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Geo-Polymer Binder as Portland Cement Alternative: Challenges, Current Developments and Future Prospects

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ABSTRACT

Ordinary Portland Cement (OPC), a material which built the world is now devastating it. Environmental impact has raised concerns over its continued usage while its multifaceted problems are also biting the production companies hard. Hence, alternative geopolymer binder has demonstrated excellent properties to stand ordinary Portland cement even though it is still being faced with technical drawbacks. Therefore, these paper reviews attempt made on improving discoveries and understanding about proper implementation of geopolymer binder. The geopolymer binder is curable at ambient temperature by the use of Fly Ash/Ground Granulated Blast Furnace Slag (GGBS) blend. This has been an alternative have been discovered for cheaper activating solutions rather than the expensive Sodium Hydroxide/Sodium Silicate solution. However, various of chemical composition known as Supplementary Cementitious Materials (SCMs) still an issues to fabricate a geopolymer binder.

Keywords: Geopolymer; Green Concrete; Ordinary Portland Cement

ABSTRAK

Simen Portland Biasa (OPC), sesuatu bahan yang biasa diguna dalam pembinaan-pembinaan konkrit sedang membinasa dunia ini. Isu-isu mengenai kemusnahan alam sekitar yang disebabkan oleh penggunaan simen ini secara berlebihan telah menimbulkan kebimbangan terhadap syarikat-syarikat simen. Oleh itu, satu alternatif perlu dicadangkan dan pengikat geopolimer telah menunjukkan ciri-ciri yang sesuai untuk menguatkan simen OPC walaupun ia masih menghadapi kelemahan teknikal. Kajian ini mengulas beberapa cabaran utama yang dihadapi, pencapaian-pencapaian terkini dan percubaan-percubaan yang telah dibuat untuk mencadangkan cara-cara bagi meningkatkan penemuan dan pemahaman berkenaan dengan penggunaan pengikat geoplimer yang betul. Dalam kajian ini, ia telah menunjukkan bahawa pengikat geopolimer boleh dirapikan dalam suhu ambien berbanding dengan perapian dalam suhu tinggi yang diperlukan sekiranya gabungan Fly Ash/GGBS diguna, dan larutan pengaktifan alternatif yang lebih murah berbanding dengan penggunaan Sodium Hidroksida/ larutan natrium silikat yang lebih mahal juga ditemui. Walau bagaimanapun, perubahan dalam komposisi kimia Bahan-bahan Bersimen Tambahan (SCMs) dan ketiadaan standard masih merupakan isu-isu utama dalam merealisasikan pengikat geopolimer sebagai alternatif simen Portland yang sempurna.

Kata kunci: Geopolimer; Konkrit Hijau; Simen Portland Biasa

INTRODUCTION

The increasing demand for Ordinary Portland Cement (OPC) all around the world has been linked to the rise in the development of concrete structures. Unfortunately, this is witnessed at a time when several control measures are being intensified by both local and international bodies to reduce the global temperature rise resulting from climate change actions. Concurrently with this, the raw materials and fossil fuels required for the production of OPC are getting depleted from their reserves.

Ordinary Portland cement production is said to involve high emission of CO_2 which for every ton of OPC produced, an approximate equivalent amount of CO_2 is emitted into the atmosphere which in total constitutes about 6% of all man-made carbon emissions in the world (Imbabi et al. 2012). This was reported to be about 2.157 billion tonnes of CO_2 in 2015 (CO2 Earth 2018). Similarly, data from the International Panel on Climate Change (IPCC), shows that since 1970, CO_2 emissions have continued to rise up to about 90% and projected it to hit about 41billion tonnes (that is if measures are adhered to) in the year 2020 against the current 35.948billion tonnes annual generation (USEPA 2016). Similarly, in developing countries, 10% of energy is consumed by cement producing industries where the United States (US) have already experienced a growth in the demand for OPC of about 7.4 million metric tonnes in 2017 alone. This was said to be increasing at a rate of 30% per decade as of 2016 (Nazari & Sanjayan 2017). Should the world then continue to produce OPC, our future climate is then probably in danger if its production is not reduced, or possibly stopped.

