GEOPOLYMER CONCRETE: THE GREEN ALTERNATIVE WITH SUITABLE STRUCTURAL PROPERTIES

Majid Muttashar*
Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Health, Engineering and Sciences, School of Civil Engineering and Surveying, University of Southern Queensland (USQ), Toowoomba, Queensland 4350, Australia.
Civil Engineering Department, College of Engineering, Thi Qar University, Iraq.
majid.alzaidy@gmail.com (Corresponding Author)

Weena Lokuge
Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Health, Engineering and Sciences, School of Civil Engineering and Surveying, University of Southern Queensland (USQ), Toowoomba, Queensland 4350, Australia. weena.lokuge@usq.edu.au

Warna Karunasena
Centre of Excellence in Engineered Fibre Composites (CEEFC), Faculty of Health, Engineering and Sciences, School of Civil Engineering and Surveying, University of Southern Queensland (USQ), Toowoomba, Queensland 4350, Australia. karu.karunasena@usq.edu.au

ABSTRACT

Concrete is the most widely used building material around the world because of the availability of raw materials, the simplicity in preparation and the moulding into different shapes. One of the main ingredients in a normal concrete mixture is Portland cement. However recent literature reveals that cement industry accounts for approximately 5 % of the current man made carbon dioxide (CO_2) emission worldwide. World cement demand and production are ever increasing with the expected growth is from approximately 2836 million tons in 2010 to between 3680 (low estimate) and 4380 million tons (high estimate) by 2050. Knowing that about 1.5 tons of raw materials are needed in the production of every ton of Portland cement concrete and about one ton of CO_2 is released in to the environment during the production, developing alternative construction materials is required. This paper will review the utilization of geopolymer concrete as an alternative for Ordinary Portland Cement concrete. The use of new greener material instead of concrete requires two main characteristics: reduced environmental impact which is a main concern in the world and better structural performance. This paper aims at investigating these characteristics using the available literature.

KEYWORDS

Geopolymer concrete, green alternative, structural performance, mechanical properties.

INTRODUCTION

From massive dams to the high skyscrapers all over the world, concrete was used as the main construction material. While Ordinary Portland Cement (OPC) is an essential ingredient to make concrete (Mehta 1999), too many environmental problems are associated with the process of the production of OPC. As World Business Council for Sustainable Development/ International Energy Agency WBCSD/IES (2009) mentioned, cement industry accounts for approximately 5% of the overall CO_2 emissions. The worldwide consumption of concrete increases as the population increases and the requirement to new structures is increased. As a result, the amount of CO_2 released to the atmosphere will increase due to the energy consumption to produce the cement. Except cement, all other ingredients used in concrete production are natural and as a result engineers and scientists start to develop alternative binding materials to replace the water and cement binder. Less environmental impact and durability are the crucial characteristics required for the new material. Geopolymer, an inorganic polymer, is one such alternative material that acts as the binding agent to replace water cement binder in concrete. Fly ash, a by-product of coal industry combined with sodium hydroxide and sodium silicate solution as an activator makes geopolymer reacting as environmentally friendly material. In addition, as Davidovits (1999) proposed that ancient buildings such as the Roman Coliseum and Egyptian Pyramids were made out of a material similar to the geopolymer concrete (GPC) which means it is more durable than OPC. This paper highlights the main features of GPC to be used as a suitable alternative construction material.

RESEARCH SIGNIFICANCE

Many researches discussed about the mechanical properties of GPC and highlighted this material as a green material. This paper attempts to summarise the environmental impact and properties of geopolymer concrete such as durability and strength which make this material the future construction alternative.

ENVIRONMENTAL IMPACT

The emission of greenhouse gases such as CO_2 and CO (carbon monoxide) is the main reason for the global warming. If fact the producing of one ton of Portland cement emits nearly one ton of CO_2 into the atmosphere (WBCSD/IES 2009). As a consequence, partial or full replacement of cement from the concrete mixture will overcome this detrimental environmental impact. GPC has been researched as a popular alternative during the last three decades. The use of fly ash and slag which would otherwise be ending up in landfills in GPC further proves that it is an environmentally friendly material. The reduced greenhouse gas emission by using Australian geopolymer products is estimated to be 44 – 64% compared with that of OPC (McLellan et al. 2011). The reduction in CO_2 emissions for geopolymer system is due to the use of minimum processed natural minerals and industrial wastes to form the binding agents. The process of using this waste material as a component to produce the binder helps to mitigate the environmental problems and provides new environmentally friendly green concrete (Joshi & Kadu 2012; Satpute et al. 2012; Subramanian 2007).

