concrete production (Marie and Quiasrawi Marinkovic et al.). Attempts have been made in the past to utilize solid waste as aggregate in concrete work. Most of the studies focus on the use of these waste materials as aggregates in standard cement binders. The goal of this article is to discuss the effects of the use of recycled aggregate geopolymer matrices and highlights the various properties of C&D waste-based geopolymer concrete.

The findings of the article define that the use of C&D waste in the preparation of geopolymers concrete can be considered as one of the most environmentally friendly and cost-effective strategies for reducing CO2 emissions by reducing the requirements of Portland cement and aggregate processing, thus providing a suitable solution for the disposal of waste from the Construction. The article encompasses all the associated properties of the geopolymer concrete and its future use for the mitigation of environmental impacts due to carbon emissions during manufacturing of conventional cement.

2. Geopolymer Concrete

Geopolymer is relatively a new building material, formed by a complex chemical reaction between an alkali hydroxide or a silicate solution and a solid aluminosilicate solution, which leads to an amorphous alkali-aluminosilicate product (Davidovits). The reaction involves various steps and typically begins with the dissolution of amorphous Si and Al atoms from the source material through the action of hydroxide ions, as shown in Fig1. (Van Jaarsveld, Van Deventer, and Lorenzen Yusuf et al.) Apart from the chemical definition of geopolymers, they are most commonly referred to as inorganic polymer concrete, low-temperature aluminosilicate glass, geo-cement, and hydro ceramic. (Duxson et al.). The polymerization process can be considered in three phases (De Silva, Sagoe-Crenstil, and Sirivivatnanon). First is the dissolution of Si and Al in the alkali solution from the source materials (i.e. fly ash). The second is the dissolved ingredient agglomeration (coagulation), and the third, is the dissolved substance poly-condensation. This polymerized method, also referred to as geopolymerization, leads to the creation of silico-aluminate structures in 3D networks. Therefore, geopolymerization will take into account any materials which accumulate high concentrations of silica and alumina.

Bottom ash, fly ash, ground granulated blast-furnace slag (GGBS) and metakaolin are some of the most commonly used Supplementary cement materials (SCMs) in the production of geopolymer concrete. Fig. 2 defines the composition of geopolymer concrete (Etxeberria, Marí, and Vázquez). Geopolymer concrete comprises about 43% aggregate and 49% mortar and aggregate mix. Other compounds like ceramic, bituminous aggregates, etc. constitute about 8% of the total mix.

The geopolymer network can be broadly divided into two separate systems and methods based on dissolution of gehlenite (sorosilicate compound: Ca2Al-aluminosilicate) in precursor materials: 1) classical or conventional alkali-activation system and 2) potassium-calcium aluminosilicate system (Rafeet et al.). In the past, it has been identified that GGBS and type C fly ash include major and minor gehlenite phases, respectively (Perná, Šupová, and Hanzlíček). For the geopolymerization of these materials, the potassium-calcium (K-Ca) aluminosilicate composition terminology needs to be used. Moreover, metakaolin and type F fly ash, without gehlenite phases, are capable of forming the geopolymeric networks using conventional methods or using the K-Ca compound along with other gehenite-rich materials. Due to varying chemical compositions, the use of various SCMs in geopolymer concrete preparation results in variation in the properties of the final product. Four chemical ratios are mainly influenced by the properties of geopolymer concrete produced by conventional methods: SiO2 to Al2O3, R2O to Al2O3, SiO2 to R2O, and liquid-solid ratios where R is Na+ or K+ (Singh et al.).

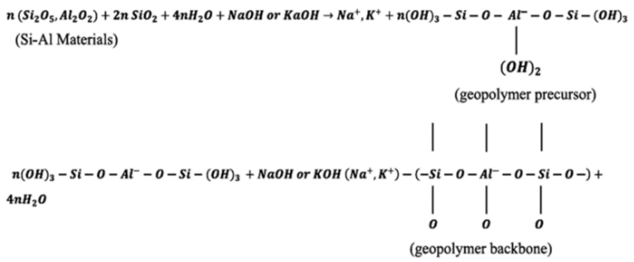

FIGURE 1. Chemical reaction of the Geopolymerization

Alteration in the quantity and molarity of the alkaline activators which includes potassium hydroxide (KOH), sodium silicate (Na2SiO3), sodium hydroxide (NaOH), and potassium silicate (K2SiO3), will result in a change in the concentrations of sodium and potassium in suspension. Van et al. (2014) and Xu et al. (2014) examined the influence of the ratio of SiO2 to R2O of the geopolymer materials concerning the mechanical strength (Xu and Van Deventer). It has been demonstrated that the compressive strength of geopolymer binders improves with an increment in R2O or a decrement in SiO2 in the aluminosilicate network. The effect of activators showed that crystalline zeolite was produced only for the Si/Na ratio of 4/4 molarities or less when geopolymers were formed by NaOH. It has also been inferred that the addition of even a small amount of sodium silicate to NaOH solution will suppress the crystallization process.

