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Geopolymer Concrete for Sustainable Developments: Opportunities, Limitations, and Future Needs

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ABSTRACT

In the last two decades considerable interest has been generated in concrete manufactured with geopolymer cement; i.e., pozzolans combined with suitable alkaline activators. This is especially of interest in light of today's critical issues of sustainability and reduction of greenhouse gas emissions from portland cement-based industries. Concrete manufactured in this way is generally known as geopolymer concrete (GPC). The technology of geopolymerization is not new and is believed to have been used in the construction of the Pyramids at Giza, Egypt, (circa 2550 B.C.) and other ancient construction of the Mohenjo-daro, in Sindh, Pakistan, (circa 2600 BC). Significant claims for the reduction of carbon footprint of the GPC compared to conventional concrete are being made. This paper critically discusses opportunities, limitations, and future needs for the development in GPC for producing a sustainable concrete.

INTRODUCTION

Portland cement concrete is the key construction material for all the development activities across the world. The concrete industry is the single largest consumer of the natural resources i.e. rocks, sand, and water. Each one of the constituent material of concrete has some adverse effects on the environment (Mehta, 2001). The manufacturing of the main constituent of concrete i.e. Portland cement is responsible for emission of about 7% of the total global anthropogenic carbon dioxide gas that is the key greenhouse gas held responsible for the global warming and climate change (Hendriks et al, 2008; Naik, 2008). Compounded with the faster rates of depletion of materials needed for the manufacturing of Portland cement and good quality aggregates, concrete industries give rise to sustainability issues also. On the other hand, there are ample possibilities for recycling of suitable industrial by-product materials for their high-volume high-end utilization in the concrete industry (Kumar and Naik, 2010). In light of the above facts, wide-spread innovative researches are being carried out all over the Globe for the high-valued utilization of suitable industrial by-products for the high-volume or complete replacement of the Portland cement from the concrete. Geo-polymer concrete (GPC) is a recent attempt in this direction. Natural or/and artificial pozzolans when combined with suitable alkaline activators yields to geopolymer which is used for binding aggregates to produce concrete for a wide range of applications. Concrete manufactured in this way is popularly known as geopolymer concrete. In last a couple of decades, considerable interest have been generated in this concrete, particularly in light of today's burning issues i.e., sustainability and reduction of green house gas emissions from cement-based industries, responsible for global warming. The technology of geopolymerisation is not new and has been used in the construction of the Pyramids at Giza and other ancient civilizations structures (Davidovits, 1984; Barsoum et al, 2006).

GOEPOLYMER CONCRETE

Geopolymer concrete (GPC) proposed by Devidovits (1988 and 1994) is currently recognized as an innovative technology for the cement-based construction industry, where immense potential for its utilization in the manufacturing of sustainable concrete are being visualized. For GPC, portland cement is not used as a binding material. Therefore, the primary difference between GPC and conventional concrete is that of their binders. Instead of portland cement, industrial by-product materials rich in Silicon (Si) and Aluminum (Al) such as fly ash, rice-husk ash, silica fume, slag, and other similar materials are added to react with highly alkaline liquid (typically a combination of sodium silicate and sodium hydroxide solution) to produce binders (Davidovits, 1988, 1994; Gourley and Johnson, 2005). The polymerization reaction under highly alkaline conditions is substantially fast on silicon-aluminum minerals resulting in a three-dimensional polymeric chain and ring structure (Rangan, 2008). The use of this geopolymerization process in concrete-making could significantly reduce the CO_2 emission into the atmosphere caused by the cement industry (Gartner, 2004). A comparative study on CO_2 footprint between the conventional concrete and GPC has indicated a very low CO_2-footprint for GPC (Duxson et al, 2007). This technology further reduces or eliminates the need for large amounts of raw materials for the manufacture of portland cement and provides additional potential for recycling of Al and Si rich by-products materials.

The main constituent of today's GPC is the ASTM Class F fly ash (a by-product from coal-fired thermal plants) because of its availabilities in the most parts of the world. Such low-calcium fly ash, with Si and Al constituent of about 80% by mass and Si to Al ratio about two, are being used at experimental levels for making geopolymer concrete (Gourley and Johnson, 2005; Hardjito and Rangan, 2005; Wallah and Rangan, 2006; Sumajouw and Rangan, 2006) as the ultimate structure of geopolymer depends largely on the ratio of Si to Al. Geopolymer paste acts as binder. The geopolymerisation process occurs through alkaline solution. It starts when fly ash dissolves. Formation of geopolymer structure into molecular chains and networks from the solution is the second step of the process to create the hardened binder. Aggregates suitable for making conventional concrete are also suitable for the manufacturing of GPC. Similar to conventional concrete, coarse and fine aggregates constitute about 75-80% of the mass of GPC. A combination of sodium silicate and sodium hydroxide solution is commonly used as alkaline liquids to start the polymerization of the resource material. Figure 1 shows a typical geopolymer concrete made with ASTM Class F fly ash.

