EFFECTS OF PALM OIL FUEL ASH AND METAKAOLIN BLEND ON PROPERTIES OF GEOPOLYMER MORTAR

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This thesis is dedicated to

My beloved wife, Khadijah Toyin Yusuf and lovely children Aishah, Abdulhamid, Ibrahim and Yusra for their uncommon perseverance buoyed by sublime love

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ABSTRACT

Geopolymer, an inorganic polymeric binder material synthesized from materials containing alumina and silica compounds, has evolved to become an alternative to Portland cement. The drawbacks of using Portland cement are its carbon dioxide emission, high energy consumption during production, and inadequate durability performance of its concrete. The valorization of wastes such as fly ash and blast furnace slag is an important feature of geopolymer that in a broad sense contributes to its environmental friendliness. In the same manner, palm oil fuel ash (POFA) waste generated from industrial production of palm oil for construction purposes is also beneficial and contributes towards a more sustainable environment since it aids in the disposal of waste and leads to economic gains. POFA has been successfully developed as supplementary material for Portland cement. Its emerging use in geopolymer production is made possible by blending it with alumina rich material like Metakaolin, which addresses its deficient alumina content. The maximization of POFA and the minimization of metakaolin use in geopolymer preparation underscore the need to study the behavior of high volume POFA blends with metakaolin geopolymers with specific objectives of determining the effect of high volume blend on the strength, durability performance and microstructure characteristics. The ratio of blends studied range from 0:100 to 80:20 POFA: Metakaolin. The geopolymer specimens were prepared with sodium hydroxide and sodium silicate and were cured in both ambient and oven conditions. The analysis of formulations revealed the extent of influence of the synthesis factors on the geopolymer. The evaluation of strength and durability properties of geopolymer specimens was accomplished with mortar for various mixes at varying ages. High volume POFA was found to improve the strength and durability properties as well the microstructure characteristics, which were mainly due to the participation of Si-O-Si and Si-O-Al bonds in the reaction products. Test results show that all mixes developed appreciable mechanical strength under the studied curing conditions. The aspects of durability studied are permeability properties, resistance to acid, resistance to sulfate, and effects of elevated temperature. The test results showed that the geopolymer specimen was highly resistant to water penetration and aggressive conditions. Microstructure tests in the form of FESEM, XRD, EDX, FTIR and TGA were performed on selected specimens to study the interactions of the geopolymerization products. It is therefore concluded that geopolymer mortar produced with up to 80% POFA could give adequate strength and durability properties.

ABSTRAK

Geopolimer merupakan bahan pengikat bukan organik yang disintesis daripada bahan yang mengandungi sebatian alumina dan silika. Ia telah pun berkembang sehingga menjadi alternatif kepada simen Portland. Pemprosesan simen Portland amat bermasalah dan melibatkan pelepasan karbon dioksida, penggunaan sumber tenaga yang tinggi serta konkrit yang dihasilkan mempunyai ketahanlasakan yang lemah. Pemantapan harga sisa industri seperti abu terbang dan sanga relau bagas merupakan ciri geopolimer penting yang menyumbang kepada sifatnya yang mesra alam. Persekitaran lestari juga dapat diwujudkan apabila sisa abu minyak kelapa sawit (POFA) digunakan sebagai bahan binaan kerana proses ini membantu pelupusan sisa di samping boleh meningkatkan kegiatan ekonomi. Selain itu, POFA telahpun berjaya digunakan sebagai bahan tambahan untuk simen Portland. POFA yang dahulunya kekurangan kandungan alumina, kini boleh digunakan untuk menghasilkan geopolimer apabila ia dicampur dengan bahan yang tinggi kandungan aluminanya seperti Metakaolin. Penggunaan POFA secara maksima dan Metakaolin secara minima di dalam kajian ini mendorong kepada objektif kajian iaitu mengkaji keberkesanan campuran jumlah POFA yang tinggi dengan geopolimer Metakaolin terhadap kekuatan, ketahanlasakan dan ciri-ciri mikrostrukturnya. Nisbah campuran POFA:Metakaolin yang dikaji ialah di antara 0:100 hingga 80:20. Spesimen geopolimer ini disedia menggunakan natrium hidroksida dan natrium silikat dan ianya diawet di dalam oven dan persekitaran ambien. Analisis kajian campuran menunjukkan sejauh mana faktor sintesis mempengaruhi geopolimer. Penilaian kekuatan dan ketahanlasakan spesimen geopolimer dijalankan dengan menggunakan pelbagai campuran mortar pada peringkat umur berbeza-beza. Jumlah POFA yang tinggi meningkatkan ciri-ciri kekuatan dan ketahanlasakan mikrostrukturnya disebabkan oleh ikatan Si-O-Si and Si-O-Al dalam hasil tindak balas. Keputusan kajian turut menunjukkan semua nisbah campuran menjadi lebih kuat dari segi mekanikal untuk semua keadaan pengawetan yang dikaji. Aspek ketahanlasakan yang dikaji ialah ciri-ciri kebolehtelapan, rintangan terhadap asid, rintangan terhadap sulfat, dan kesan daripada peningkatan suhu. Keputusan kajian menunjukan spesimen geopolimer mempunyai rintangan tinggi terhadap ujian penyusupan air dan persekitaran yang agresif. Ujian mikrostruktur seperti FESEM, EDX, FTIR dan TGA dijalankan bagi mengkaji proses interaksi ‘geopolimerization’ di dalam produk. Kesimpulannya, geopolimer mortar yang menggunakan POFA sehingga 80% boleh menghasilkan kekuatan dan ketahanlasakan yang memadai.

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LIST OF SYMBOLS AND ABBREVIATIONS

Al_2O_3	-	Aluminium Oxide
ANFIS	-	Adaptive Neural Fuzzy inference system
ANOVA	-	Analysis of Variance
BET	-	Brunauer and Edward Teller method
CI	-	Confidence Interval
CO_2	-	Carbon Dioxide
DF	-	Degree of Freedom
DTA	-	Differential Thermal Analysis
EDX	-	Energy-dispersive X-ray spectroscopy
F^{cv}	-	Critical F Distribution
f'_c	-	Characteristic compressive strength
f_{cm}	-	Mean cylinder Strength
$f_{ct.sp}$	-	Characteristic Splitting Tensile Strength
f_{st}	-	Tensile Strength
HCl	-	Hydrochloric acid
H_2O	-	Water
IUPAC	-	International Union of Physical and Applied Chemistry
Ln	-	Natural logarithm
LSD	-	Least significant Difference
MIP	-	Mercury Intrusion Porosimetry
MK	-	Metakaolin
mm	-	Millimetre
MPa	-	Mega Pascal
MSE	-	Mean Square Error
MSTR	-	Mean square Treatment

Na_2O	-	Sodium Oxide
Na_2O(ss)	-	Sodium Oxide in Sodium silicate
Na_2SiO_3	-	Sodium silicate
Na_2SO_4	-	Sodium Sulfate
NaOH	-	Sodium Hydroxide
OPC	-	Ordinary Portland cement
P_f	-	Probability of failure
POFA	-	Palm Oil fuel Ash
PVC	-	Polyvinyl Chloride
Sdt Dev.	-	Standard Deviation
SiO_2	-	Silicon Dioxide
TGA	-	Thermo gravimetric Analysis
XRF	-	X-ray Fluorescence
Σ	-	Stress

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The entrenchment of sustainable environment has become very important in order to preserve valued environmental conditions as well as available resources. As part of measures toward fostering sustainability; the reduction in emissions of greenhouse gasses, the depletion of fossil fuel and waste generation and disposal has become critical issues for consideration. The construction industry through its activities has strong impact on the environment. Although these impacts are both positive and negative, the latter gives an underlying motive for the concern to seek mitigations for environmental problems.

Portland cement as a binder is a key material use for construction purposes. The production of Portland cement, however, is characterized by high energy consumption and emission of greenhouse gasses which is almost equivalent to the weight of cement produced in tons (0.9 ton/ton of cement) (Komnitsas, 2011, Gartner, 2004). The role of Portland cement production in carbon dioxide emission to the atmosphere and its high energy consumption have therefore accelerated the search for alternative cementing materials (Juenger *et al.*, 2011; Lawrence, 2003; Schneider *et al.*, 2011; Winnefeld *et al.*, 2010). Furthermore, the search for alternative cement is also motivated by the shortcomings of Portland cement in some situations, for instance, where structures are prone to harsh environments with high acidity leading to deterioration or where Portland cement cannot meet the need for rapid repair applications (Juenger, *et al.*, 2011).

Geopolymer cement, which is an activated aluminosilicate based material has evolved as an alternative cement with comparable minimal carbon dioxide emission footprint and energy consumption requirement (Kong, 2007; Rees *et al.*, 2008; Rovnaník, 2010; Villa *et al.*, 2010). Geopolymer cement has superior mechanical strength, chemical and heat resistance, low thermal conductivity and low shrinkage in comparison to Portland cement (Kong, 2007; Lee *et al.*, 2010). These properties of geopolymer have made it to become a formidable alternative to Portland cement. However, the evolution of geopolymer is still on-going and one of the main tasks needing attention is how to entrench its application in construction. The role of materials use for its preparation is very critical to the full scale application for construction. Being a relatively new material, researches are on-going to establish the application of geopolymer in construction.