Curing conditions, along with chemical ratios, were found to affect the mechanical properties of geopolymer concrete. On a similar note, Najafi et al. (2009) analyzed the influence of curing temperature on the compressive strength of a natural polymeric binder based on pozzolana, by considering curing of binders at three different curing temperatures i.e. at 45°C, 65°C, and 85 °C (Zhang, Mackenzie, and Brown). The maximum value of compressive strength of geopolymer concrete was achieved at a curing temperature of 85 ° C, when cured for 20 hours, immediately after 7 days of pre-curing. Heah et al. (2011) suggested that curing of kaolin-based geopolymer binder at ambient/room temperature is not ideal; however, mechanical strength increase significantly with the increase in curing temperature up to 100 °C, even for one day of curing period (Kani and Allahverdi). Currently, researchers are identifying the effect of relative humidity on the mechanical properties of geopolymers. According to Yousefi Oderji et al. (2017), 70 percent relative humidity is considered the ideal curing humidity for fly ash geopolymers (Heah et al.). Several attempts were also made in the past to determine the effect of SCMs and various admixtures on geopolymer materials. The effect of using two distinct GGBSS in NaOH solution-activated fly ash-based geopolymer binder has been assessed and found to give similar compressive strengths for GGBS, having close chemistry and mineralogy. Adak et al. (2014) investigated the role of nano-silica on the fly ash-based geopolymer mortar mechanical properties. The properties of 6 percent nano-silica incorporating geopolymer mortar and curing at ambient temperatures are comparable to those of heat-activated fly ash-based geopolymer & Pachecon-Torgal et al. (2011), worked on metakaolin-based mortars by partially replacing metakaolin (5% and 10%) with CaOH. It was noted that the use of 10 percent CaOH in high NaOH molarity (14 M and 16 M) and 3 percent superplasticizer quantity prepared metakaolin-based geopolymer mortar could result in higher workability with higher compressive and flexural strengths.

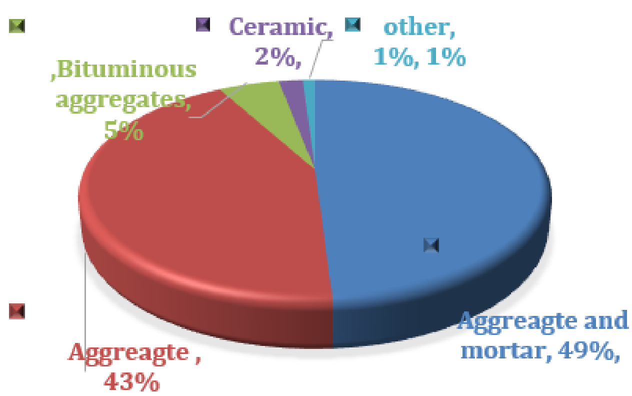

FIGURE 2. Composition of C&D waste

3. Use of C&D Waste as cementitious materials

The development of the construction industry has contributed to the growth of C&D waste for the past few years. The construction industry has shifted from the use of traditional materials to focus on finding suitable solutions for waste concrete disposal. The replacement of natural aggregates with C&D waste as raw material in concrete production should be considered a sustainable construction practice. The possibility of using C&D waste as alternate aggregates has been taken into account in past studies with the focus on the incorporation of C&D waste as a replacement for coarse aggregate, for the manufacturing of sustainable concrete with adequate durability and mechanical performance. The findings, however, were varied and there were disagreements between them in some instances. This disparity has been related to the variation in the properties of the interfacial transition zone (ITZ), formed between the new binders and coarse C&D waste aggregates. Pereira-de-Oliveira et al. (2018) identified a significant quantity of old hydrated cement paste attached to the surfaces of C&D waste aggregates. This product has unknown properties and thus influenced concrete's final output in both fresh and hardened states. To overcome this problem, previous research suggested using fine recycled aggregates (FRA) from C&D waste to reduce the influence of such unknown compounds on the properties of the final product. Khatib et al. (2005) replaced natural fine aggregates in concrete with fine C & D waste aggregate at replacement percentages of 0%-100% . It was indicated that at 25 percent and 100 percent fine C & D waste aggregate replacement rates, compressive strength fell by 15 and 30 percent, respectively. Fan et al. (2016) identified the influence of fine C & D waste aggregates produced by various crushing methods on the properties of sustainable concrete. The main concrete parameters i.e. resilience, mechanical properties, etc. were found to depend on the quantity of C&D waste aggregate in concrete. Application of cement materials (SCMs) was found to be beneficial to concrete composed of fine recycled aggregates. Author prepared concrete with FRA and several replacements of fly ash. The compressive strength of mortars was found to increase with an increase in the concentration of fine recycled aggregate when the samples were cured for 28 days. Gorjinia Khoshkenari et al. (2014) used fine C&D waste aggregates along with silica fume, indicated that the use of fine aggregate alone can result in a decrease in compressive strength, however, with the addition of silica fume and reduction in water to cement ratio, a substantial improvement in the compressive strength of C & D waste-based concretes can be obtained as compared to the control mix. They suggested a washing process to obtain a final product has good physical properties. A new method of recycling was introduced by Koshiro et al., (2014) where higher quality fine recycled aggregates were obtained by using a heat grinder system. Three distinct crushing-sieving techniques were provided by Floreaet al.(2013), to obtain C&D waste aggregates with distinct properties such as density, particle size distribution, and mineralogical composition. The results helped in identifying that the crushing-sieving method has a significant impact on the properties of aggregates, and better properties can result from an optimized crushing method.