This is thus detrimental and requires immediate alternative to save the world. In view of this, researchers have been set on the balance in choosing the most suitable alternative to OPC with most economical and eco-friendly properties. Geopolymer has demonstrated good properties to stand OPC even though there are some technical drawbacks it is facing regarding its practical application (Djwantoro & Rangan 2005). Geopolymer binder is obtained when industrial by-products such as Fly-Ash, Ground Granulated Blast Furnace Glass (GGBS), Silica Fume, Rice Husk Ash or thermally activated natural materials like Metakaolin are dissolved in an alkaline activating solution in the presence of moisture. Millions of tons of these materials have been reported by Nazari and Sanjayan (2017) to be produced annually in the world where only about 50% of them are fully utilized. In the production of a geopolymer, it does not involve the long production chain of Portland cement in crushing, burning, clinker cooling etc. but rather utilizes the waste from industries which have pozzolanic properties. (Duxson et al. 2007).

Considering this efficiency proven low cost binder material, researches have been intensified on developing a standardized geopolymer binder and several discoveries have been made. This report thereby intends to highlight some of the challenges as well as the progress so far observed alongside the prospects reserved in geopolymer binder as a total replacement for Ordinary Portland Cement. These are discussed in the subsequent section of this report.

MAJOR CHALLENGES WITH GEOPOLYMER BINDER

Despite the good durability and mechanical properties demonstrated by geopolymer binder from laboratory tests, its applicability has since become an issue due to some reasons. Part of these challenges have been investigated and resolved, some are under research while some are still yet to record a success. To mention a few, they include:

1. The application of high temperature curing to geopolymer based concretes to be able to attain its full strength.
2. Variations in the chemical compositions of the base Supplementary Cementitious Materials (SCMs) to be used in the preparation of the geopolymer.
3. High cost of alkaline solutions.
4. Non-availability of Standards and long term data as geopolymer is a developing innovation and still under research.

Other related issues

1. Development of admixtures to retain both fresh and hardened properties of geopolymer concretes such as super plasticizers are not yet available. The available ones are mainly for PCC which are practically not suitable for geopolymers.
2. Field data on green concrete applications are limited. Field applications of green concrete in various structural forms are required alongside standardization to encourage to generate long-term data and guide their applications.

HIGH HEAT CURING REQUIRED BY GEOPOLYMER CONCRETE

Unlike ordinary Portland cement, geopolymer concrete builds over 70% of its compressive strength between 48 hrs-72 hrs when cured at high temperature of up to 85°C where the strength was observed not to significantly increase after wards (Singh et al. 2015). In relation to this, Heah et al. (2011) in his study which investigated the effect of curing temperature on metakaolin based geopolymer concretes concluded that curing at ambient temperatures is not adequate as the strength was found to be increasing as the temperature of curing was increased, he however added that curing at high temperature for longer period of more than three days affects the long term durability of the concrete. While Kusbiantoro et al. (2012) found oven curing to yield the best strength in his study when 7% of fly ash was replaced by rice husk ash, Kumar et al. (2016) in his conclusion on the applications of geopolymer concrete noted too, that the outcome properties of a geopolymer concrete is adversely affected by its curing time and curing temperature and need to be carefully taken care of. With regard to the durability, Venkateswara et al. (2017) studied the acid resistance of Fly ash based geopolymer concrete without replacement with any material (100%), alongside Fly ash – Ground Granulated Blast Furnace Slag (GGBS) based geopolymer concrete with composition of 80% and 20% respectively. They cured 100% Fly ash samples at 60^{o}C heat for 48hrs and its counterpart at ambient temperature. Both samples were subjected to sulphuric and nitric acid solutions with concentration of 2% and 10% respectively for a period of 6 (six) months. They were tested for weight loss, compressive strength loss and the depth of penetration of acid into the sample. The result showed that 100% Fly ash samples cured using heat regime exhibited better resistance to weight loss when compared to the 80% Fly Ash – 20% GGBS samples cured at ambient temperature. However, in the long term, compressive strength and depth of acid penetration were better in the ambient cured samples. Taking these problems into consideration this problem, it will seem impractical or rather uneconomical at the field to cure a concrete at high temperatures as these.

DEVELOPMENTS ON HEAT CURING

On this note, efforts have been put on by researchers to resolve this issue and attempts have been made to proffer solutions. It has been reported that with the use of Fly Ash (FA) being partially replaced with Ground Granulated Blast Furnace Slag (GGBS), geopolymer concrete can be cured gradually at ambient temperature without the use of heat while still maintaining its good performance. In a study conducted by Luhar (2014), it confirmed that a compressive strength of 55Mpa was attained at 28 days when GPC was cured at room temperature with 30% replacement of fly ash with GGBS. Similarly, Adak et al. (2015) added 6% of nano-silica to fly ash based geopolymer concrete and cured it without heat application. They found that the compressive strength and water absorption is relatively comparable to that of normal fly ash based geopolymer concrete cured with heat.