1.2 Background of the Problem

Geopolymer requires materials containing appropriate proportions of silica and alumina that react with alkali (potassium and/ or sodium hydroxide) and polymerize to form 3-dimensional alkali aluminosilicate gel binding aggregates. The starting materials containing alumina and silica are mainly metakaolin (Davidovits, 1991a; Xu and Van Deventer, 2000), fly ash (Chindaprasirt *et al.*, 2007b) and blast furnace slag (Cheng and Chiu, 2003; Li and Liu, 2007). Several pioneer researchers have utilized these materials for geopolymer production (Chindaprasirt, *et al.*, 2007b; Davidovits, 1991a; Duxson *et al.*, 2007b; Elimbi *et al.*, 2011; He *et al.*, 2012; Pacheco-Torgal *et al.*, 2008a, 2008b; Xu and Van Deventer, 2000).

1.2.1 Advantages of metakaolin

Metakaolin is a mineral based material produced by dehydroxylation of kaolin while fly ash and blast furnace slags are industrial by-products. Being a natural mineral product, metakaolin is homogeneous in composition, making it more predictable than the waste based products (Pacheco-Torgal, *et al.*, 2008a; Pavel, 2010). There exists wide variability in composition of waste based aluminosilicate materials which, for instance, depends on the source of the parent material, processing methods and handling. Among the geopolymer starting material, metakaolin has about the highest alumina content, a very important constituent for geopolymer synthesis. This is responsible for its reactivity. These facts coupled with the vast availability of its source material (kaolin) explain the reason for it utilization for geopolymer production (Xu and Van Deventer 2002). The high reactivity of metakaolin due to its high alumina content makes it more suitable for upgrading aluminosilicates materials with low alumina content.

1.2.2 Problems of Metakaolin utilization in Geopolymer Preparation

However, metakaolin utilization in geopolymer production is faced with some problems. Metakaolin based geopolymer has a higher environmental impact compared to geopolymer made from industrial by-products (fly ash and blast furnace slag) mainly due to its source as a mineral based material and its lower silica/alumina ratio that places high demand for alkali silicate requirement (Habert *et al.*, 2011). It has been recently shown that the use of silicate for geopolymer also impose problem of negative environmental impact as its production can be as much energy consuming as Portland cement production (Turner and Collins 2013).

Also, the stability of metakaolin based geopolymer during prolong ageing could be a problem as loss of strength results from the ageing process. In fact, Lloyd (2009) questions the suitability of pure metakaolin based geopolymer based on its inability to remain stable when subjected to prolonged ageing.

Furthermore, the morphology of metakaolin places high demand for water during processing to ease workability (Kong 2007; Duxson and Provis 2008). The fresh state of metakaolin is characterized by a stiff matrix of material requiring high water content to make it workable. This places additional limitation on its applicability to large scale geopolymer application as an attempt to increase water/binder ratio excessively will result in weaker strength, high shrinkage value, lower resistance to fire exposure and weaker microstructure compare to fly ash based geopolymer (Kong and Sanjayan 2010).

1.2.3 Enhancing Performance of Metakaolin in Geopolymer Preparation

For metakaolin based geopolymer system to be sustainable in terms of resource utilization and practical applicability, it is important to examine the system for possible modifications. A previous review on environmental sustainability of geopolymer system suggests that the environmental impact of metakaolin geopolymer could be mitigated if combined with other waste based materials having a lower environmental footprint (Habert, *et al.*, 2011)). It is also recommended that kaolin based source of alumina be replaced with other materials that will ensure strength as well as cost effectiveness (Khale and Chaudhary 2007).

Furthermore, it is important that such a material should as much as possible be able to improve the fresh and hardened properties of the system to enhance the applicability especially for high performance geopolymer. It is opined that sustainable development can be enhanced through recycling of industrial waste to produce new construction materials as this would have the effect of reducing landfill disposal, preserve non-renewable raw materials (Bignozzi *et al.*, 2013), reduce greenhouse gas emission and improve the properties of the concrete or mortar.

One waste material requiring adequate utilization in Malaysia is palm oil fuel ash (POFA) generated from production of palm oil. Palm oil production being a main driver of the economy of some South East Asia countries (Indonesia, Malaysia and Thailand) has continued to generate POFA at an increasing rate without commensurate outlets for recycling of these wastes. Another important feature of POFA is that it is generated from renewable resources unlike other waste materials like fly ash and slag. Renewable resources support environmental sustainability because they ensure the preservation of natural resources. Like some other industrial waste materials such as fly ash and slags, the adoption of POFA for construction purposes apart from providing economic benefit, would also serve the purpose of aiding the disposal of the waste material, thereby solving likely associated problems such as pollution and land usage which tend to increase with expanding production capacity of palm oil.

POFA has been developed for use as supplementary material to Portland cement as pozolanic material (Awal and Hussin, 1997; Bamaga *et al.*, 2013; Sata *et al.*, 2007; Tangchirapat *et al.*, 2007). However, the reported relative low alumina content (Bamaga, *et al.*, 2013; Chindaprasirt *et al.*, 2007a; Tangchirapat *et al.*, 2009) is a hindrance towards its utilization as a stand-alone geopolymer starting material for high performance geopolymer due to inability of adequate aluminum taking part in the chain forming reaction. As a result, it will be pertinent to improve its performance in geopolymer preparation by blending with material rich in alumina which invariably modifies the silica and alumina ratio to levels that support the synthesis of high performance geopolymer.

Researchers have recently used this approach to adjust the silica and alumina ratio, a key variable influencing the synthesis of geopolymer. In an attempt to improve the processing route of geopolymer, Fernandez-Jimenez et al. (2008) blended pulverized fly ash (PFA) and metakaolin at 50:50 and obtained compressive strength of 28 MPa at 28 days. Similarly, Riahi et al. (2012) blended PFA with up to 40 % rice husk bark ash (RHBA) and obtained the highest compressive strength of about 58.9 MPa at 30 % RHBA replacement.

It may be noted, however, that blending of PFA and metakaolin may not extend the scope of materials available for use as a feedstock geopolymer as the materials themselves (PFA and metakaolin) are already in use independently for geopolymer synthesis. Also, the use of RBHA although would contribute to the solution disposal problem and valorize the, is feasible predominately rice growing regions.

A blend of PFA with POFA has been reported and about 30 % POFA replacement achieved the highest compressive strength of 28 Mpa (Mohd Ariffin, Hussin et al. 2011). A higher percentage of POFA utilization is desirable to enhance sustainability, economic advantage and make it a main material for the production of high performance geopolymer. The more the POFA incorporation in the metakaolin geopolymer, the more the decline of POFA available for disposal, the more kaolinite clay is conserved, the lesser the attributable CO_2 emission and energy consumption.

In furtherance of this, the development of high volume POFA geopolymer system becomes necessary. There is a strong possibility that an aluminosilicate material having a high alumina composition could be used for this purpose. Metakaolin is being therefore identified to be likely material that could ensure high volume POFA utilization in geopolymer production because of its high reactivity and alumina content. On the other hand, a blend with POFA could also assist to improve the shortcomings of metakoalin in geopolymer production by the adjustment of silica and alumina ratio.

The issues thus arising from this background are whether it is possible to prepare high performance geopolymer using high volume POFA blends with metakaolin, what would be the effect of the blend on the engineering properties and to what extent can the blend be varied in terms of POFA and metakaolin replacement to obtain optimum properties. These issues are best resolved through the implementation of rational approach to mix design of the geopolymer.

The major problem with metakaolin based geopolymer is that it loses strength during ageing making it unreliable for practical construction purposes (Lloyd, 2009). It is also prone to have a negative impact on the environment because of its being a mineral base material and its relatively high demand for sodium silicate during synthesis due to high alumina content (Habert, *et al.*, 2011). Sodium silicate is known to impact negatively on the environment (Turner and Collins, 2013).

Most reports of studies of blended metakaolin with waste materials (Hajjaji *et al.*, 2013; Hawa *et al.*, 2013; He, *et al.*, 2012) were based on short time results of mechanical properties. The blending of metakaolin and POFA could play complementary roles and remedy the enumerated problems of the two materials, especially if high volume POFA is involved necessitating the need to ascertain the impact.

1.3 Statement of the Problem

Despite the growing knowledge of its beneficial utilization as a cemetitious material, the amount of POFA not being recycled is still significant and is disposed in landfills with attendant negative environmental impact. The option of land filling places huge financial burden on the waste generators who are liable for future environmental problems that may arise. Recycling of the waste through utilization for construction purposes would be a better option and its application in geopolymer would further extend the scope of demand. Widening the scope of its utilization as cementitious material in geopolymer is thus necessary towards maximization of its recycling potentials.

Although rich in reactive silica, the poor performance of POFA as a sole aluminosilicate material for geopolymer synthesis due to low alumina content has prompted recent studies to consider the option of its combination with other materials rich in alumina such as fly ash and metakaolin. However, the scanty available studies reported the achievement of significant strength only at the low POFA content.

The relatively low alumina content of Fly ash when compared to Metakaolin, does not allow the use of high content POFA in preparation of geopolymers thereby preventing the maximum use of POFA that stand to increase sustainability. The high alumina of Metakaolin on the other hand has allow the use of smaller quantity to upgrade the alumina content of POFA thus allowing the use of much higher quantity of POFA that can enhance sustainability.