4. Role of Construction and demolition (C &D) waste in geopolymer concrete

C&D wastes are one of the serious issues for all developing nations worldwide. Only a partial replacement of aggregate is in the process nowadays, causing a large quantity of C&D waste dumped in landfills. For applications where average compressive strength is required, such as in the case of back-fill material and road sub-bases, C&D waste is often used in OPC concrete, as an aggregate. To fulfill a broader range, global trends require more efficient recycling of C & D waste. The European Union, for instance, has specified that 70 percent of C&D waste should get recycled by 2020. However, the recycling rate in 2012 was only 47 percent. This shows the urgent need for techniques to be developed to enable the recycling of C&D waste for high-performance tasks.

Collection and utilization of C & D waste could provide the solution for recycling crushed and ground concrete that can be used as an ingredient in geopolymeric binders. It was suggested that samples of concrete prepared with recycled aggregates, using 100 percent of waste successfully, do not accurately represent real-world conditions. The strength of geopolymeric binders was found to depend largely on the characteristics of the binder's matrix rather than on the aggregate interaction. A research study conducted by Lampris et al. (2009) has produced silt-based geopolymers taken from C&D waste plants. It was presented and concluded that concrete having 100 percent silt geopolymers, results in average compressive strength of 18.7 MPa for 7 days of curing when cured at ambient temperature. Partial silt replacement along with the addition of metakaolin and PFA increased the average compressive strength of geopolymers to 30.5 and 21.9 MPa respectively. The effect of curing time was found to play a vital role in the improvement of compressive strengths at higher temperatures. Samples prepared in the study were found to be suitable for use as aggregate materials; however, the addition of metakaolin to the silt sample was found to increase the compressive strength of the geopolymers.

Ahmari et al. (2012) produced a geopolymeric binder with varying proportions of ground concrete waste (GCW) and fly ash. The composition of this mix influenced the binder's unconfined compressive strength (UCS). The addition of GCW increased the UCS of binders, by up to 50%, but a further increase in the content of GCW resulted in a drop in UC strength. Allahverdi et al. (2008) focused on the usage of waste concrete and bricks as raw materials in geopolymer concrete. Compressive strength tests indicated that the use of waste and crushed bricks can serve as a possible source of raw material for geopolymer concrete because of the presence of calcinated alumino-silicate content in waste bricks. An increase in the Na_2O material a found to improve the compressive strength of waste brick-based geopolymer concrete.

Mohammadinia et al. (2016a) examined the performance of reclaimed asphalt pavement (RAP), recycled crushed aggregate, and crushed brick (CB), as pavement base or sub-base materials through geopolymerisation. The use of slag resulted in the improvement of the strength, density, and stiffness of C & D waste. Recycled concrete aggregate (RCA), which was found to qualify for use as a base material, offered the best results. The findings of this study suggested that C & D waste geopolymerisation, particularly RCA and RAP, is one of the viable and sustainable choices for the material stabilization of pavement base/sub-base.

The strength production of C & D waste geopolymers was further investigated by Mohammadinia et al. (2016b). The authors suggested that an increase in the fly ash content and curing at a high temperature can improve the strength gain rate of geopolymer concrete (Fig. 3).