In another experimental study on replacing fly ash with GGBS by Pithadiya and Nakum (2015), it was revealed that the strength of geopolymer concrete increased progressively while it is cured at ambient temperature. This was updated by Katti (2016) when they investigated geopolymer concrete using fly ash and GGBS and discovered that using 6M (Molar) of Alkaline Activating Solution (AAS), 50% fly ash with 80% GGBS gave the highest strength in 7-days while being cured at ambient temperature. And most recently, Hashim (2018) in his research developed a high strength geopolymer concrete using silica fume based activating solution which is believed to save more cost when compared to the popular NaOH/Na_2SiO_3 solution. His geopolymer concrete sample was a mix in which fly ash replaced by GGBS and cured at ambient temperature. At 20% replacement of fly by GGBS, he obtained a compressive strength of 57.1MPa at 28days, a value higher than when fly ash was used alone (100%).

VARIATIONS IN CHEMICAL COMPOSITIONS OF ALUMINOSILICATE MATERIALS

To understand geopolymer and be able to associate the properties of its mixes, a good information on the aluminosilicates sources is vital (Jansen and Christiansen 2015). Supplementary Cementitious Materials (SCMs) such as Fly Ash, GGBS, Silica Fume, Rice Husk Ash etc. used in geopolymer concrete production are obtained as waste by-products from industrial or agricultural processes or as natural minerals. However, the individual chemical composition of these by-products vary from site to site which is always a reflection of the composition of the base material as well as the processing technique used in obtaining the by-product. Particularly fly ash, its chemical property is dependent on the amount of impurities in the parent coal and also the temperature at which the coal is fired. So this will vary from one plant to another. At the same time, when waste glass is used, their chemical composition would also be different based on the processing condition and type of glass source. These factors have consequently been reported to affect the microstructure and behaviour of the geopolymer concrete both in fresh and hardened state. As a result of these inconsistencies, in a bid to obtaining a good performance geopolymer concrete which could outstand the Portland Cement Concrete (PCC), the mix of every geopolymer concrete is then designed based on the governing properties of the base aluminosilicate material because the proportions of the activating solution, water/solids ratio are consequently duly affected.

But then, it is important just as Nazari and Sanjayan (2017) stressed for a good knowledge and understanding of the variations in geopolymer precursor so as to be able to envisage the best binder proportions and optimum performance of a geopolymer concrete. This is an issue which is still being investigated and as long as there exist uncertainties, perhaps no standardized provision for manufacturing and deployment of each of these aluminosilicates, geopolymer concrete technology will remain a lingering issue as it will be difficult for a general adoption.

TABLE 1. Energy Dispersive X-Ray (EDX) results showing variations in chemical composition of Fly Ash obtained from two different sources in Malaysia (Lafarge and YTL)

Chemical Compound	Composition	
	LAFARGE	YTL
SiO_2	58.72	31.39
Al_2O_3	28.25	16.13
Fe_2O_3	4.84	25.23
CaO	2.71	17.64
Na_2O	3.76	-
K_2O	0.96	1.64
MgO	-	5.58
$SiO_2 + Al_2O_3 + Fe_2O_3$	91.81	72.75
SO_3	0.76	2.39
S	-	-
Total	100	100

DEVELOPMENTS ON VARIATION IN CHEMICAL COMPOSITION OF SCMS

The issue of variations in chemical composition in SCMs is still a challenge in the application of geopolymer concrete. However, there have been some proposals from researchers in regard to overcoming the drawback. Liew et al. (2017) suggested the adoption of the simplex-centroid design method proposed by Wang and Chen (1997) for ordinary Portland cement to easily obtain individual proportions of binary or ternary blends SCMs and even use that to predict target compressive strengths. Several authors have attempted to characterize potential SCMs using the expensive Magic Angle Spinning Nuclear Magnetic Resonance (MAS-NMR) and Electron Energy Loss Spectroscopy (EELS) whose results revealed information on their micro compositions, but it is believed that the use of a more cheaper characterization method of SCMs needs to be used as compared to the expensive MAS-NMR and EELS so as to reduce the cost of producing GPC especially in developing nations where the cost of research is not affordable. In this regard, Liew et al. (2017) recommends the use of analytical and numerical modelling such as ANN (Artificial Neural Networks) in complement with experimental procedures to broadly comprehend, evaluate and forecast the response of geopolymer concrete.