Conversely, apart from metakaolin negative impact on the environment as a result of it being a mineral base material and its high demand for alkali silicate, geopolymer prepared from metakaolin has a serious problem of long term strength instability due to the formation of a type of metastable zeolite from alumina rich metakaolin, that changes the structure with ageing thereby making the geopolymer unreliable for practical construction. The rich alumina content of metakaolin when adjusted with silica from waste material could remedy these problems. Incidentally, the scanty available studies of blended metakaolin and waste materials have reported majorly the short term mechanical properties of resulting geopolymer making it impossible to observe the long term strength stability.

Although a POFA and metakaolin blend promises to harness the complementary and synergic advantages of a blend of the two precursors in the synthesis of geopolymer, it is apparent that the deficiency of reported studies bothering on low POFA incorporation, short term strength development, lack of information on durability of the blended geopolymer and effect of the blend on the microstructure strongly indicates important gaps to be filled in the process of development of an efficient POFA and metakaolin geopolymer for practical construction purposes. This deficiency necessitates the study of the system for possible influences that would properly and adequately define the high volume POFA and metakaolin blended geopolymer in terms of mechanical properties, durability behavior and microstructure characteristics

Furthermore, most studies on blended geopolymer have adopted the mix designs of single source aluminosilicate materials where alkaline solution used is based on optimized experimental trials of the single source aluminosilicate material. However, as the silica and alumina content vary with blending, new sets of experimental trials need be carried out to ascertain the optimum mix design. Doing this for every blended ratio will be cumbersome. A rational approach for blended precursors may therefore be the determination of mix design base on the aluminosilicate content of the intended geopolymer mix from high volume POFA.

The performance of geopolymer prepared from a high volume POFA blend with metakaolin in particular has thus remained to be evaluated. This lack of evaluation of the impact of high volume POFA and metakaolin blend on geopolymer performance leaves an important gap in the development of geopolymer from the blended aluminosilicate materials and this has continued to limit information on the ability to maximize the complementary advantages of the two materials in geopolymer preparation thereby constraining the efficient application of POFA and metakaolin for geopolymer production.

This research is designed to measure the effects of POFA blended with metakaolin on strength development, durability and microstructural properties of the blended geopolymer.

1.4 Aim and Objectives of the Study

The aim of this study is to investigate the effect of POFA on metakaolin based geopolymer system activated with sodium hydroxide and sodium silicate with specific objectives as stated:

1. To characterize POFA and metakaolin and determine their effects on formulation and fresh properties of POFA geopolymer mortar.
2. To determine the effect of POFA on the mechanical properties of geopolymer mortar.
3. To assess the effect of POFA and metakaolin the durability of the blended geopolymer mortar.
4. To characterize the effect of POFA and metakaolin on microstructure of the blended geopolymer mortar.

1.5 Research Questions

1. What are the effects of the composition factors on fresh and strength properties of POFA and metakaolin blended geopolymer
2. How does POFA blend with metakaolin affect mechanical properties of geopolymer mortar
3. How does geopolymer prepared from a POFA blend with metakaolin affect the durability properties of the geopolymer
4. What is the effect of POFA blend with metakaolin on the microstructure of the geopolymer mortar

1.6 Significance of the Study

The advantage of the rich amorphous silica of POFA can be explored in geopolymer preparation by enriching with alumina through blending with material rich in alumina such as metakaolin so as to make it suitable for geopolymer production. The merit of its utilization becomes more visible when POFA is used in high volume as the paradigm is maximization of waste utilization for obvious environmental and economic advantage. This is a strong reason why the investigation into utilization of POFA becomes necessary.

The use of POFA in high volume will benefit palm oil producers who have the direct responsibility for disposal of the waste, the locality where factories are situated due to their being relieved of any adverse effect of the traditional waste disposal method of using it as land fill. Entrepreneurs could also take advantage by utilizing the cheaper waste material for production of geopolymer concrete materials. In a broader sense also, the use POFA could mitigate the emission of greenhouse gasses, minimize energy consumption thereby enhancing environmental sustainability.

The results obtained from this research bordering on possible application of a high volume POFA blend with metakaolin for production of high performance geopolymer would contribute to the pool of knowledge on the emerging alternative cement material.

1.7 Scope of the Study

The research work which is experimental in nature is primarily concerned with the behavior of metakaolin and POFA blend geopolymer mortar activated with sodium hydroxide and sodium silicate. The processing variables of interest considered are basically the role of the blend, alkali hydroxide and silicates, curing and water content. These were used to model the strength behavior. Mixes with varying blending was then used to obtain responses related to microstructure and some durability properties of the mortar. The intent here is to broadly examine the applicability of the system for engineering purposes through characterization of strength, durability performance and microstructure. Optimized mixes were also used to observe the strength capacity of the blended system applied to concrete production.

1.8 Research Motivation

Geopolymer cement has no doubt evolved as a veritable alternative to Portland cement. The ability for geopolymer to extensively impact as a cement depends on availability of the raw materials among other factors.

Being a relatively new material, research efforts have focused on evolving geopolymer capable of meeting the objective of an alternative cement material that is relatively environmentally friendly. The efficiency and effectiveness of application of materials for its production go a long way to aid the achievement of the objective. The ability to provide knowledge base for materials, especially for the purpose to expand the useable feed stocks will enhance ease of procurement, availability and affordability of the material technical knowledge relating to utilization. The utilization of POFA for geopolymer preparation in the locality where it is available would in no doubt further the cause of geopolymer in general and make the environment more sustainable.

1.9 Organization of Thesis

The thesis of the research is structured in eight chapters. Following the introductory chapter, the layout of other chapters is as stated below.

- Chapter two presents the review of available literature relevant to the research. Evolution of geopolymer as alternative cement and composition factors as they affect synthesis reaction are discussed. The properties of geopolymer are explored to create understanding and basis for the proposed experimentation and discussions.

- Chapter three describes the experimental investigation involving methods for characterization of materials used and procedures for the determination of fresh, hardened and durability properties of synthesized geopolymer following standard practices.

- Chapter four presents the results and discussion of experimental tests on physical and chemical characterization of materials (POFA and metakaolin), fresh and hardened properties of geopolymer. It also discussed the effect of synthesis variables on formulation of design mix and fresh properties.
- Chapter five discussed the results of strength tests covering compressive, flexural, tensile splitting and static modulus of elasticity properties. The discussion included consideration of statistical analysis of data and regression models for purpose of strength prediction.

- Chapter six is mainly on the role of high volume POFA on the durability performance of the geopolymer. Water absorption, sorptivity, resistance to acid and sulfate attack, resistance to carbonation and fire endurance were aspects considered and reported.

- Chapter seven reports the microstructure tests conducted on mortar specimens covering Field Emission Scanning Electron Microscopy (FESEM), Energy

Dispersive X-ray microscopy (EDX), Fourier Transform Infrared (FTIR) microscopy, X- ray diffraction (XRD) thermogravimetry analysis (TGA) and mercury intrusion porosimetry (MIP). These results indicating the influence of POFA on the microstructure were discussed.

Chapter eight concludes the thesis by stating the major findings of the research, suggestions for future research in a related field and contributions of the research to knowledge with a view to entrench the emerging material.

REFERENCES

Aaron Richard, S. Reinforced geopolymer composites for enhanced material greenness and durability. *Sustainable Cities and Society*.

Abdul Awal, A. S. M. and Warid Hussin, M. (2011). Effect of Palm Oil Fuel Ash in Controlling Heat of Hydration of Concrete. *Procedia Engineering*. 14(0), 2650-2657.

Abdul Aziz, A. h., Manaf, L. A., Man, H. C. and Kumar, N. S. (2014). Kintic Modeling and Isotherm Studies for Copper(ii) Adsorption onto Palm Oil Boiler Mill Fly Ash (POFA) as a Natural low- cost Adsorbent. *BioResources*. 9(1), 336-356.

ACI Committee 318-08 (2008). Building Code Requirements for Structural Concrete and Commentary. *An ACI Standard, American Concrete Institute.* Michigan (USA)

ACI Committee 211.1 (1991). Standard practice for selecting proportions for normal heavyweight and mass, concrete. *An ACI Standard, American Concrete Institute* Michigan (USA)

Ahmari, S., Ren, X., Toufigh, V. and Zhang, L. (2012). Production of geopolymeric binder from blended waste concrete powder and fly ash. *Construction and Building Materials*. 35(0), 718-729.

Álvarez-Ayuso, E., Querol, X., Plana, F., Alastuey, A., Moreno, N., Izquierdo, M., Font, O., Moreno, T., Diez, S., Vázquez, E. and Barra, M. (2008). Environmental, physical and structural characterisation of geopolymer matrixes synthesised from coal (co-)combustion fly ashes. *Journal of Hazardous Materials*. 154(1-3), 175-183.

Ambily, P. S., Ravisankar, K., Umarani, C., Dattatreya, J. K. and Iyer, N. R. (2013). Development of ultra-high-performance geopolymer concrete. *Magazine of Concrete Research*. 66(2), 82-89.

Andini, S., Cioffi, R., Colangelo, F., Grieco, T., Montagnaro, F. and Santoro, L. (2008). Coal fly ash as raw material for the manufacture of geopolymer-based products. *Waste Management*. 28(2), 416-423.