5. Properties of the CDW-based geopolymer concrete

5.1. *Strength*

5.1.1. The influence of SiO_2/Al_2O_3

The molar ratio of SiO_2/Al_2O_3 is one of the most important factors controlling the mechanical properties of geopolymers. Cheng et al. (2003), for instance, reported that when the ratio of SiO_2/Al_2O_3 remains between 3.16 and 3.46, concrete with maximum strength is obtained. For the production of optimal geopolymers, Silva et al. (2007) suggested this range as 3.4 to 3.8. The overall molar ratio was varied; however, its proportion is likely to depend upon the chemical

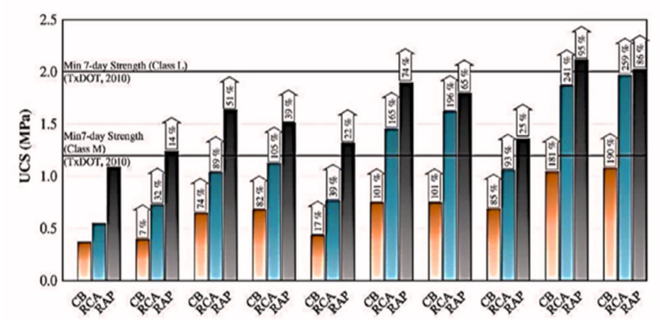

FIGURE 3. UCS value of C&D materials (cured for 7 days)

composition of source material as well as the composition of alkaline activators. Ahmari et al. (2012) reported, that for SiO_2/Al_2O_3 ratios ranging from 4.1 to 8.2, compressive strength of 30 MPa is achieved, with an optimal strength of about 35 MPa at a SiO_2/Al_2O_3 ratio of 6.76.

The same pattern was presented for combined C&D waste and concrete waste (CW) by Zaharaki et al. (2016) (SiO_2/Al_2O_3 ratios ranging between 8.1 and 8.9) and Vásquez et al. (2016) (SiO_2/Al_2O_3 ratios ranging between 9.5-10.5). These findings showed that there is an optimal range of the SiO_2/Al_2O_3 molar ratio irrespective of the source material. One of the important findings includes that C&D waste-based geopolymers (produced from concrete waste) have the lowest compressive strength at all SiO_2/Al_2O_3 ratios when compared with C&D waste-based geopolymers (produced from brick and ceramic products). Robayo-Salazar et al. (2017) analyzed the SEM micrographs of concrete waste (CW) and brick-based geopolymers. The micrographs indicated that with a much greater number of unreacted CW particles, the paste matrix becomes heterogeneous of CW-based geopolymers.

5.1.2. NaOH concentration

Most of the researchers used a mixture of activators such as potassium hydroxide, sodium hydroxide (NaOH), sodium silicate, and potassium silicate in geopolymer technology. However, NaOH is the most commonly used activator because of its easy availability and lower price. The most important advantage of using NaOH is the possibility of the development of various molarity of NaOH solution. Moreover, other activators such as potassium silicate or sodium silicate have been used more commonly in commercial types. In the past, the influences of various molarities of NaOH on the properties of geopolymers were investigated in several studies. Also, the quantity of NaOH can affect the Na2O content of the alkaline solution and, ultimately affect the Na2O/SiO2 ratio in the final geopolymer material. To activate silt generated from C & D waste washing plants, Lampris et al. (2009) investigated the effect of NaOH molarity from 4 to 10 M, by exposing the samples to different curing conditions. A curing period of 7 days at 600C temperature, accelerated geopolymerization for molarities between 8 and 10 M and resulted in higher compressive strength. However, as can be observed in the curve found by Lampris et al. (2009), the optimum result achieved was 9 M. L. Reiget al. (2013) used NaOH molarity from 2 M to 10 M for the geopolymerization of red clay brick waste (RCBW) and indicated an optimum NaOH molarity of 5 M at curing temperature of 65 °C. L. Reiget al. (2013) also worked on 6 to 9 molarities and defined an optimum point of 7 M for porcelain stoneware and RCBW alkali activation for the curing temperature of 65 °C. Komnitsas et al. (2015) explored the influence of NaOH concentration (in the range of 8 M and 14 M) on the geopolymerization of various C & D waste by considering different curing temperatures. The results showed that variation in NaOH molarities have almost no effect on the activation of concrete waste at a curing temperature of 600C and 80 °C, whereas the addition of tile and brick exhibited the maximum compressive strength, with optimum NaOH concentration values of 8 M for brick and 10 M for tile and at 80 °C curing temperature, after 7 days of curing. The SEM micrographs of C&D waste-based geopolymers were investigated by L.Reig (2013). The micrographs epitomize the microstructure of porcelain and brick-based geopolymers with two distinct NaOH molarities (7 and 9 M). In contrast to 7 M, the brick-based geopolymers displayed lower compressive strength at a NaOH concentration of 9 M. These findings indicate that the microstructure and the mechanical strengths of matrices and geopolymers respectively, may be negatively affected by excess sodium hydroxide.