MECHANICAL PROPERTIES

Geopolymer binders result from a chemical reaction where silica and alumina molecules contained in an active pozzolanic material (such as fly ash or slag) react under highly alkaline conditions (Diaz-Loya et al. 2011). The resulting binder reacts as a gel to produce GPC. Mechanical properties of this material have been studied by many researchers. These researches showed that the chemical composition of geopolymer concrete plays an important role in having different mechanical properties compared with OPC. Reviewing the previous research on the performance of geopolymer concrete shows an excellent behaviour for this material, making it as an alternative construction material.

Compressive Strength

Compressive strength is one of the most important characteristics of concrete. Compressive strength of GPC depends on different factors such as curing temperature, mixing ratio and the molarity of alkaline activator. GPC can develop high strength in the earlier age under high curing temperature (Guo et al. 2010; Hardjito et al. 2004, 2005; Kong & Sanjayan 2008; Nasvi et al. 2012; Yost et al. 2013) and it gains target 28 day strength under ambient condition when slag material is added to the mix (Kumar et al. 2010; Li & Liu 2007; Manjunath & Giridhar 2011). The improvement in physical properties is related to the intrinsic structure developed due to enhanced geopolymerisation (Kumar & Kumar 2011;

Kumar et al. 2010). Curing at 60 ^{o} C for 24 hours produces very rapid strength gain which gives a compressive strength at one day ranging between 47 and 53 MPa (Yost et al. 2013). This feature makes geopolymer concrete suitable for precast applications.

Flexural and Tensile Strength

In addition to its higher compressive strength, GPC has higher tensile strength than that for OPC. As a result, it improves section capacity, delays the first crack appearance and decreases the percentage of reinforcement to be used. Olivia and Nikraz (2012) indicated that the tensile strength of GPC is about 8 to 12 % greater than that of OPC. Consequently, the flexural strength of related samples is 1.4 times higher than that of OPC. This behaviour is a result from enhancing the aluminosilicate network associated with the polymerisation process (Nuruddin et al. 2011). Other studies showed that the splitting tensile strength and flexural strength are functions of compressive strength and the ratios between them and compressive strength are comparable with conventional OPC (Hardjito et al. 2005). Bhikshma et al. (2012) explained that higher tensile strength of geopolymer concrete is related to its chemical composition. They observed that the tensile strength is varying from 3.72 MPa to 4.95 MPa for the alkaline liquid to fly ash ratio ranging from 0.3 to 0.5.

Shrinkage and Creep

In addition to the high strength, GPC has low shrinkage and creep properties. Pei-Wei et al. (2007) found 33% to 40% reduction in the shrinkage and expansion strain for GPC. Other researchers (Hardjito & Rangan 2005; Hardjito et al. 2004; Olivia & Nikraz 2012) observed that drying shrinkage strains are extremely small in the order of 100 micro strains after one year compared with the range of values of 500 to 800 micro strains experienced by OPC. In fact, this behaviour is caused by the lower amount of water used in producing GPC. On the other hand, geopolymer concrete has low creep. The value of creep deceases with the increase of compressive strength and it is estimated that GPC has not more than 0.4 compared with 0.7 for OPC (Hardjito & Rangan 2005; Hardjito et al. 2004; Wallah 2010). Since GPC is not affected by these factors, it has many advantages over OPC.

FIRE RESISTANCE

Since all the types of concrete are inflammable, exposing concrete to extreme heat creates a very hazardous situation. When concrete members are subjected to high temperature, they start spalling and this drastically reduces the capacity of those members. When compared with OPC, geopolymer concrete is considered as a fire resistant material. At early part of the curing cycle, high temperature improves the compressive strength of GPC (Satpute et al. 2012). Mane and Jadhav (2012) observed that even when exposed to high temperature of 500 ^{o}C , geopolymer specimen show less reduction (29%) in the capacity than that for OPC (36%). This reduction results from the differential thermal expansion between the aggregate and paste (Kong & Sanjayan 2010; Mane & Jadhav 2012). In general, GPC has a good fire resistance compared to OPC when exposed to more than 800 ^{o} C (Guerrieri & Sanjayan 2010; Kong & Sanjayan 2010; Rashad & Zeedan 2011; Zhao & Sanjayan 2011).