Andreasen, J. H. (1994). Reliability-based design of ceramics. *Materials & Design*. 15(1), 3-13.

Ariffin, M. A. M., Bhutta, M. A. R., Hussin, M. W., Mohd Tahir, M. and Aziah, N. (2013). Sulfuric acid resistance of blended ash geopolymer concrete. *Construction and Building Materials*. 43(0), 80-86.

Arioz, O. (2007). Effects of elevated temperatures on properties of concrete. *Fire Safety Journal*. 42(8), 516-522.

Awal, A. S. M. A. and Hussin, M. W. (1997). The effectiveness of palm oil fuel ash in preventing expansion due to alkali-silica reaction. *Cement and Concrete Composites*. 19(4), 367-372.

Awal, A. S. M. A. and Shehu, I. A. (2013). Evaluation of heat of hydration of concrete containing high volume palm oil fuel ash. *Fuel*. 105(0), 728-731.

ASTMC 39/C39M 2013a. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens *American Society of Testing Materials*, USA

ASTMC 109, 2003. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). *American Society of Testing Materials*, USA.

ASTMC C191, 2013. Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle. *American Society of Testing Materials*, USA.

ASTMC 267, 2012. Standard Test Methods for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacings and Polymer Concretes. *American Society of Testing Materials*, USA.

ASTMC 311/C311M, 2013. Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete. *American Society of Testing Materials*, USA.

ASTMC 348, 2008. Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars. *American Society of Testing Materials*, USA.

ASTMC 430, 2008. Standard Test Method for Fineness of Hydraulic Cement by the 45-µm (No. 325) Sieve. *American Society of Testing Materials*, USA.

ASTMC 496/C496M, 2011. Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. *American Society of Testing Materials*, USA.

ASTMC 618, 2012a. Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. *American Society of Testing Materials*, USA.

ASTMC 642, 2006. Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. *American Society of Testing Materials*, USA.

ASTM C902 – 14, 2014. Standard Specification for Pedestrian and Light Traffic Paving Brick. *American Society of Testing Materials*, USA.

ASTMC 1239, 2007. Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics. *American Society of Testing Materials*, USA.

ASTM C1272 − 14a, 2014 Standard Specification for Heavy Vehicular Paving Brick. *American Society of Testing Materials*, USA.

ASTMC 1437, 2007b. Standard Test Method for Flow of Hydraulic Cement Mortar.

American Society of Testing Materials, USA

ASTM C1585, 2013. Standard test method for measurement of rate of absorption of water by hydraulic cement concretes; 2004. *American Society of Testing Materials*, USA

ASTME 119 2012a. Standard Test Methods for Fire Tests of Building Construction and Materials. *American Society of Testing Materials*, USA.

Bakharev, T. (2005a). Durability of geopolymer materials in sodium and magnesium sulfate solutions. *Cement and Concrete Research*. 35(6), 1233-1246.

Bakharev, T. (2005b). Geopolymeric materials prepared using Class F fly ash and elevated temperature curing. *Cement and Concrete Research*. 35(6), 1224-1232.

Bakharev, T. (2005c). Resistance of geopolymer materials to acid attack. *Cement and Concrete Research*. 35(4), 658-670.

Bakharev, T., Sanjayan, J. G. and Cheng, Y. B. (2001). Resistance of alkali-activated slag concrete to carbonation. *Cement and Concrete Research*. 31(9), 1277-1283.

Bamaga, S. O., Ismail, M., Majid, Z. A., Ismail, M. and Hussin, M. W. (2013). Evaluation of Sulfate Resistance of Mortar Containing Palm Oil Fuel Ash from Different Sources. *Arabian Journal for Science and Engineering*. 38(9), 2293-2301.

Bankowski, P., Zou, L. and Hodges, R. (2004). Reduction of metal leaching in brown coal fly ash using geopolymers. *Journal of Hazardous Materials*. 114(1–3), 59-67.

Basu, B., Tiwari, D., Kundu, D. and Prasad, R. (2009a). Is Weibull distribution the most appropriate statistical strength distribution for brittle materials? *Ceramics International*. 35(1), 237-246.

Basu, M., Pande, M., Bhadoria, P. B. S. and Mahapatra, S. C. (2009b). Potential fly-ash utilization in agriculture: A global review. *Progress in Natural Science*. 19(10), 1173-1186.

Bernal, S. A., Mejía de Gutiérrez, R., Pedraza, A. L., Provis, J. L., Rodriguez, E. D. and Delvasto, S. (2011). Effect of binder content on the performance of alkali-activated slag concretes. *Cement and Concrete Research*. 41(1), 1-8.

Bernal, S. A., Rodríguez, E. D., de Gutiérrez, R. M., Provis, J. L. and Delvasto, S. (2012). Activation of metakaolin/slag blends using alkaline solutions based on chemically modified silica fume and rice husk ash. *Waste and Biomass Valorization*. 3(1), 99-108.

Beygi, M. H., Kazemi, M. T., Nikbin, I. M. and Amiri, J. V. (2013). The effect of water to cement ratio on fracture parameters and brittleness of self-compacting concrete. *Materials & Design*. 50, 267-276.

Bhutta, M. A. R., Nur Farhayu Ariffin, Mohd Warid Hussin, Nor Hasanah Abdul Shukor Lim (2013). Sulfate and Sulfuric Acid Resistance of Geopolymer Mortars Using Waste Blended Ash. *Jurnal Teknologi*. 61(3).

British Standard Institution (2010). *Solid biofuels —Determination of ash content.* BS EN 14775:2009.

Buchwald, A., Hilbig, H. and Kaps, C. (2007). Alkali-activated metakaolin-slag blends—performance and structure in dependence of their composition. *Journal of Materials Science*. 42(9), 3024-3032.

Burciaga-Diaz, O., Escalante-Garcia, J. I. and Gorokhovsky, A. (2012). Geopolymers based on a coarse low-purity kaolin mineral: Mechanical strength as a function of the chemical composition and temperature. *Cement and Concrete Composites*. 34(1), 18-24.

Carpinteri, A., Xu, J., Lacidogna, G. and Manuello, A. (2012). Reliable onset time determination and source location of acoustic emissions in concrete structures. *Cement and Concrete Composites*. 34(4), 529-537.

Cassagnabère, F., Mouret, M., Escadeillas, G., Broilliard, P. and Bertrand, A. (2010). Metakaolin, a solution for the precast industry to limit the clinker content in concrete: Mechanical aspects. *Construction and Building Materials*. 24(7), 1109-1118.

Cassagnabère, F., P. Diederich, M. Mouret, G. Escadeillas, M. Lachemi (2013). *Cement and Concrete Composites*. 37(0), 95-107.

Chan, Y. N., Peng, G. F. and Anson, M. (1999). Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures. *Cement and Concrete Composites*. 21(1), 23-27.

Chandara, C., K. A. Mohd Azizli, Z. A. Ahmad, S. F. Saiyid Hashim, E. Sakai (2012). Heat of hydration of blended cement containing treated ground palm oil fuel ash. *Construction and Building Materials*. 27(1), 78-81.

Cheema, D. (2012). Low calcium fly ash geopolymer concrete–a promising sustainable alternative for rigid concrete road furniture. *Proceedings of the 2012 25th APRB conference–shaping the future: linking policy, researches and outcomes, perth, Australia*,

Chen, X., Wu, S. and Zhou, J. (2013). Influence of porosity on compressive and tensile strength of cement mortar. *Construction and Building Materials*. 40(0), 869-874.

Cheng, T. and Chiu, J. (2003). Fire-resistant geopolymer produced by granulated blast furnace slag. *Minerals Engineering*. 16(3), 205-210.

Cheng, Y. H., Hazlinda, K., Mohd Mustafa AL-Bakri, A., Luqman, M., Nizar, K. & Liew, Y. (2011). Potential Application of Kaolin without Calcine as Greener *Concrete: a Review*.

Chindaprasirt, P., Homwuttiwong, S. and Jaturapitakkul, C. (2007a). Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Construction and Building Materials*. 21(7), 1492-1499.

Chindaprasirt, P., Jaturapitakkul, C. and Sinsiri, T. (2007b). Effect of fly ash fineness on microstructure of blended cement paste. *Construction and Building Materials*. 21(7), 1534-1541.

Chotetanorm, C., Chindaprasirt, P., Sata, V., Rukzon, S. and Sathonsaowaphak, A. (2012). High-calcium bottom ash geopolymer: sorptivity, pore size, and resistance to sodium sulfate attack. *Journal of Materials in Civil Engineering*. 25(1), 105-111.

Chub-uppakarn, T., Thaenlek, N. and Thaisiam, R. (2011). Palm ash – Based Geopolymer Mortar Incorporating Metakaolin Geopolymer Mortar

Incorporating Metakaolin. In Pattanaprateeb, P. (Ed.), *Pure and Applied Chemistry International Conference* (pp. 347-350). Srinakharinwirot University.

Collins, F. and Sanjayan, J. G. (2000). Effect of pore size distribution on drying shrinking of alkali-activated slag concrete. *Cement and Concrete Research*. 30(9), 1401-1406.

Danzer, R., Supancic, P., Pascual, J. and Lube, T. (2007). Fracture statistics of ceramics – Weibull statistics and deviations from Weibull statistics. *Engineering Fracture Mechanics*. 74(18), 2919-2932.