5.1.3. Role of R2O/SiO2

The molar ratio of R2O/SiO2 is considered one of the most important factors influencing the geopolymerization process. The term 'R' denotes Na+ and/or K+. In the alkali activators, the ratio indicates the sum of soluble sodium and silicate. Till now, limited studies defining the impact of the ratio of R2O/SiO2 on C & D waste-based geopolymers have been conducted. Variation in the compressive strength of red clay brick waste(RCBW) based geopolymers concerning change in the ratio of R2O/SiO2's was analyzed by Robayo et al. (2016). by considering a range of 0.06-0.15 of R2O/SiO2 ratios. Ahmari et al. (2012) and Sun et al. (2013) varied the R2O/SiO2 ratios from 0.055 to 0.1, and 0.11 to 0.24, respectively. The key dissolving component for activating the Si and Al in the system is Na+ and/or K+, according to Ahmari et al. (2012). However, the highest Na+ content results in lower intensity due to the availability of other compounds such as calcium (Ca2+), which inhibits geopolymeric networks. On the other hand, Robayo et al. (2016), Pacheco-Torgal et al. (2008) identified that compressive strength variations are caused by the number of sodium silicates in the solutions. It was believed that better geopolymerization conditions and compressive strength depend on the availability of soluble silica in an alkali activator. The authors, however, indicated that the properties and characteristics of activators can create some optimum points. Geopolymerisation of C&D wastes depends upon the ratio of R2O/SiO2, Al2O3/R2O, and liquid/solid ratios, hence further research is needed to have a concrete conclusion defining the influence of such ratios on the geopoymeristion process.

5.1.4. Effect of other properties: Amorphous and soluble silica

The role of amorphous phases and the availability of soluble silica and alumina in the geopolymer binders and mortars have not been investigated thoroughly. Rakhimova et al. (2014) firstly suggested a new method from the literature for classifying SCMs for alkali-activated slag cement. Three classes were identified a) Chemically activated materials characterized as amorphous structure phases, b) Physically activated materials characterized as crystalline contents. And, Finally, physically active and reactive materials contain the properties of the two previously defined classes. They identified the impact of the amorphous content of four separate clay brick wastes in the RCBW-GGBS-based geopolymer binder, but no meaningful conclusion was drawn. Keppert et al. (2018) measured the compressive strength of two distinct CaO content of ceramic-based geopolymer pastes. The author evaluated the amount of SiO2/Al2O3, based on an amorphous portion of chemical oxides in the precursors. The results clearly showed that it was necessary to take into account the amorphous phases of the geopolymer paste mixture design process. In addition, it was claimed that, because of the expected formation of calcium silicate hydrates (CSH), the presence of higher CaO content in products of ceramic waste powder caused higher nanoporosity and greater pore size of the final geopolymer material.

5.2. High temperature resistance

One of the parameters not commonly considered by researchers is the thermal stability of C & D waste-based geopolymers, i.e. behavior of CDW-based geopolymers at high temperatures. Zaharaki et al. (2016) measured the compressive strengths of geopolymer binders after subjecting them to a very high temperature of 400 °C to 800 °C and suggested that increase in temperature results in a decrease in the compressive strength of geopolymer binders. According to their research, at high temperatures, C & D waste-based geopolymers were found to indicate volumetric shrinkage, weight loss, and microcracks, which affected the matrix's porosity and mechanical properties. In addition, Chuah et al. (2015) and Renet al. (2016) suggested that high-temperature exposure of SCM-based geopolymers can cause partial decomposition of aluminosilicate networks.

5.3. Rheology

Rheological features such as viscosity, shear stress, and yield stress of C & D waste-based geopolymers, have been investigated in the past. Rovnaník et al. (2018) and Keppert et al. (2018) studied the rheological properties of geopolymers composed of red clay bricks and ceramic powders respectively. Thixotropic behavior and plastic viscosity of the final product was found to reduce after the addition of brick powder to geopolymers based on metakaolin. Delay in the yield stress was obtained with the increment of the brick powder in the geopolymer compound. Keppert et al. (2018) identified the influence of the CaO content on the rheological properties of two geopolymers containing two different ceramic powders. The results suggested that the magnitude of the yield stress of geopolymers was dropped after the addition of ceramic products, however, a ceramic powder containing higher CaO content has produced higher yield stress as compared with ceramic powder with low lime content. Allahverdi et al. (2009) and Rakhimova et al. (2015) focuses on identifying the setting time of geopolymer products. According to them, it took longer to set all geopolymer binders at a lower Na2O concentration (6 percent). For geopolymer binders, the final setting time is comparable to normal cement binders. Furthermore, because of the high thixotropic properties of fresh binders, the researchers suggested an initial false set in all geopolymer binders. It was concluded that the final setting time may decrease with an increase in Na2O concentration, by keeping the ratio of Na2O/SiO2 constant. Rakhimova et al. (2014) studied the variation in the initial and final setting time of geopolymer binders, by considering the role of two different activators and the specific surface area of blended powders. It was concluded that with the increase in the specific surface area of blended powders from 300 m2/kg to 900 m2/kg, a decrease in both the initial and final setting time was observed. Sodium carbonate was found to increase both the initial and final setting time of geopolymer binders as compared to sodium silicate as it has a constant specific surface area.