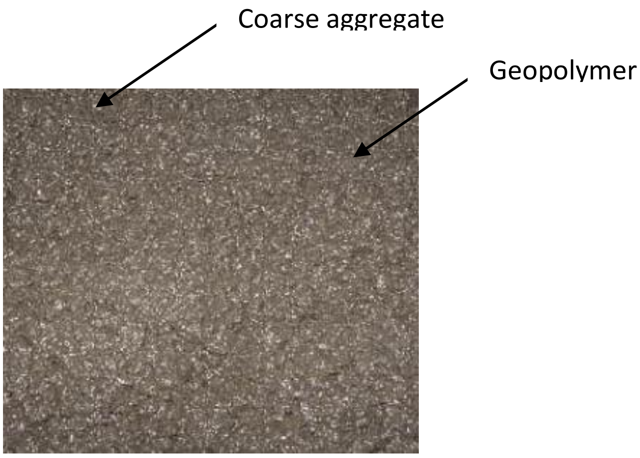

Figure 1. A typical low calcium fly ash based geopolymer concrete

Mass of water in the alkaline solutions is the major component of the water for the GPC mix. In order to increase the workability of the geopolymer concrete, a high-range water reducing agent and some extra water are added sometimes to the concrete mix. The compressive strength and workability of GPC are governed by constituent materials of the geopolymer mix. Similar to the water-to-cementitious materials ratio for conventional concrete, water-to-geopolymer solid ratio has been proposed (Hardjito and Rangan, 2005). Further, conventional procedures are adopted for the mixing, casting, and compaction of the geopolymer concrete. However, unlike the conventional concrete, for GPC heat curing either in the form of steam curing or dry curing is required for the low-calcium fly ash based GPC. Dry curing results in a higher compressive strength development that steam curing. Curing temperature also plays a vital role in the development of strength of the geopolymer concrete. In general, curing time and lowest temperature advocated are about 24 hours and 30 ^{o}C, respectively (Hardjito and Rangan, 2005). These pre-required conditions could be provided by ambient conditions of tropical regions. Curing temperature of GPC plays a major role in the development of its strength. The effect of curing temperature on compressive strength development of a fly ash based geopolymer concrete is shown in Figure 2. An increase in compressive strength of GPC with increase of curing temperature can clearly be seen in Figure 2. The test specimens (cylinders) of the mixtures were kept in an oven for 24 hours for drying curing while all other test variables were held constant. As evident a higher curing temperature resulted in higher compressive strength, although an increase in the curing temperature beyond 60 ^{0}C did not significantly increase the compressive strength.

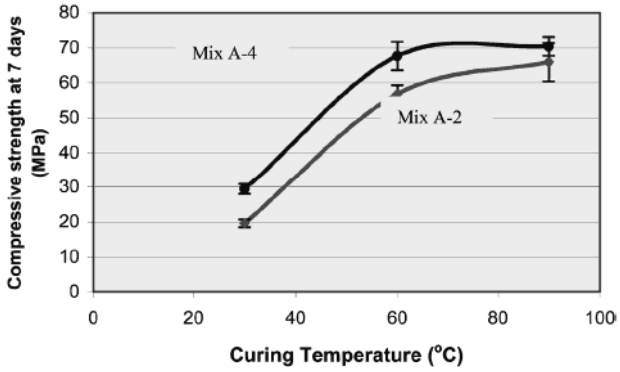

Figure 2. Effect of curing temperature on the strength development of geopolymer concrete mixes (Hardjito et al, 2004)

Concrete Mix A-2 contained 1294 kg of coarse aggregate, 554 kg of fine sand, 476 kg fly ash, 48 kg 8M NaOH solution, 120 kg of sodium silicate while Mix A-4 contained the same amount of materials except 120 kg of 14M NaOH to maintain the same ratio of sodium silicate to NaOH liquid.

Since GPC, does not require either portland cement, or water for curing, hence, it is claimed to be more eco-friendly and sustainable than conventional concrete. A typical low calcium fly ash based geopolymer concrete mixture proportions are given in Table 1.

Table 1. A Typical Low-calcium Fly Ash Based Geopolymer Concrete Mixture Proportions

Constituent Materials	Quantity (kg/m^3)
Coarse aggregates 20 mm 14 mm 7 mm	 277 370 647
Sand	554
ASTM Class F fly ash	408
Sodium silicate solution (Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass)	103
Sodium hydroxide solution (8 Molar), made by mixing 11 kg of sodium hydroxide solids with 97-98% purity in 30 kg of water	41
Super plasticizer	6

However, after considering the energy consumptions during processing of the high alkaline solutions and curing process, the claim for eco-friendliness and low carbon foot print of GPC are questionable.