Davidovits, J. (1991a). Geopolymers. *Journal of Thermal Analysis and Calorimetry*. 37(8), 1633-1656.

Davidovits, J. (1991b). GEOPOLYMERS Inorganic polymerie new materials. *Journal ofThamal Analysis*. Vol. 37 (1991), 1633-1656.

Davidovits, J. (1999). Chemistry of geopolymeric systems, terminology. *Proceedings of the 1999 Geopolymer*, 9-40.

De Silva, P. and Sagoe-Crenstil, K. (2008a). The effect of Al 2 O 3 and SiO 2 on setting and hardening of Na 2 O–Al 2 O 3–SiO 2–H 2 O geopolymer systems. *J. Aust. Ceram. Soc*. 44(1), 39-46.

De Silva, P. and Sagoe-Crenstil, K. (2008b). Medium-term phase stability of Na_2O–Al_2O_3–SiO_2–H_2O geopolymer systems. *Cement and Concrete Research*. 38(6), 870-876.

Deb, P. S., Nath, P. and Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials & Design*. 62(0), 32-39.

Demie, S., Nuruddin, M. F. and Shafiq, N. (2013). Effects of micro-structure characteristics of interfacial transition zone on the compressive strength of self-compacting geopolymer concrete. *Construction and Building Materials*. 41, 91-98.

Diamaruya, M., Kobayashi, H. and Nonaka, T. (1997). Impact Tensile Strength and Fracture of Concrete. *J. PHYS. IV FRANCE*. 07(C03), C3-253 - C253-258.

Diamond, S. (2000). Mercury porosimetry: an inappropriate method for the measurement of pore size distributions in cement-based materials. . *Cement and Concrete Research*. 30, 1517–1525.

Diaz, E. I., Allouche, E. N. and Eklund, S. (2010). Factors affecting the suitability of fly ash as source material for geopolymers. *Fuel*. 89(5), 992-996.

Duxson, P., A. Fernandez-Jimenez, J. L. Provis, and G. C. Lukey, A. P. a. J. S. J. v. D. (2007). Geopolymer technology: the current state of the art. *J Mater Sci*. 42, 2917–2933.

Duxson, P., Grant C. Lukey and Deventer, J. S. J. v. (2006). Evolution of Gel Structure during Thermal Processing of Na-Geopolymer Gels. *Langmuir*. 22, 8750-8757.

Duxson, P., Mallicoat, S. W., Lukey, G. C., Kriven, W. M. and van Deventer, J. S. J. (2007a). The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 292(1), 8-20.

Duxson, P. and Provis, J. L. (2008). Designing Precursors for Geopolymer Cements. *Journal of American Ceramic Society*. 91(12), 6.

Duxson, P., Provis, J. L., Lukey, G. C., Mallicoat, S. W., Kriven, W. M. and van Deventer, J. S. J. (2005a). Understanding the relationship between geopolymer composition, microstructure and mechanical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 269(1-3), 47-58.

Duxson, P., Provis, J. L., Lukey, G. C., Mallicoat, S. W., Kriven, W. M. and van Deventer, J. S. J. (2005b). Understanding the relationship between geopolymer composition, microstructure and mechanical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 269(1–3), 47-58.

Duxson, P., Provis, J. L., Lukey, G. C. and van Deventer, J. S. J. (2007b). The role of inorganic polymer technology in the development of 'green concrete'. *Cement and Concrete Research*. 37(12), 1590-1597.

Edwards, K. L. (2005). Selecting materials for optimum use in engineering components. *Materials & Design*. 26(5), 469-473.

Elgueta, M., Díaz, G., Zamorano, S. and Kittl, P. (2007). On the use of the Weibull and the normal cumulative probability models in structural design. *Materials & Design*. 28(9), 2496-2499.

Elimbi, A., H. K. Tchakoute, D. Njopwouo (2011). Effects of calcination temperature of kaolinite clays on the properties of geopolymer cements. *Construction and Building Materials*. 25(6), 2805-2812.

Fernández-Jiménez, A., Garcia-Lodeiro, I. and Palomo, A. (2007). Durability of alkali-activated fly ash cementitious materials. *Journal of Materials Science*. 42(9), 3055-3065.

Fernández-Jiménez, A., Monzó, M., M. Vicent, A. Barba and Palomo, A. (2008). Alkaline activation of metakaolin–fly ash mixtures: Obtain of Zeoceramics and Zeocements. *Microporous and Mesoporous Materials*. 108(1–3), 41-49.

Fernandez-Jimenez, A. and Palomo, A. (2009). Chemical durability of geopolymers. In Provis, J. L. & Derventer, J. S. J. v. (Eds.) *Geopolymers, Structure, Processing, Properties and Industrial Applications* (1st ed., pp. 167-193) Woodhead Publishing Limited.

Fernández-Jiménez, A. and Palomo, A. (2003). Characterisation of fly ashes. Potential reactivity as alkaline cements☆. *Fuel*. 82(18), 2259-2265.

Ferone, C., Roviello, G., Colangelo, F., Cioffi, R. and Tarallo, O. (2013). Novel hybrid organic-geopolymer materials. *Applied Clay Science*. 73(0), 42-50.

Gartner, E. (2004). Industrially Interesting Approaches to “Low-CO2” Cements. *Cement and Concrete Research*, 34, 1489-1498.

Gartner, E. M. and MacPhee, D. E. (2011). A physico-chemical basis for novel cementitious binders. *Cement and Concrete Research*. 41(7), 736-749.

Gourley, J. and Johnson, G. (2005). Developments in geopolymer precast concrete. *Proceedings of the 2005 World Congress Ceopolymer*, 139-143.

Granizo, M. L., Alonso, S., Blanco-Varela, M. T. and Palomo, A. (2002). Alkaline activation of metakaolin: effect of calcium hydroxide in the products of reaction. *Journal of the American Ceramic Society*. 85(1), 225-231.

Habert, G., d’Espinose de Lacaillerie, J. B. and Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of Cleaner Production*. 19(11), 1229-1238.

Hajimohammadi, A., Provis, J. L. and van Deventer, J. S. J. (2010). The effect of Alumina Release Rate on the Mechanism of Geopolymer Gel Formation. *Chemistry of Materials*. 22, 10.

Hajjaji, W., Andrejkovičová, S., Zanelli, C., Alshaaer, M., Dondi, M., Labrincha, J. A. and Rocha, F. (2013). Composition and technological properties of geopolymers based on metakaolin and red mud. *Materials & Design*. 52(0), 648-654.

Hall, C. (1989). Water sorptivity of mortars and concretes: a review. *Magazine of Concrete Research*. 41(147), 51-61.

Hardjito, D. and Fung, S. S. (2010). Fly Ash-Based Geopolymer Mortar Incorporating Bottom Ash. *Modern Applied Science*. 4(1), 44-52.

Hardjito, D. and Rangan, B. V. (2005). Development of and properties of low-calcium fly ash-based geopolymer concrete (Engineering, F. o., Trans.) (pp. 94). Curtin University of Technology, Perth Australia.

Hardjito, D., Steenie E. Wallah, Dody M.J. Sumajouw and Rangan, a. B. V. (2004). Factors influencing the compressive Strength of Fly Ash-Based geopolymer concrete. *Civil Engineering Dimension*. 6(2), 88–93.

Hassan, I. O., Ismail, M., Forouzani, P., Majid, Z. A. and Mirza, J. (2014). Flow characteristics of ternary blended self-consolidating cement mortars incorporating palm oil fuel ash and pulverised burnt clay. *Construction and Building Materials*. 64(0), 253-260.

Hawa, A., Danupon Tonnayopas and Prachasaree, W. (2013). Performance Evaluation and Microstructure Characterization of Metakaolin-Based Geopolymer Containing Oil Palm Ash. *The ScientificWorld Journal*. 2013.

He, J. (2012). *Sytheses and Characterization of Geopolymers for Infrastructural Applications.* Doctor of Philosophy, Louisiana State University and Agricultural and Mechanical College.

He, J., Zhang, J., Yu, Y. and Zhang, G. (2012). The strength and microstructure of two geopolymers derived from metakaolin and red mud-fly ash admixture: A comparative study. *Construction and Building Materials*. 30(0), 80-91.

He, X. X. and ZhiHui, X. (2011). Experimental Study on Statistical Parameters of Concrete Strength Based on Weibull Probability Distribution. *Key Engineering Materials*. 477, 224-232.

Heah, C., Kamarudin, H., Bakri, A., Binhussain, M., Luqman, M., Nizar, I. K., Ruzaidi, C. and Liew, Y. (2011). Effect of curing profile on kaolin-based geopolymers. *Physics Procedia*. 22, 305-311.

Hos, J., McCormick, P. and Byrne, L. (2002). Investigation of a synthetic aluminosilicate inorganic polymer. *Journal of Materials Science*. 37(11), 2311-2316.

Husem, M. (2006). The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete. *Fire Safety Journal*. 41(2), 155-163.

Ismail, M., ElGelany Ismail, M. and Muhammad, B. (2011). Influence of elevated temperatures on physical and compressive strength properties of concrete containing palm oil fuel ash. *Construction and Building Materials*. 25(5), 2358-2364.