5.4. Durability

The product formed after the polymerization reaction is different from the chemical reaction, which causes geopolymer concrete to be more durable than Portland cement concrete. Geopolymer concrete, when produced in the same NaOH solution, with recycled aggregate has high permeability, water absorption, and absorptive rate as compared to concrete produced with natural aggregate. The higher the replacement of natural aggregate with recycled aggregate in geopolymer concrete, the higher the number of pores in the interfacial zones, which further leads to a reduction in matrix density. The amount of water absorbed by a concrete indicates the permeability of the concrete's pore system. Hence, a concrete with higher porosity will have high water absorption, resulting in higher chloride penetration. If geopolymer concretes are produced with both aggregates, then a mixture containing more quantity of NaOH will decrease the chloride penetration. An increase in the concentration of NaOH solution improves the dissolution of Si and Al in the source material which can produce a better polycondensation process in the geopolymer system and can help in decreasing the porosity and chloride ingression. It has been suggested that ITZ deboning (between the recycled aggregate and binder) decreases with the increase in the ratio of sodium silicate to sodium hydroxide from 2 to 3, which can further improve the chloride resistance of the system.

Geopolymer-based binder has high sulphuric acid resistance because of low lime content and low water absorption. The presence of Si, Al, O, and Na, in the geopolymer binders, is the reason for providing better resistance to acid attack when compared with Portland cement mixtures. After the immersion of geopolymer concrete for 14 days in sulphuric acid solution weight loss of samples was found to increase significantly. This has happened due to the damage of aggregate particles which is caused after the sulphuric acid reacts with calcium compounds. The weight loss was found to depend upon the concentration of sodium hydroxide solution after 28 days of calcareous aggregate geopolymer. It has been suggested that geopolymer concrete prepared with recycled aggregate has high acid resistance than those prepared with natural aggregates at the same concentration due to the higher absorption of water, sorptivity of recycled aggregates, and greater volume of permeable void. Furthermore, the reaction of calcium compounds with the acid solution can cause more deterioration in the old cement mortar.

6. Other benefits and limitations

Geopolymers are being widely used as construction material. Work defining the potential benefits of using biopolymers in the construction industry has been carried out in the past. Some of the benefits of using geopolymer in the construction industry are described below:

6.1. Fire resistance

Geopolymers are widely known for their ability to resist fire attempts have been made to develop a non-combustible, heat-resistant, and inflammable material after several additions of catastrophic fibers in France in the early 1970s. Cheng et al. (2003) observed that granulated blast furnace slag can be used as a fire-resistant biopolymer. Furthermore, an increase in the K2O content while preparing the geopolymer was found to improve the setting time, fire resistance, and compressive strength of the geopolymer.

6.2. Insulation

Colangelo et al. 2013 suggested the use of recycled plastic aggregates as a heat dispersion compound for geopolymers. Such improvement in the thermal behavior of geopolymers offers a better reduction in Co2 emissions for the overall life of geopolymer building materials

6.3. Pervious pavement

Tho et al. (2012) prepared a fly ash-based geopolymer concrete having pervious structure and mechanical properties similar to that of OPC-based concrete. This indicates that OPC concrete can be replaced with geopolymer concrete to produce porous pavement to improve surface water runoff and for heat mitigation.

6.4. Efflorescence

Efflorescence is defined as the formation of white carbonate deposits on the surface of the concrete. Efflorescence is one of the biggest problems associated with geopolymers, when exposed to water and air. Kramar et al. (2016) found that efflorescence can be the largest in geopolymers containing alkali content. Kani et al. identified some methods to reduce efflorescence in geopolymers concrete and suggested that the addition of high alumina cement as an admixture can reduce the probability of efflorescence on the geopolymer concrete surface. In the case of OPC concrete, efflorescence was found to have a negative effect on aesthetic view; however, more research needs to be conducted to identify the impact of efflorescence on the mechanical properties of concrete.

6.5. Workability

Just like in the case of OPC, additives can also be provided in geopolymer concrete. Kuo et al. (2014) investigated the role of superplasticizers on the mechanical and physical behavior of geopolymer binders and reported an improvement in workability, volume stability, and compressive strength of a geopolymer binder when produced from GGBFS and desulphurization slag. Llloyd et al. (2010) identified that geopolymer concrete takes almost 120 mins to begin setting and can be easily handled up to that period, indicating a great improvement in the workability of geopolymer concrete when compared with OPC based concrete.

