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Geopolymer Concrete: A Building Material for the Future

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ABSTRACT:
The consumption of Ordinary Portland Cement (OPC) as construction material is one of the main sources of CO_2 emission and global warming.. The manufacturing process of 'clinker' which is an essential element of cement requires burning of fossil fuels, thus increasing the CO_2 emission and decreasing the global stock of fuels. Concept of a novel binding material named 'Geopolymer' appeared in the 1940s as a viable solution to these issues. Geopolymer concrete (GPC) is produced from industrial byproducts such as Fly Ash (FA) rich in aluminosilicate, Blast furnace slag (BFS) or natural minerals such as Kaolinite clay using alkalis as activators. In this paper, economical, social and ecological sustainability of GPC have been put forth. Comparison have been made between the behavior of low-calcium fly ash based GPC and metakaolin based GPC under different environmental conditions using alkali activators such as Sodium hydroxide (NaOH) or Potassium hydroxide (KOH) with Sodium silicate (Na_2SiO_3) . Evolution of GPC, hydration process as opposed to OPC, mechanical properties, structural behavior, alkali-silica resistance (ASR), fire and acid resistance behavior of GPC have also been discussed in this paper.

1 INTRODUCTION

Portland cement concrete is the most widely used construction material due to its versatility and energy efficiency next to steel and aluminium (Hardjito *et al.*, 2004).The contribution of OPC reported by Rangan et al. to greenhouse gas emissions is estimated to be 1.35 billion tons per annum or appx. 7% of the total greenhouse gas (GHG) emissions to the earth's atmosphere.

Although researchers are putting effort on calling the gases 'greenhouse gas', CO_2 is the primary greenhouse gas among others to be the most important waste product and has the most effect on the environment. Each year the concrete industry produce almost 12 (twelve) billion tons of concrete (Attwir and Kabir, 2010) globally and utilizes 1.65 billion tons of cement for that purpose. Production of 1 ton of cement requires 2.8 and 1.5 tons of raw materials including fuel reported on four different occasions (Björk, 1999 ; Reddy *et al.*, 2010 ; Anuar *et al.*, 2011 ; Guo *et al.*, 2010). So, it can be seen that cement production not only is emitting harmful greenhouse gas to the atmosphere but also is consuming precious natural fossil fuels. Alarming issue is that only one ton of cement production emits one ton of CO_2 to the earth's atmosphere (Hardjito et al., 2004 ; Reddy *et al.*, 2011) during the calcinations process of lime ($CaCO_3$) – the primary component of cement clinker. Global cement industry renders 1.65 billion tons of GHG every year (Ahmed *et al.*, 2011) on a 3% increment rate. Among the GHGs CO_2 is responsible for 65% of the total global warming. As of now, it can be seen that even a small reduction of greenhouse gas emissions per ton of manufactured concrete can make a significant impact (Flower and Sanjayan, 2007). Table1 shows the global production of cement and their trend.

2 EFFECT OF CO_2 AND GLOBAL WARMING

CO_2 is a natural element of earth's atmosphere which is essential for plant photosynthesis. CO_2 absorbs outgoing infrared radiation along with water vapor and other trace gases from the earth which keeps the surface temperature of our planet in a tolerable limit.

The pre-industrial level of CO_2 over the last 1000 years was about 280 ppm. By 2003, the level of CO_2 rose to around 370-380 ppm (Manahan, 2006). Furthermore, the global CO_2 level are increasing by

Table1: The global production of cement and their trend

	Cement production						Average annual growth rate	
	1970	1975	1980	1985	1990	1995	1970-1995	1990-1995
Region/Country	Tg	Tg	Tg	Tg	Tg	Tg	Tg	Tg
China	27	47	81	148	211	477	12.2%	17.7%
Europe	185	194	223	178	196	181	- 0.1%	1.7%
India	14	16	18	31	49	70	6.6%	7.3%
North America	76	73	79	81	81	88	0.5%	1.5%

about 1 ppm per year as a result of combustion of carbon containing fossil fuels (including cement manufacturing) and deforestation (Manahan, 2006). Increasing level of CO_2 is a concern now-a-days because it is leading to –an excess of a good thing, global atmosphere warming which is known as 'the greenhouse effect'. Although there is some advantage of mild global warming, the net effect is certainly dire. The projected trend of global warming will lead to melting of polar and Greenland ice caps, expansion of warmer ocean water and rise of water as much as 0.5-1.5 meters, decreased rainfall and increased water evaporation, severe drought and water shortage (Manahan, 2006).