However, the Zeo-bond group in Australia was reported to have proposed a geopolymer binder in a form of a dry cement which are processed at the same time with the activator to give a powder like binder just like Portland cement (Deventer et al. 2012; Nazari & Sanjayan 2017). This is however in small laboratory quantities as large proportions linked with chemical composition variation of source materials might result in differences which would affect the general performance of the geopolymer concrete (GPC).

This literally suggests that a generalized characterization technique needs to be found which would help in determining geopolymer constituents and optimum performance of GPC irrespective of the source.

HIGH COST OF ALKALINE ACTIVATING SOLUTIONS (AAS)

Previous cost evaluations in the production of geopolymer binder has revealed that the highest cost factor is the activating solution (Nazari & Sanjayan 2017). Affordable alkaline activating solutions (AAS) are paramount in describing the cost effectiveness of GPC as this would improve its versatility and wide acceptance of the yet-to-be field applied geopolymer binder. This therefore requires the development of either alternatives to AAS or derive a means to reduce the quantity of AAS used in geopolymer production. Whichever of these steps taken, emissions of Greenhouse gas (GHG) should also be considered in their manufacture. It was noted by Nazari and Sanjayan (2017) in his research that the production of sodium hydroxide and sodium silicate was a major contributing factor to the carbon footprint as well as to cost. The cost of geopolymer binders is grossly affected by the cost of the alkaline activating solution. In a study by Abdollahnejad et al. (2015), it showed that at least, the production of 1m^3 of fly ash based geopolymer concrete activated with Sodium Hydroxide and Sodium silicate (NaOH and $NaSiO_3$) solution costs about 300Euros/m^3.

There was also conducted in India by Thaarrini et al. (2016) on the production of geopolymer concretes activated with sodium hydroxide and sodium silicate solution in comparison to conventional concretes. The production cost covered the cost of materials labour and other surcharges. Prices of items were recorded based on bulk purchases in the Indian market. However, some raw materials were considered free where obtained free in the cost analysis. They found that for a 30MPa GPC and OPC concrete, the cost of producing 1m3 of GPC is higher than its OPC counterpart with about 1.7% even though a higher grade of 50MPa showed OPC to be more cost effective. Similarly, Dange and Suryawanshi (2017) in Pune city of India reported a huge cost difference between geopolymer concrete and OPC concrete. Their study concluded that the cost of producing 1m3 of GPC in Pune, India 34% higher than what is needed to produce OPC concrete of the same grade of 40MPa. In addition, Bozkurt and İslamoğlu (2013) compared the cost of cement concrete pipes and polymer based concretes pipes used in sewers in Turkey where all costs of materials were considered based on their unit prices and reported that the cost of the polymer based concrete pipes is 120% higher than that of cement based concrete pipe. However, when this cost was summed and analysed on annual basis, it was found to go lower than the cost of producing a polymer based concrete by 2.5%.

RECENT DEVELOPMENT ON ALTERNATIVES TO ALKALINE ACTIVATING SOLUTION

Considering the high cost of (NaOH and $NaSiO_3$), Puertas et al., (2014) conducted a study to investigate the possibility of dissolving waste glass in NaOH/Na_2CO_3 to produce activator like waterglass solution to use as an alkaline activator in geopolymer binders. They further concluded after experimenting on GGBS that the solution obtained from the treatment could act as an alkaline activator. In contrast to this, Mellado et al., (2015) in his research which studied the carbon footprint of geopolymer mortars used waterglass as the alkaline activating solutions and reported that waterglass is the highest fraction of geopolymer which contributes to CO_2 emission. However, they suggested an alternative which is the refluxing of rice husk ash (RHA) in NaOH solution. A method which retained the mechanical properties of the geopolymer mortar with a 50% reduction in the amount of CO2 emitted as compared to the normal water-glass solution.

Several efforts have been made to discovering an alternative activating solution which have yielded options like aluminogermanate, phosphoric acid and boroaluminosilicates. Amongst these, Nazari & Sanjayan (2017) investigated the use of boroaluminosilicate (also called borax) and found that it is also suitable as an activating solution without compromising the strength of the GPC. They suggested that there are potentials of utilizing waste feedstock also as alkaline activators, but so far, there is no any experimental investigation into that yet.