6.6. Shrinkage

Wallah et al. (2009) defined that when an FA-based geopolymer concrete gets cured under heat then a low drying shrinkage was observed. Moreover, the authors identified that the mixes possessing different compressive strengths and exposed to different curing conditions did not indicate any significant differences in the shrinkage strain values. Hardjito et al. (2005) reported that when the samples are exposed to the heat curing, the water remains inside the pores of the concrete, and since most of the water gets released during the chemical reaction gets evaporated during the heat curing and hence it produces low drying shrinkage of the geopolymer concrete.

7. Economic Benefits

For the past years, fly ash is obtained a significant position in the production of geopolymer concrete and is considered an energy-saving process and indirectly helps in reducing the emission of greenhouse gases into the atmosphere, especially by reducing the production and utilization of cement. The utilization of fly ash is essential for resource and environmental protection. Lloyd et al. (2010) suggested that compared to OPC, class-F fly ash-based GPC with heat curing results in benefits in terms of the economy. The cost of fly ash is almost negligible as compared to OPC cost. Moreover, even after the addition of alkaline solution, the cost of GPC per cubic meter is almost 10-30% economical as compared to OPC cost. It was found that only 1 tonne of FA can produce three cubic meters of good quality GPC, indicating that GC receives economic benefits through carbon credits. GPC has lots of advantages such as they offer low shrinkage and creep, low permeability, and better resistance to acid and sulfate attack as compared to OPC-based concrete. This concrete possesses better long-term and durability performances. Vilamova et al. (2016) reported that the cost of concrete having prepared with partial replacement of cement and FA was remain lower than that of geopolymer concrete with 100% FA. Mathew et al. (2013) observed the preparation of GPC cost 7% higher than that of OPC-based concrete, where the cost of aggregates and alkaline solution were based on local market price.

8. Challenges for industrial applications

In the last two decades, global climate change action plans have demanded supplementary cement materials to be used in the cement and concrete industries significantly. Bouzouba'et al. (2005), for example, indicated that SCMs producers are unable to meet the requirement of SCMs in the Candian market, which forced them to purchase the material from the US and Norway. An increase in the SCM consumption rate creates an opportunity to consider the use of C& D waste to moderate market demand, either on their own or in combination with SCMs. The use of C & D waste in the geopolymer sector, however, presents several challenges. While several studies have been conducted over the last few years on the geopolymerization of building and demolition waste, very little progress has been made in industrial applications. The complexity of geopolymerization and activation of C & D waste of different chemical compositions are the primary reason for the decrement of this technique. The production involves changes in SiO2/Al2O3 ratios, activators, concentrations, curing conditions, etc. depending on the type of role to be served by concrete. Apart from this, the chemical composition of raw material also influences the characteristics of C & D waste-based geopolymers. In addition, current methods of activation, which include the use of high-temperature curing and alkaline chemical activators, are demanding the need for professional trainers and manufacturing practices for the production of such goods. Therefore, it is important to consider simplifying certain production processes based on the availability and functionality of the raw materials, curing conditions, and activators.

9. Environmental Analysis

For environmental analysis, Yang et al. (2013) described that binders contribute to a large amount of CO2 emissions when prepared with OPC concrete. Van Deventer et al. (2012) suggested that carbon emission can vary from 100-200 CO2 per tonne for E-Crete (the proprietary geopolymer technology product of Zeobond, consisting of fly ash, slag, and NA) to 300-900CO2 per tonne for OPC concrete. Yang et al. (2013) confirmed the emissions of the quantity of CO2 into the atmosphere as 100 to 200 CO2 per tonne in different alkali-activated binders. Mastaliet al. (2018) further investigated the impact of types and concentrations of recycled aggregated on fly ash-based alkali-activated concrete under different curing conditions. The results defining the compressive strength of fly ash-based alkali-activated binders in comparison to greenhouse gas (GHG)emissions are shown in Fig 3. As per the results, the use of RA can result in a reduction of GHG emissions and does not depend upon the curing condition. The decrease in emissions of GHGs may be attributed to an increase in the absorption of carbon dioxide. It has been suggested after comparison that instead of using NA and curing at ambient conditions, RA carbonization and flow through CO2 curing can reduce GHG emissions by almost 50%. The goal of this investigation was to build bricks with RA-containing alkali-activated binders with very low GHG emissions. The prepared material can be used in footpaths, driveways, and brick construction because the produced bricks were found to provide a strength of 5 MPa, which is generally required in such types of constructions.