Possible Opportunities for Applications of Fly Ash based GPC

The following important opportunities are being claimed in literature for fly ash based GPC.

- High-volumes recycling of fly ash in cement-based construction industry wherever available in abundant for the replacement of portland cement binder.
- Geopolymer concrete gives a glossy appearance hence gives a beautiful appearance if used in constructing floors and walls.
- Manufacturing of more durable concrete as there is absence of transition zone in GPC
- Strength remains almost independent of the age
- Very much suitable for new generation of precast concrete products such as RCC box culverts (Llyod and Rangan, 2010), sewer pipes, wall panels with or without synthetic fibre reinforcement with increased durability and reduced embodied carbon dioxide footprint.
- Manufacturing of precast segmental units (Figure 3) with high compressive and flexural strength, lower drying shrinkage, increased resistance to sulphate and acid attack and high resistance to chloride ingress.
- The ratio of compressive to tensile strength of fly ash based geopolymer concrete is very high unlike portland cement concrete indicating significant reduction in

brittleness of concrete. In other way, this concrete can withstand more tensile stress without requiring much reinforcing steel.

- Geopolymer concrete can be very suitable for the construction of underwater structures where early strength and rapid setting is required.

Figure 3: A typical view of precast unit

- For quick repair and rehabilitation of distressed civil infrastructures
- Lesser construction period as curing period is very shorter than conventional concrete
- Excellent surface finishing (Figure 4)

Figure 4: A finished surface of a GPC road (www.engineering.civil.com)

- GPC develops much higher ratio for tensile strength to compressive strength in comparison with conventional portland cement concrete resulting in enhanced resistance to cracking of concrete.
- To manufacture very durable, more heat resistance, higher abrasion resistant concrete products.

LIMITATIONS OF GPC TECHNOLOGY

Till today, the GPC technology is at the developmental stage due to several limitations over its acceptance. Some of the important limitations of GPC that need to be overcome before its wide acceptance in the field are as follows:

- Development of strengths and other keys properties of GPC are directly dependent on the purity of the resource materials. Maintaining homogeneity in the source materials such as fly ash etc and purity of alkaline materials obtained from different manufacturers for preparing activator solutions make the design of this concrete mix proportions difficult for its manufacture on a recipe.
- Requirement of heat curing either steam or dry for setting of GPC is another major limitation for its utilizations in similar ways to that of the conventional concrete.
- Cost of alkaline solution is high depending on the purity of its alkalies. Further, it is required to prepare the alkaline liquid by mixing both the solutions together at 24 hours prior to use.
- High alkalinity environment possess health hazards to the workers. Higher alkalinity of the materials requires more processing resulting in more energy consumption and hence generation of greenhouse gases.
- Unavailability of widely accepted specifications and guidelines.
- Production of GPC requires great care in contrast to portland cement concrete.

FUTURE RESEARCH NEEDS

From the literature, today's GPC appears to be well suited for precast concrete products due to better control on the needed curing process and availability of skilled manpower for its careful handling. For a wide scale acceptance of GPC in concrete industry much more studies and development are needed. First and foremost, GPC should be cured under ambient conditions without requiring heat curing. Secondly, it should be more user friendly i.e. capable of being mixed with a relatively lower alkaline solutions and require lass expertise in its design and handling during construction. Considerable research work is needed for the production of versatile, cost effective and low carbon footprint geopolymer cement that could be easily mixed and hardened. Corrosion aspect study of geopolymer concrete is lacking for its utilization in the construction of the reinforced structures.

SUMMARY

GPC technology is still mostly confined at laboratory levels. Geopolymers are synthetic aluminosilicate materials consisting of Al and Si tetrahedral linked by shared oxygen atoms. Depending on the composition of resource materials, geopolymer can have high early strengths, low shrinkage, good acid and fire resistance etc. The choice of the resource materials for making GPC depends on their availability, cost, and type of applications. Water-to-geopolymer solid ratio governs most of the properties of GPC. Dry or steam curing requirements has restricted its application to precast concrete products. To ensure its wide acceptability in the concrete industry, extensive research is needed to make this technology for manufacturing of concrete more cost effective, low embodied energy product and user friendly for practical uses like that of ordinary Portland cement concrete. Mare making porland cement free and reduced water requirement for manufacturing of GPC at one hand while heat requirement for curing and higher energy requirement for high processing of alkaline salts raise doubts about the claims for its lower carbon footprint.

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