Hashim (2018) was able to use silica-fume as an activating solution and results from the experiment revealed the demonstration of good fresh and hardened properties. Jamieson et al. (2017) has formulated the use of concentrated bayer liquor of caustic alumina as activating solutions and concluded by recommending it as an alternative to the expensive solution of NaOH/Na_2SiO_3.

NON-AVAILABILITY OF STANDARDS

In spite of the diverse researches that have been conducted in regard of geopolymer concrete, lack of regulating standard in its respect still needs to be addressed. This should be, with immediate attention, be created by a global committee (Nuruddin et al. 2016). As earlier discussed, the peculiar chemical compositions of SCMs have reflected on the delayed creation of standards in relation to geopolymer concrete production and are believed to validate Jensen's statement which says that "Prescriptive regulations and standards have also delayed geopolymer technology from gaining acceptance within the concrete industry

In a survey conducted in Australia by Heidrich et al. (2015) on barriers that are retarding the wide acceptance of geopolymer concrete, more than 60% of respondents believe that the key obstacle is the absence of standard where the second is the absence of long term durability record.

This has been a major drawback and sadly, up to this moment, all over the world, there is still no standard available for geopolymer binders or geopolymer concrete production. In the bid to support the embracement of geopolymer as a whole, applicable standards need to be set up as a matter of urgency with an inter-organizational synergy of effort from the construction industry.

PROSPECTS OF GEOPOLYMER BINDERS

While ordinary Portland cement (OPC) has faced several criticism about its continued production, the geopolymer technology has expressed satisfactory performance promises. Notwithstanding, there is great optimism that all the unresolved issues earlier discussed will be solved in the shortest possible time soon. There is a great expectation on geopolymer technology as regarding its application in the construction industry, but in a broader note, it is even beyond just the construction industry for the following reasons:

1. Geopolymer binder production has competitively low CO_2 emission footprint as compared to Ordinary Portland Cement. As reported that the concentration of climate forcing substances in the atmosphere has already exceeded the safe level, and if the global temperature is not kept below 2°C, there is much danger posed to water supply, human habitability, sea-level rise, agricultural productivity etc.; so CO_2 being a contributor of more than 60% if controlled from Portland cement manufacturing would assist in reducing global temperature.
2. As a process which utilizes waste materials from industries, environmental problems associated which such waste would be reduced.
3. Results from researches conducted on various aluminosilicate materials have revealed that geopolymer concrete has a very high resistance to fire and acid by over 50% as compared Portland cement concrete (PCC). The adoption of geopolymer would thus cut the cost of construction having lesser production cost with higher performance when compared to PCC.
4. When improved, this would not only benefit the concrete users but also the ceramic tiles and bricks manufacturers.

A notable breakthrough is a 175MPa Ultra High Performance Geopolymer Concrete developed by Ps et al. (2014). As a whole, geopolymer concretes reserves enormous civil engineering application with outstanding performance but only needs more investigations in exploring these values.

CONCLUSIONS

This report briefly discussed geopolymer binder as a suitable alternative to ordinary Portland cement for the construction industries. Reviews have been attempted pertaining to the challenges and breakthroughs that have been attained in the development of geopolymer binder. Based on these developments, geopolymer binder has demonstrated good performance in laboratory tests as compared to ordinary Portland cement binder but still requires more investigation for better understanding of its behaviour which will allow for its practical application. Thus, the following conclusions are reached:

1. Fly ash blended with GGBS based geopolymer have shown excellent performance (compared to other SCMs) based on laboratory investigations where this could also allow for ambient temperature curing.
2. Silica fume, boroaluminosilicate and refluxing of RHA in NaOH solution have been found to be good alternatives to the expensive $NaOH/Na_2SiO_3$ solution.
3. All efforts should not be directed towards getting an alternative to completely replace OPC, but rather researches should also be facilitated in obtaining new models for the production of Portland cement which would be based on low CO_2 emission, cost and energy minimization.
4. There should be collaboration between inter-disciplines especially from the geopolymer chemistry experts and stakeholders in the concrete sector to accelerate researches relating to geopolymer binders.
5. An in-depth understanding of the chemistry of geopolymer gel is very crucial because only with this that geopolymer additives could be produced. This factor is one of the key interests of contractors as it got to do with setting time, durability and workability of the geopolymer concrete.

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