10. Future Research and recommendation

Production of GPC with some modifications in the mix design of OPC has been suggested by some

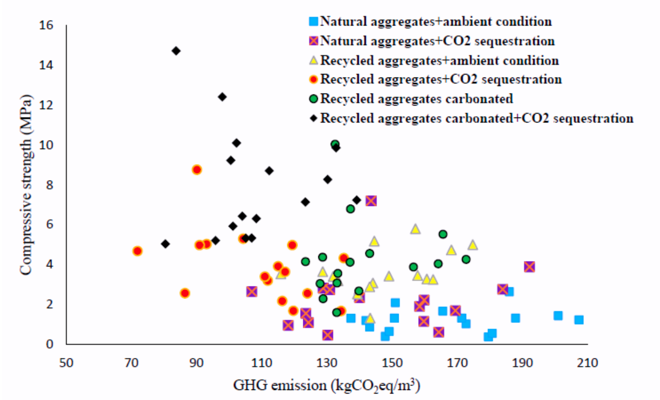

FIGURE 4. Impacts of different curing regimes (ambient conditions or CO2 sequestration) on the compressive strength versus GHG emissions of different fly ash-based alkali-activated concretes containing NA or RA

researchers. However, an optimal mix design needs to be incorporated for the preparation of economical geopolymer concrete.

a. Researchers have identified the impact of curing temperature, the molarity of NaOH, rest period, duration of curing, and the ratio of Na2SiO3on the properties of GPC. However, an optimal value for all these parameters has not been established and needs to be investigated in future works.

b. The mechanical behavior of FA-based GPC at ambient temperature has not been studied in detail. To utilize and cast GPC in the field, the behavior of GPC at the ambient, field and stabilized temperature in the lab needs to be explored.

c. Since the durability of a new product needs to be established to obtain its long-term performance. Hence, GPC should be tested for long-term stability.

d. To utilize geopolymer concrete in civil engineering applications, more studies need to be performed to identify the structural behavior of concrete subjected to various loadings.

e. Some empirical relationships need to be established between the compressive strength, flexural strength, and young's modulus of geopolymer concrete.

11. Concluding remarks

This paper suggested the use of building and demolition wastes in the production of geopolymer concrete, by considering C&D waste as a replacement for fine aggregate. The new concrete can be provided with supplementary cement materials such as brick, concrete, and ceramic wastes if required. The utilization of CDWs in the production of geopolymers can be considered one of the most cost-effective and environmentally friendly strategies for reducing CO2 emissions by reducing the requirements of Portland cement and aggregate processing, thus providing a suitable solution for the disposal of CDWs. The following findings are concluded based on the investigations outlined in this article.

1. While CDW may substitute fine recycled aggregates in standard concrete partially or entirely, most researchers have reported a lower-quality finished product because of the low quality and low load-bearing capacity of the fine recycled aggregate. However, with the growth and advancement in crushing techniques, the efficiency of fine recycled aggregates and properties of final concrete goods gets improved.

2. The addition of fly ash, metakaolin and blast furnace slag to geopolymers results in comparatively better properties than ordinary cement concrete. However, physical properties, the chemical composition of raw materials, concentrations of activator, and curing conditions (including curing period and temperature) play a vital role in influencing the properties of geopolymers.

3. In geopolymer applications, construction and demolition waste can be successfully used, especially when it is rich in silica and alumina. CDW possesses diverse chemical characteristics as usually observed in SCM-based geopolymers and hence each mixture requires a specific mix design, curing conditions, and activation method.

4. The key parameters in the traditional method of geopolymerization are variables such as SiO2/Al2O3 ratio, R2O/SiO2 ratio, NaOH concentration, curing state, and presence of soluble silica and alumina.

5. Analysis of Variables (ANOVA) confirmed that geopolymersition process depends upon several chemical factors, and each factor is linked to one another. Hence, it is important to create a process of mixed design that takes into account the chemical factors.

6. With the increase in the demand for environmental protection, the demand for SCMs is increasing which created a great opportunity for the utilization of CDWs in a large amount.

7. It becomes necessary to specify that certain critical parameters and features of building waste-based geopolymers have not been studied in detail. Rheological features such as time setting, shear tension, viscosity, and yield stress need to be further explored. Durability-related parameters defining the alkali-aggregate reaction, chloride diffusivity, carbonation, freeze-thaw cycle, and electrical resistivity are still in need to further research.

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Embargo period: The article has no embargo period.

To cite this Article: Anwer, Mohsin, Ashray Saxena, and Saif Ullah Khan. "**Construction and Demolition Waste-based Geopolymer Concrete: A Brief Review**." International Research Journal on Advanced Science Hub 04.05 May (2022): 108–119. http://dx.doi.org/10.47392/irjash.2022.031