Ismail, M., Yusuf, T. O., Noruzman, A. H. and Hassan, I. O. (2013). Early Strength Characteristics of Palm Oil Fuel Ash and Metakaolin blended Geopolymer Mortar. *Advanced Materials Research*. Vols. 690-693 (2013) 1045-1048.

ISO (2012). Fire resistance tests. Element of building construction. *International Standard Organization* (ISO 834: Part 12)

Juenger, M. C. G., Winnefeld, F., J.L. Provis and Ideker, J. H. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research*. 41(12), 1232-1243.

Kearsley, E. P. and Wainwright, P. J. (2002). The effect of porosity on the strength of foamed concrete. *Cement and Concrete Research*. 32(2), 233-239.

Khale, D. and Chaudhary, R. (2007). Mechanism of geopolymerization and factors influencing its development: a review. *Journal of Materials Science*. 42, 729-746.

Khaliq, W. and Kodur, V. (2011). Effect of high temperature on tensile strength of different types of high-strength concrete. *ACI Materials Journal*. 108(4).

Komnitsas, K. and Zaharaki, D. (2007). Geopolymerisation: A review and prospects for the minerals industry. *Minerals Engineering*. 20(14), 1261-1277.

Komnitsas, K., Zaharaki, D. and Perdikatsis, V. (2009). Effect of synthesis parameters on the compressive strength of low-calcium ferronickel slag inorganic polymers. *Journal of Hazardous Materials*. 161(2–3), 760-768.

Komnitsas, K. A. (2011). Potential of geopolymer technology towards green buildings and sustainable cities. *Procedia Engineering*. 21(0), 1023-1032.

Kong, D. L. and Sanjayan, J. G. (2008). Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites*. 30(10), 986-991.

Kong, D. L., Sanjayan, J. G. and Sagoe-Crentsil, K. (2007). Comparative performance of geopolymers made with metakaolin and fly ash after exposure to elevated temperatures. *Cement and Concrete Research*. 37(12), 1583-1589.

Kong, D. L., Sanjayan, J. G. and Sagoe-Crentsil, K. (2008). Factors affecting the performance of metakaolin geopolymers exposed to elevated temperatures. *Journal of Materials Science*. 43(3), 824-831.

Kong, D. L. Y. and Sanjayan, J. G. (2010). Effect of elevated temperatures on geopolymer paste, mortar and concrete. *Cement and Concrete Research*. 40(2), 334-339.

Konstantinos A, K. (2011). Potential of geopolymer technology towards green buildings and sustainable cities. *Procedia Engineering*. 21(0), 1023-1032.

Kroehong, W., Sinsiri, T. and Jaturapitakkul, C. (2011a). Effect of Palm Oil Fuel Ash Fineness on Packing Effect and Pozzolanic Reaction of Blended Cement Paste. *Procedia Engineering*. 14(0), 361-369.

Kroehong, W., Sinsiri, T., Jaturapitakkul, C. and Chindaprasirt, P. (2011b). Effect of palm oil fuel ash fineness on the microstructure of blended cement paste. *Construction and Building Materials*. 25(11), 4095-4104.

Kumanan, S., Jesuthanam, C. P. and Kumar, R. A. (2008). Application of multiple regression and adaptive neuro fuzzy inference system for the prediction of surface roughness. *Int J Adv Manuf Technol* 35, 778–788.

Kumar, S. and Kumar, R. (2011). Mechanical activation of fly ash: Effect on reaction, structure and properties of resulting geopolymer. *Ceramics International*. 37(2), 533-541.

Kumaran, M. K., Lackey, J. C., Normandin, N., Tariku, F. and Reenen, D. v. (2004). Heat, Air, and Moisture Transport Properties of Several North American Bricks and Mortar Mixes. *Journal of Testing and Evaluation*. Vol. 32 (5), 1-7.

Lawrence, C. D. (2003). The Production of Low-Energy Cements *Lea's Chemistry of Cement and Concrete (Fourth Edition)* (pp. 421-470). Oxford: Butterworth-Heinemann.

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L. L. and Sausen, R. (2010). Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*. 44(37), 4678-4734.

Li, C., Sun, H. & Li, L. (2010). A review: The Comparison between Alkali-Activated Slag (Si+ Ca) and Metakaolin (Si+ Al) Cements. *Cement and Concrete Research*, 40, 1341-1349.

Li, Z. and Liu, S. (2007). Influence of slag as additive on compressive strength of fly ash-based geopolymer. *Journal of Materials in Civil Engineering*. 19(6), 470-474.

Lin, K.-L. (2005). The influence of municipal solid waste incinerator fly ash slag blended in cement pastes. *Cement and Concrete Research*. 35(5), 979-986.

Liu, X., Chia, K. S. and Zhang, M.-H. (2011). Water absorption, permeability, and resistance to chloride-ion penetration of lightweight aggregate concrete. *Construction and Building Materials*. 25(1), 335-343.

Lloyd, R. R. (2009). Accelerated ageing of geopolymers. In Provis, J. L. & Derventer, J. S. J. v. (Eds.) *Geopolymers, Structure, Processing, Properties and Industrial Applications* (1st ed., pp. 139-166)Woodhead Publishing Limited.

Lyon, R. E., Balaguru, P. N., Foden, A., Sorathia, U., Davidovits, J. and Davidovics, M. (1997). Fire-resistant aluminosilicate composites. *Fire and Materials*. 21(2), 67-73.

Madlool, N. A., Saidur, R., Hossain, M. S. and Rahim, N. A. (2011). A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews*. 15(4), 2042-2060.

Mandal, T. K., Ghosh, S. and Naik, S. Study on the Strength of Fly Ash based Geopolymer Concrete (Engineering, D. o. C., Trans.). Jadavpur University, Kolkata.

Martín-Morales, M., Zamorano, M., Ruiz-Moyano, A. and Valverde-Espinosa, I. (2011). Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08. *Construction and Building Materials*. 25(2), 742-748.

McLellan, B. C., R. P. Williams, J. Lay, A, van Riessen, G. D Corder (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of Cleaner Production*. 19(9–10), 1080-1090.

McPolin, D. O., Basheer, P. A. M. and Long, A. E. (2009). Carbonation and pH in Mortars Manufactured with Supplementary Cementitious Materials. *JOURNAL OF MATERIALS IN CIVIL ENGINEERING*. 21(5).

Medeiros, M. H. F. and Helene, P. (2009). Surface treatment of reinforced concrete in marine environment: Influence on chloride diffusion coefficient and capillary water absorption. *Construction and Building Materials*. 23(3), 1476-1484.

Mijarsh, M. J. A., Megat Johari, M. A. and Ahmad, Z. A. (2014). Synthesis of geopolymer from large amounts of treated palm oil fuel ash: Application of the Taguchi method in investigating the main parameters affecting compressive strength. *Construction and Building Materials*. 52(0), 473-481.

Mohd Ariffin, M. A., Hussin, M. W. and Bhutta, M. A. R. (2011). *Advanced Materials Research*. Vol. 339, pp 452-457.

Mohsen, Q. and Mostafa, N. Y. (2010). Investigating the possibility of utilising low kaolinitic clays in production of geopolymer bricks. *Ceramics-Silikaty*. 54(2), 160-168.

Natali, A., Manzi, S. and Bignozzi, M. C. (2011). Novel fiber-reinforced composite materials based on sustainable geopolymer matrix. *Procedia Engineering*. 21(0), 1124-1131.

Neville, A. M. (2011). Properties of concrete.

Ng, T. S., Voo, Y. L. and Foster, S. J. (2012). Sustainability with ultra-high performance and geopolymer concrete construction *Innovative Materials and Techniques in Concrete Construction* (pp. 81-100)Springer.

Nordina, A. and Majid, M. A. A. (2013). Analysis of carbon dioxide emission of gas fuelled cogeneration plant *2nd InternationalConferenceonMechanicalEngineeringResearch(ICMER2013)* (Vol. 50). IOP Publishing.

Noruzman, A. H., Muhammad, B., Ismail, M. and Abdul-Majid, Z. (2012). Characteristics of treated effluents and their potential applications for producing concrete. *Journal of Environmental Management*. 110, 27-32.

Nour, W. M. N. and Awad, H. M. (2008). Effect of MgO on Phase Formation and Mullite Morphology of Different Egyptian Clays. *Journal of the Australian Ceramic Society* 44 (2), 27-37.

Nyale, S. M., Babajide, O. O., Birch, G. D., Böke, N. and Petrik, L. F. (2013). Synthesis and Characterization of Coal Fly Ash-based Foamed Geopolymer. *Procedia Environmental Sciences*. 18(0), 722-730.

Olivia, M., Sarkar, P. and Nikraz, H. (2008). Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete. *Proceedings of the 2008 International Conference on Construction and Building Technology*: ICBT, 517-530.

Pacheco-Torgal, F., Castro-Gomes, J. and Jalali, S. (2008a). Alkali-activated binders: A review. Part 2. About materials and binders manufacture. *Construction and Building Materials*. 22(7), 1315-1322.

Pacheco-Torgal, F., Castro-Gomes, J. and Jalali, S. (2008b). Properties of tungsten mine waste geopolymeric binder. *Construction and Building Materials*. 22(6), 1201-1211.