CHEMICAL RESISTANCE

Durability of reinforced concrete structures is an important factor affecting the lifetime of structures. The penetration of aggressive substances into the concrete will damage concrete and corrode reinforcement. GPC had been shown by many researches to have better resistance against aggressive environments. As a result, GPC can be used to build structures that are exposed to marine conditions (Reddy et al. 2011). Most of the previous researches were focused on three types of aggressive substance, sulphate, acid and chloride. Wallah and Rangan (2006) studied the effect of immersing low calcium fly ash GPC concrete in 5 % sodium sulphate solution under various time durations up to one year. They concluded that the specimens have an excellent resistance to sulphate attack. All specimens showed no change in the appearance compared to the condition before they were exposed. Furthermore, there was no sign of surface erosion, cracking or spalling on the specimens. In terms of acid resistance, GPC shows good performance compared with OPC. An experimental investigation for the performance of GPC immersed in sulphuric acid and magnesium sulphate, conducted by Sanni and Khadiranaikar (2012) showed that the mass loss of GPC specimens was about 3 % for 45 days exposure . On the other hand, the mass loss observed to be 20 to 25 % for 45 days of exposure for the OPC samples. Further to this behaviour, all specimens showed a decrease in mass loss up to 1% for OPC with negligible change for the case of GPC. In addition to its lower mass change, GPC showed less compressive strength loss with an average of 15 % compared with 25 % for OPC (Sanni & Khadiranaikar 2012).

BOND STRENGTH

Even though GPC has higher tensile strength compared with OPC, its structural performance still depends on the bonding between concrete and steel bars. Bonding strength between the reinforcement and surrounding concrete is an essential factor to examine the structural performance of the material. GPC shows higher bond strength to the reinforcement because of its higher tensile strength (Sarker 2010; Sarker 2011; Sofi et al. 2007). Due to the similarity of failure behaviour for GPC specimen compared with OPC, the existing design equations for the bond strength of OPC concrete with steel reinforcing bars can still be used (Sarker 2010; Sofi et al. 2007).

STRUCTURAL BEHAVIOUR OF GEOPOLYMER CONCRETE

Yost et al. (2013) conducted an experimental program on the structural performance of geopolymer concrete beams. They observed that the GPC beams perform similar to OPC beams of comparable strength and aggregate content. GPC beams failed in a more brittle manner than the OPC concrete beams. The researchers suggested that the same analysis and design procedure which established for OPC concrete beams can be used for the case of GPC beams to check the flexural and shear strength. The performance of GPC columns has been studied also to ensure that this material is capable to perform as a structural material in columns. Rahman et al. (2011) investigated the behaviour of GPC columns under combined axial load and biaxial bending using twelve reinforced concrete slender columns. They observed that the failure of the columns was identical to that of OPC under the same loading conditions.

ECONOMIC BENEFIT

Use of fly ash and slag which are a by-product of coal industry enhances economic benefits of GPC. This makes GPC cheaper than Portland cement in terms of the materials cost. Hardjito and Rangan (2005) found that, with negligible price of fly ash, the cost of producing 1 m^3 of GPC is approximately AUS $50 which is the silicate solution’s cost. However, GPC seems to be cheap and the difference between its price and Portland cement price is ranging from 10% to 30% depending on the transportation method. Transportation method plays an important role affecting the final price of GPC production which makes the cost ranging from 7% lower to 39% higher than OPC (McLellan et al. 2011). Furthermore, the usage of one ton fly ash will earn one carbon- credit which means a saving of 20$/ton of CO_2. In addition to the lower price of the production of GPC, its superior properties in shrinkage, creep, resistance to fire and chemical yield in excellent durability and long lifetime for the structure. As a result, fewer damages and less rehabilitation costs will be incurred, which is beneficial for the economic growth of a country.

LIMITATIONS OF GPC

For each developed technology, there are always several limitations over its acceptance. Main limitations related to the acceptance of GPC in the construction field are: the high cost of alkaline solution which depends on its alkalis content, the mixing method prior to use which takes 24 hours to prepare the alkaline solution, some health hazards due to the high alkalinity environment possess, and , the brittle behaviour of GPC (Aleem & Arumairaj 2012).

CONCLUSIONS

Geopolymer concrete has many superior properties compared with its counterpart OPC concrete. The chemical composition of GPC and the curing conditions play important roles in its mechanical properties. GPC is an environmentally friendly sustainable construction material which is becoming increasingly popular. For a particular compressive strength, GPC exhibits higher tensile strength compared to OPC concrete, which is suitable for structural applications. Higher bond strength is shown between reinforcement and GPC. It has excellent resistance to sulphate attack, fire and good resistance to acids. It has low creep and low drying shrinkage. At the moment, standards and codes for OPC concrete are being used in the design of GPC structural members. However, more attention should be paid to the structural design in regards to brittleness of GPC.

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