3 HISTORY OF GEOPOLYMER CONCRETE

Geo-polymer concrete was introduced to reduce to amount of CO_2 emitted during the production of cement. Wallah (Wallah, 2010) indicated that the geopolymer technology could reduce the CO_2 emission into the atmosphere caused by cement and aggregates by 80%. It also indicated higher mechanical properties such as compressive strength, good acid resistance, low creep and low shrinkage. It was first noticed by purdon in 1940 that alkali solutions (Na, K), although harmful for concrete, speed up the process of hydration and as such facilitate the process of new hydration products. Prof. Glukhovskij from the then Soviet Union made an attempt to define the alkali activation of materials as amorphous three dimenstional aluminosilicate binders. Since 1973 extensive research have been taking place in the Institute of Glass and Ceramics Prague on alkali activation of materials. In between 1976-1978 French scientist Davidovits consigned a new term 'Geopolymer' for metakaolin based aluminosilicate binders in alkaline environments (Zhang *et al.*, 2005a).

Contrary to the Portland cement concrete hydration process, water does not play any pivotal role in the case of geopolymer concrete. Geopolymer concrete's binding capacity comes from the dissolution of Si-Al in alkaline environment whereas Portland cement produces calcium silicate hydrate gel which is responsible for strength. This difference results in different alkali-silica reactivity, water penetration or heat resistant from those of Portland concrete (Lloyd and Rangan, 2010).

4 USE OF GPC AS SUSTAINABLE MATERIAL

The prime factor for environmental regulation is zero waste in which all waste is recycled and no waste is left as landfill. Industrial waste products such as fly ash, blast furnace slag, bauxites, quarry wastes and clays are such materials which are mostly being used as landfills (Drechsler and Graham, 2005). This procedure is a grave concern for the environment. Although using mixture of fly ash as cement replacement in concrete industry is established, it does not take care of all the fly ash produced throughout the world. The next two figures clearly indicate the production and consumption trend of fly ash all over the world for the last forty years duration.

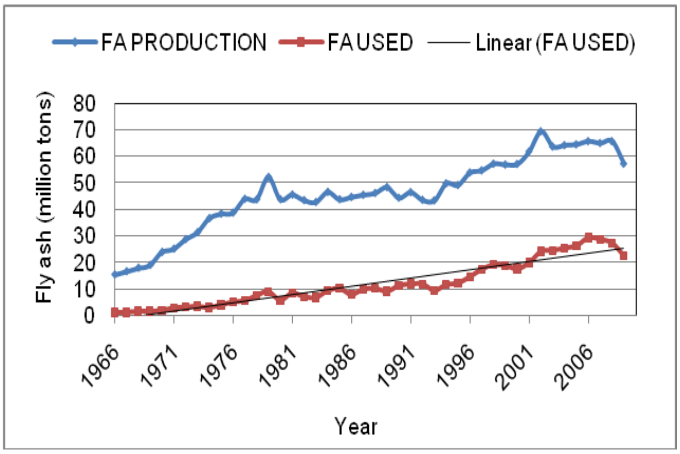

Figure 1: Comparison of Fly Ash production and consumption per year (Kelly *et al.*, 2010) by Kelly and Sullivan

It is evident from Figure 1 that production and consumption of fly ash has always been increasing throughout the decades. Although there were some spikes of increasing and decreasing in one sudden year, the general trend was quite linear. Figure1 shows that the production and utilization of fly ash increased almost thrice and ten times since 1966 although there is still almost 40 million tons of fly ash is left abundant and used as landfills. The 93.87% R^2 is also indicating that the consumption behavior of fly ash still remains fairly linear and will keep on increasing in this manner.

Due to alumino-silicate composition, high workability and low water demand fly ash has become material of choice in the construction industry off late. Geopolymer concrete uses mostly class F fly ash because high calcium content hinders the polymerization process of silica-aluminate and may alters the microstructure of geopolymer. Geopolymer concrete is able to utilize this waste material as future generation of binding material and has great potential for reducing the environmental impact borne by it (Drechsler and Graham, 2005).

Attempts have been made to create efficient and sustainable construction material by making durable concrete, using less cement in concrete, replacing cement with other cementitious materials such as, fly ash, ground granulated blast furnace slag, metakaolin, rice husk ash, condensed silica fume, using non limestone based cements such as magnesia based cements, geopolymer concretes and geopolymer-concrete-composites (Kayali *et al.*, 2008).