Pacheco Torgal, F. and Jalali, S. (2009). Utilization of mining wastes to produce geopolymer binders. In Provis, J. L. & Derventer, J. S. J. v. (Eds.) *Geopolymers, Structure, Processing, Properties and Industrial Application* (1st ed., pp. 267-293)Woodhead Publishing Limited

Pan, Z., Sanjayan, J. G. and Rangan, B. V. (2011). Fracture properties of geopolymer paste and concrete. *Magazine of Concrete Research*. 63(10), 763- 771.

Panias, D., Giannopoulou, I. P. and Perraki, T. (2007). Effect of synthesis parameters on the mechanical properties of fly ash-based geopolymers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 301(1), 246-254.

Pavel, R. (2010). Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer. *Construction and Building Materials*. 24(7), 1176-1183.

Pelisser, F., Guerrino, E. L., Menger, M., Michel, M. D. and Labrincha, J. A. (2013). Micromechanical characterization of metakaolin-based geopolymers. *Construction and Building Materials*. 49(0), 547-553.

Peng, G.-F., Bian, S.-H., Guo, Z.-Q., Zhao, J., Peng, X.-L. and Jiang, Y.-C. (2008). Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures. *Construction and Building Materials*. 22(5), 948-955.

Pimraksa, K., Chareerat, T., Chindaprasirt, P., Mishima, N. and Hatanaka, S. (2008). Composition and microstructure of fly ash geopolymer containing metakaolin. *Proceedings of the 2008 Excellence in Concrete Construction through Innovation: Proceedings of the conference held at the Kingston University, United Kingdom, 9-10 September 2008*: CRC Press, 201.

Plešingerová, B., Súči, G. and Fabián, M. (2011). Surface area change of Kaolin causing annealing. *Acta Metallurgica Slovaca*. 17(3), 169-176.

Prasad, M. S., Reid, K. J. and Murray, H. H. (1991). Kaolin: processing, properties and applications. *Applied Clay Science*. 6(2), 87-119.

Provis, J. L. and van Deventer, J. S. J. (2007). Geopolymerisation kinetics. 1. In situ energy-dispersive X-ray diffractometry. *Chemical Engineering Science*. 62(9), 2309-2317.

Provis, J. L. and Van Deventer, J. S. J. (Eds.). (2009). ***Geopolymers** Structure, Processing, Properties and Industrial Applications*. Woodhead Publishing Limited.

Provis, J. L., Yong, S. L. and P.Duxson (2009). Nanostructure/microstructure of metakaolin geopolymer. In Deventer, J. l. P. a. J. S. J. v. (Ed.) *Geopolymers Structure, Processing, Properties and Industrial Applications* (pp. 72-88)Woodhead Publishing Limited.

Provis, J. L. & van Deventer, J. S. (2014). Alkali Activated Materials, Springer.

Ptáček, P., Šoukal, F., Opravil, T., Havlica, J. and Brandštetr, J. (2011). The kinetic analysis of the thermal decomposition of kaolinite by DTG technique. *Powder Technology*. 208(1), 20-25.

Qing, Y., Zenan, Z., Deyu, K. and Rongshen, C. (2007). Influence of nano-SiO< sub> 2</sub> addition on properties of hardened cement paste as compared with silica fume. *Construction and Building Materials*. 21(3), 539-545.

Quinn, J. B. and Quinn, G. D. (2010). A practical and systematic review of Weibull statistics for reporting strengths of dental materials. *Dental Materials*. 26(2), 135-147.

Rajamma, R., Labrincha, J. A. and Ferreira, V. M. (2012). Alkali activation of biomass fly ash–metakaolin blends. *Fuel*. 98, 265-271.

Ranjbar, N., Mehrali, M., Behnia, A., Alengaram, U. J. and Jumaat, M. Z. (2014). Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. *Materials & Design*. 59(0), 532-539.

Rao, S. V., M. V. Seshagiri Rao and Ramaseshu, D. (2011). Strength and Durability studies of conventional concrete and self compacting concrete. *International RILEM Conference on Advances in Construction Materials Through Science and Engineeing* (pp. 271-280) RILEM Publications SARL.

Rashad, A. M. (2013). Alkali-activated metakaolin: A short guide for civil Engineer – An overview. *Construction and Building Materials*. 41(0), 751-765.

Rattanasak, U. and Chindaprasirt, P. (2009). Influence of NaOH solution on the synthesis of fly ash geopolymer. *Minerals Engineering*. 22(12), 1073-1078.

Rees, C. A., Provis, J. L., Lukey, G. C. and van Deventer, J. S. J. (2008). The mechanism of geopolymer gel formation investigated through seeded nucleation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 318(1–3), 97-105.

Riahi, S., Nazari, A., Zaarei, D., Khalaj, G., Bohlooli, H. and Kaykha, M. M. (2012). Compressive strength of ash-based geopolymers at early ages designed by Taguchi method. *Materials & Design*. 37(0), 443-449.

Rouquerol, J., Avnir, D., Fairbridge, C., Everett, D., Haynes, J., Pernicone, N., Ramsay, J., Sing, K. and Unger, K. (1994). Recommendations for the characterization of porous solids (Technical Report). *Pure and Applied Chemistry*. 66(8), 1739-1758.

Rovnaník, P. (2010). Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer. *Construction and Building Materials*. 24(7), 1176-1183.

Rowland, R. A. (1955). Differential thermal analysis of clays and carbonates. *Bulletin*. (169), 151.

Sabir, B. B., Wild, S. and O'Farrell, M. (1998). A water sorptivity test for mortar and concrete. *Materials and Structures/Mat~riaux et Constructions*. 31, 568-574.

Safiuddin, M. and Hearn, N. (2005). Comparison of ASTM saturation techniques for measuring the permeable porosity of concrete. *Cement and Concrete Research*. 35(5), 1008-1013.

Safiuddin, M., Salam, M. A. and Jumuat, M. Z. (2011). Utilization of palm oil fuel ash in concrete: a review. *Journal of Civil Engineering and Management*. 17(2), 234-247.

Sakulich, A. R. (2011). Reinforced geopolymer composites for enhanced material greenness and durability. *Sustainable Cities and Society*. 1(4), 195-210.

Salam, M. A., Safiuddin, M. and Jumaat, M. Z. (2013). Microstructure of Self-Consolidating High Strength Concrete Incorporating Palm Oil Fuel. Ash. *Physical Review & Research International*. 3(4), 674-687.

Salih, M. A., Abang Ali, A. A. and Farzadnia, N. (2014). Characterization of mechanical and microstructural properties of palm oil fuel ash geopolymer cement paste. *Construction and Building Materials*. 65(0), 592-603.

Sarker, P. K., Haque, R. and Ramgolam, K. V. (2013). Fracture behaviour of heat cured fly ash based geopolymer concrete. *Materials & Design*. 44(0), 580-586.

Sata, V., Jaturapitakkul, C. and Kiattikomol, K. (2007). Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. *Construction and Building Materials*. 21(7), 1589-1598.

Sata, V., Sathonsaowaphak, A. and Chindaprasirt, P. (2012). Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cement and Concrete Composites*. 34(5), 700-708.

Sathonsaowaphak, A., Chindaprasirt, P. and Pimraksa, K. (2009). Workability and strength of lignite bottom ash geopolymer mortar. *Journal of Hazardous Materials*. 168(1), 44-50.

Schmücker, M. and MacKenzie, K. J. (2005). Microstructure of sodium polysialate siloxo geopolymer. *Ceramics International*. 31(3), 433-437.

Schneider, M., Romer, M., Tschudin, M. and Bolio, H. (2011). Sustainable cement production--present and future. *Cement and Concrete Research*. 41(7), 642-650.

Scrivener, K. L. and Nonat, A. (2011). Hydration of cementitious materials, present and future. *Cement and Concrete Research*. 41(7), 651-665.

Shi, C., Jiménez, A. F. and Palomo, A. (2011). New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and Concrete Research*. 41(7), 750-763.

Škvára, F., Doležal, J., Svoboda, P., Kopecký, L., Pawlasová, S., Lucuk, M., Dvořáček, K., Beksa, M., Myšková, L. and Šulc, R. (2007). Concrete based on fly ash geopolymers. *Proceedings of the 2007 Proceedings of 16th IBAUSIL*, 1079-1097.

Somna, K., Jaturapitakkul, C., Kajitvichyanukul, P. and Chindaprasirt, P. (2011). NaOH-activated ground fly ash geopolymer cured at ambient temperature. *Fuel*. 90(6), 2118-2124.

Songpiriyakij, S., Kubprasit, T., Jaturapitakkul, C. and Chindaprasirt, P. (2010). Compressive strength and degree of reaction of biomass- and fly ash-based geopolymer. *Construction and Building Materials*. 24(3), 236-240.

Sperinck, S., Raiteri, P., Marks, N. and Wright, K. (2011). Dehydroxylation of Kaolinite to Metakaolin – A Molecular Dynamics Study. *Journal of Materials Chemistry*. 21(7), 2118-2125.

Spiesz, P. and Brouwers, H. Efficiency of the saturation of concrete with liquid under vacuum conditions.

Stawarczyk, B., Özcan, M., Trottmann, A., Hämmerle, C. H. F. and Roos, M. (2012). Evaluation of flexural strength of hipped and presintered zirconia using different estimation methods of Weibull statistics. *Journal of the Mechanical Behavior of Biomedical Materials*. 10(0), 227-234.

Stevenson, M. and Sagoe-Crentsil, K. (2005). Relationship between composition, structure and strength of inorganic polymers: part 1—metakaolin-derived inorganic polymers. *J. Mater. Sci*. 40, 2023-2036.

Sun, W., Zhang, Y.-s., Lin, W. and Liu, Z.-y. (2004). In situ monitoring of the hydration process of K-PS geopolymer cement with ESEM. *Cement and Concrete Research*. 34(6), 935-940.

Sun, Z., Cui, H., An, H., Tao, D., Xu, Y., Zhai, J. and Li, Q. (2013). Synthesis and thermal behavior of geopolymer-type material from waste ceramic. *Construction and Building Materials*. 49(0), 281-287.

Tamimi, A. K., Abdalla, J. A. and Sakka, Z. I. (2008). Prediction of long term chloride diffusion of concrete in harsh environment. *Construction and Building Materials*. 22(5), 829-836.

Tangchirapat, W., Jaturapitakkul, C. and Chindaprasirt, P. (2009). Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Construction and Building Materials*. 23(7), 2641-2646.

Tangchirapat, W., Saeting, T., Jaturapitakkul, C., Kiattikomol, K. and Siripanichgorn, A. (2007). Use of waste ash from palm oil industry in concrete. *Waste Management*. 27(1), 81-88.

Tchakoute Kouamo, H., Elimbi, A., Mbey, J., Ngally Sabouang, C. and Njopwouo, D. (2012). The effect of adding alumina-oxide to metakaolin and volcanic ash on geopolymer products: A comparative study. *Construction and Building Materials*. 35, 960-969.

Temuujin, J., Minjigmaa, A., Rickard, W., Lee, M., Williams, I. and van Riessen, A. (2009). Preparation of metakaolin based geopolymer coatings on metal substrates as thermal barriers. *Applied Clay Science*. 46(3), 265-270.

Temuujin, J., Okada, K., MacKenzie, K. J. D. and Jadambaa, T. (1999). The effect of water vapour atmospheres on the thermal transformation of kaolinite investigated by XRD, FTIR and solid state MAS NMR. *Journal of the European Ceramic Society*. 19(1), 105-112.

Temuujin, J., van Riessen, A. and MacKenzie, K. J. D. (2010). Preparation and characterisation of fly ash based geopolymer mortars. *Construction and Building Materials*. 24(10), 1906-1910.

Thokchom, S., Ghosh, P. and Ghosh, S. (2009). Effect of water absorption, porosity and sorptivity on durability of geopolymer mortars. *ARPN Journal of Engineering and Applied Sciences*. 4(7).

Topçu, I. B., Boga, A. R. and Hocaoglu, F. O. (2009). Modeling corrosion currents of reinforced concrete using ANN. *Automation in Construction*. 18(2), 145-152.

Trustrum, K. and Jayatilaka, A. (1979). On estimating the Weibull modulus for a brittle material. *J Mater Sci* 14, 1080-1084.

Tumidajski, P. J., Fiore, L., Khodabocus, T., Lachemi, M. and Pari, R. (2006). Comparison of Weibull and normal distributions for concrete compressive strengths. *Canadian Journal of Civil Engineering*. 33(10), 1287-1292.

Turner, L. K. and Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*. 43(0), 125-130.

Van Deventer, J. S. J., Provis, J. L. and Duxson, P. Technical and commercial progress in the adoption of geopolymer cement. *Minerals Engineering*. (0).

Van Jaarsveld, J., Van Deventer, J. and Lukey, G. (2002). The effect of composition and temperature on the properties of fly ash-and kaolinite-based geopolymers. *Chemical Engineering Journal*. 89(1), 63-73.

Verdolotti, L., Iannace, S., Lavorgna, M. and Lamanna, R. (2008). Geopolymerization reaction to consolidate incoherent pozzolanic soil. *Journal of Materials Science*. 43(3), 865-873.

Villa, C., Pecina, E. T., Torres, R. and Gómez, L. (2010). Geopolymer synthesis using alkaline activation of natural zeolite. *Construction and Building Materials*. 24(11), 2084-2090.

Vrech, S. M. and Etse, G. (2009). Gradient and fracture energy-based plasticity theory for quasi-brittle materials like concrete. *Computer Methods in Applied Mechanics and Engineering*. 199(1–4), 136-147.

Wei, S., Sun, Z. and Zongjin, L. (2009). Preparation and microstructure of na-psds geopolymeric matrix. *Ceramics-Silikaty*. 53(2), 88.

Williams, R. P., Hart, R. D. and van Riessen, A. (2011). Quantification of the Extent of Reaction of Metakaolin-Based Geopolymers Using X-Ray Diffraction, Scanning Electron Microscopy, and Energy-Dispersive Spectroscopy. *Journal of the American Ceramic Society*. 94(8), 2663-2670.

Winnefeld, F., Leemann, A., Lucuk, M., Svoboda, P. and Neuroth, M. (2010). Assessment of phase formation in alkali activated low and high calcium fly ashes in building materials. *Construction and Building Materials*. 24(6), 1086-1093.

Wong, T. F., Wong, R. H. C., Chau, K. T. and Tang, C. A. (2006). Microcrack statistics, Weibull distribution and micromechanical modeling of compressive failure in rock. *Mechanics of Materials*. 38(7), 664-681.

Wongpa, J., Kiattikomol, K., Jaturapitakkul, C. and Chindaprasirt, P. (2010). Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete. *Materials & Design*. 31(10), 4748-4754.

Xu, A., Shayan, A. and Baburamani, P. (1998). *Test methods for sulfate resistance of concrete and mechanism of sulfate attack-state of the art review*.

Xu, H., Li, Q., Shen, L., Wang, W. and Zhai, J. (2010). Synthesis of thermostable geopolymer from circulating fluidized bed combustion (CFBC) bottom ashes. *Journal of Hazardous Materials*. 175(1-3), 198-204.

Xu, H. and Van Deventer, J. S. J. (2000). The geopolymerisation of alumino-silicate minerals. *International Journal of Mineral Processing*. 59(3), 247-266.

Xu, H. and Van Deventer, J. S. J. (2002). Geopolymerisation of multiple minerals. *Minerals Engineering*. 15(12), 1131-1139.

Yao, X., Zhang, Z., Zhu, H. and Chen, Y. (2009). Geopolymerization process of alkali–metakaolinite characterized by isothermal calorimetry. *Thermochimica Acta*. 493(1–2), 49-54.

Ylmén, R., Jäglid, U., Steenari, B.-M. and Panas, I. (2009). Early hydration and setting of Portland cement monitored by IR, SEM and Vicat techniques. *Cement and Concrete Research*. 39(5), 433-439.

Yunsheng, Z., Wei, S. and Zongjin, L. (2007). Preparation and microstructure of K-PSDS geopolymeric binder. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 302(1–3), 473-482.

Yunsheng, Z., Wei, S. and Zongjin, L. (2010). Composition design and microstructural characterization of calcined kaolin-based geopolymer cement. *Applied Clay Science*. 47(3–4), 271-275.

Yunsheng, Z., Wei, S., Zongjin, L., Xiangming, Z., Eddie and Chungkong, C. (2008). Impact properties of geopolymer based extrudates incorporated with fly ash and PVA short fiber. *Construction and Building Materials*. 22(3), 370-383.

Zaeni, A., Bandyopadhyay, S., Yu, A., Rider, J., Sorrell, C. S., Dain, S., Blackburn, D. and White, C. (2010). Colour control in fly ash as a combined function of particle size and chemical composition. *Fuel*. 89(2), 399-404.

Zarina, Y., Al Bakri, A. M. M., Kamarudin, H. and Nizar, I. K. (2013). Review of the Characterization and Processing of Palm Ash as a Geopolymer Composite. *Advanced Science Letters*. Volume 19(Number 1), 306-308(303).

Zhang, B., Bicanic, N., Pearce, C. J. and Phillips, D. V. (2002). Relationship between brittleness and moisture loss of concrete exposed to high temperatures. *Cement and Concrete Research*. 32(3), 363-371.

Zhang, Y. J., Li, S., Wang, Y. C. and Xu, D. L. (2012a). Microstructural and strength evolutions of geopolymer composite reinforced by resin exposed to elevated temperature. *Journal of Non-Crystalline Solids*. 358(3), 620-624.

Zhang, Z., Wang, H., Zhu, Y., Reid, A., Provis, J. L. and Bullen, F. (2014). Using fly ash to partially substitute metakaolin in geopolymer synthesis. *Applied Clay Science*. 88–89(0), 194-201.

Zhang, Z., Yao, X. and Wang, H. (2012b). Potential application of geopolymers as protection coatings for marine concrete III. Field experiment. *Applied Clay Science*. 67–68(0), 57-60.

Zhang, Z., Yao, X. and Zhu, H. (2010). Potential application of geopolymers as protection coatings for marine concrete: II. Microstructure and anticorrosion mechanism. *Applied Clay Science*. 49(1–2), 7-12.

Zhu, H., Zhang, Z., Zhu, Y. and Tian, L. (2014). Durability of alkali-activated fly ash concrete: Chloride penetration in pastes and mortars. *Construction and Building Materials*. 65(0), 51-59.

Živica, V., Balkovic, S. and Drabik, M. (2011). Properties of metakaolin geopolymer hardened paste prepared by high-pressure compaction. *Construction and Building Materials*. 25(5), 2206-2213.