The manufacturing process of GPC requires low temperature (600-800^{o}C) (Zhang *et al.*, 2005b) in contrast with OPC where clinkering process is done at about 1400^{o}C temperature level. So, energy level can be restored from the very beginning of material development process of GPC. GPC based on industrial byproducts such as BFS, FA or natural minerals such as metakaolin renders some excellent durability properties such as fire resistance, acid resistance, water absorption, alkali silica reactivity and sulfate attack. BFS based GPC activated with KOH solution showed fire resistance up to 1100^{o}C They also reported that the resistance kept increasing with higher concentration of KOH. Hardjito et al. (Hardjito et al., 2004) showed that no significant change would occur after immersion of FA based GPC in 5% Na_2SO_4 solution even after two months. On the other hand Bakharev (Bakharev, 2005) showed that, FA based GPC activated with NaOH, when immersed under Na_2SO_4 or $MgSO_4$ solution, can show an increment of compressive strength in the range of 4-12%. Similar results have been obtained by Songpiriyakij. According to Sathia et al. (Sathia *et al.*, 2008), water absorption of FA based GPC decreases with increasing concentration of alkaline activators. Porosity increases with an addition of Silica fume (SF) in FA based GPC, thus water absorption also increases. Buchwald et al. (Buchwald *et al.*, 2005a) reported that immersion of metakaolin and fly ash based GPC in H_2SO_4 and HCl showed high loss in weight in the long term, thus showed poor resistance. But, Sathia et al. (2008) found good resistance showed by FA based GPC against 10% and 3% H_2SO_4 solutions respectively. According to Latella et al. (2008) metakaolin based GPC is also good to attain reasonable compressive strength and good at fire resistance (Latella *et al.*, 2008). Kong (Kong *et al.*, 2007) reported that with same SiO_2-M_2O ratio metakaolin based GPC showed higher moisture loss from than that of FA based GPC which means high drying shrinkage in the long term. The earlier results visibly shows that GPC is a good fire resistant, acidic environment impeller, low water absorber and can show excellent resilience against sulphate attack which all are indication of good sustainable material.

Creep and drying shrinkage are another two important time dependent property. Both of these significant properties are studied by Wallah (Wallah, 2009 ; Wallah, 2010) and mentioned by Zhang et al. Creep generally means strain of hardened concrete under sustained stress. However, normally creep is taken to be the increase in strain over elastic strain. Wallah showed in his paper (Wallah, 2010) that FA based GPC undergoes less creep compared to OPC. The presence of micro-aggregates due to the block polymerization presented in GPC gives the effect of increasing the aggregate content which actually is responsible for making GPC resilient to creep function, contrary to OPC.

Alkali activated cement, precursor of GPC, appears to have a significant role in waste management. Alkali aluminosilicate reactions creates a barrier surrounding the matrix and fix certain ions in the structures of the phases formed. Fly ash, a potential activator which is rich in alumina and silicate also is such a waste. Where alkaline wastes such as NaOH or KOH are not available, their salts can be mixed with earth hydroxides such as $Ca(OH)_2$ to generate alkali activators which are used in GPC hydration system. Recent research has also shown that the effective and hazardous waste management system is based upon the activation system of aluminosilicate with alkali solutions where components can be industrial by-products fly ash, metakaolin or slag (Roy, 1999).

Despite of having many literatures available on sustainability of GPC on the ground of technical aspect, the environmental and ecological aspects have been overlooked so far until Buchwald et al. (2005) (Buchwald *et al.*, 2005b) made an approach to address these criteria scientifically. They systematically evaluated various raw materials and had given certain values against each indicator of raw materials such as energetic resource indicator, toxic loading indicator, mineral recourse indicator and follow up cost indicator. Finally they compared within various raw materials such as fly ash, slag, metakaolin and clay using a special application named multi criteria decision analysis (MCDA). The general aspect for survey used in this method is "the closer the indicator value to 1, the better the material reached the environmental relevant demand". Based on this assumption, fly ash indicator received the lowest overall score for all the indicators combined unlike other materials. So, it can be concluded that fly ash based GPC is certainly a good alternative to OPC on this basis.

5 CONCLUSIONS

In this paper, attempt has been made to render detailed information on the history, production, development and sustainability regarding environment, cost and ecology of fly ash based geopolymer concrete (GPC) with a modest indication of metakaolin based and slag based geopolymer concrete. Much work has been done on this part of research so far, yet there remain many fields to restore. Detailed attention has been given to the development, microstructure and mechanical properties of fly ash based geopolymer concrete. Now, structural applications have to be more prominent. It is evident from earlier researches that GPC is certainly economically, ecologically and environmentally more viable choice than OPC based concrete. This is such a versatile material that tailoring can be done at any part of the process-from material development, to manufacturing to hardened state. It is time now, to step further and to try to make GPC as commercially acknowledged option because as superior as GPC to OPC is, there are no codes available for GPC unlike OPC based concrete which is well developed in ACI, ASTM, BS, Euro, German, Australian, Japanese and Indian codes. GPC, with its better mechanical properties, higher resilient behavior to aggressive environments, better utilization of waste products and more environmental friendly behavior, can be the concrete for the future world and become a friendly solution to GHG emission by concrete industry without increasing the green house effect further. This paper gives an insight of the status of geo-ploymer concrete as a substitution for normal weight concrete and its advantages and disadvantages.

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