PROPERTIES OF ZEOLITE-BASED GEOPOLYMER FOAM REINFORCED NANOCELLULOSE PREPARED IN LOW ALKALINE MEDIA

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By

TAY CHAI HUA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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January 2024

Chairman : Norkhairunnisa Mazlan, PhD
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The growing interest in geopolymer foam, driven by its exceptional properties and environmental benefits, presents promising prospects for diverse industrial applications. However, its reliance on highly concentrated alkaline solutions and fresh water poses significant limitations. Concentrated alkaline solutions are expensive, low in supply, and corrosive, while fresh water is becoming scarce globally. This study developed geopolymer foams using low molarity alkaline solutions and seawater to address these issues. The geopolymer consisted of aluminosilicate zeolite, a mixture of Potassium Silicate (KSil), below 2M Potassium Hydroxide (KOH), Potassium Chloride (KCl), and seawater as the alkaline solution, with Sodium Lauryl Ether Sulphate (SLES) and Benzalkonium Chloride (BAC) as surfactants to stabilize the foam produced by Hydrogen Peroxide (H_2O_2). Nanocellulose (NC) was used as reinforcement.

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Geopolymerisation validation revealed successful depolymerization, reticulation, networking, and solidification of aluminosilicates, indicating that low molarity alkaline solution and seawater can effectively produce geopolymers. Response Surface Methodology (RSM) was used to statistically analyze the impact of each material on properties such as density, porosity, water absorption, and compressive strength. All four models displayed high R^2 values of more than 0.85, indicating that the chosen factors (SW/KSil, KOH/KCl, SLES/BAC, and H_2O_2/NC) effectively explain the variability in the tested properties. Optimization yielded a density of 1.691 g/cm^3, porosity of 52.86%, water absorption of 43.106%, and compressive strength of 0.677 MPa, each with an average error below 15%. This study is the first to report on low molarity alkaline solution and seawater-based geopolymer foam, highlighting its potential as an eco-friendly alternative for various applications.

Keywords: Low molarity; Geopolymer Concrete, Nanocellulose, Response Surface Methodology, Seawater

SDG: GOAL 12: Responsible Consumption and Production

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SIFAT-SIFAT GEOPOLIMER BERASASKAN ZEOLIT BERTETULANG NANOSELULOSA YANG DISEDIAKAN DALAM MEDIA BERALKALI RENDAH

Oleh

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Minat yang semakin meningkat dalam geopolimer berbusa, didorong oleh sifat luar biasa dan faedah alam sekitar, memberikan prospek yang menjanjikan untuk pelbagai aplikasi industri. Walau bagaimanapun, kebergantungannya pada larutan alkali yang sangat pekat dan air tawar menimbulkan had yang ketara. Larutan beralkali pekat adalah mahal, rendah bekalannya, dan menghakis, manakala air tawar semakin berkurangan di seluruh dunia. Kajian ini menghasilkan geopolimer berbusa berasaskan larutan alkali kemolaran rendah dan air laut. Geopolimer terdiri daripada zeolit aluminosilika, campuran Kalium Silikat (KSil), Kalium Hidroksida (KOH) di bawah 2M, Kalium Klorida (KCl), dan air laut sebagai larutan alkali, dan surfaktan Natrium Lauril Eter Sulfat (SLES) and Benzalkonium Klorida (BAC) untuk menstabilkan busa yang dihasilkan oleh Hidrogen Peroksida (H_2O_2). Nanoselulosa (NC) digunakan sebagai tetulang.

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Pengesahan geopolimerisasi mendedahkan kejayaan penyahpolimeran, retikulasi, rangkaian, dan pemejalan aluminosilikat, menunjukkan bahawa larutan alkali kemolaran rendah dan air laut boleh menghasilkan geopolymer dengan berkesan. Metodologi Permukaan Tindak Balas (RSM) digunakan untuk menganalisis secara statistik kesan setiap bahan terhadap sifat geopolimer seperti ketumpatan, keliangan, penyerapan air, dan kekuatan mampatan. Keempat-empat model memaparkan nilai R^2 yang tinggi iaitu lebih daripada 0.85, menunjukkan bahawa faktor yang dipilih (SW/KSil, KOH/KCl, SLES/BAC, dan H_2O_2/NC) menerangkan dengan berkesan kebolehubahan dalam sifat yang diuji. Pengoptimuman menghasilkan ketumpatan 1.691 g/cm^3, keliangan 52.86%, penyerapan air 43.106%, dan kekuatan mampatan 0.677 MPa, setiap satu dengan ralat purata di bawah 15%. Kajian ini adalah yang pertama melaporkan tentang geopolymer berbusar berasaskan larutan alkali kemolaran rendah dan air laut, menonjolkan potensinya sebagai alternatif mesra alam untuk pelbagai aplikasi.

Kata Kunci: Kemolaran rendah, Konkrit geopolimer, nanoselulosa, Metodologi permukaan tindak balas, air laut

SDG: MATLAMAT 12: Tanggungjawab terhadap pengunaan dan pengeluaran lestari

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LIST OF ABBREVIATIONS

RSM	Response Surface Methodology
SW	Seawater
KSil	Potassium Silicate
KOH	Potassium Hydroxide
KCl	Potassium Chloride
SLES	Sodium Lauryl Ether Sulphate
BAC	Benzalkonium Chloride
H_2O_2	Hydrogen Peroxide
NC	Nanocellulose
FTIR	Fourier Transform Infrared Spectroscopy
XRF	X-ray Fluorescence
XRD	X-ray Diffraction
FESEM-EDX	Field Emission Scanning Electron with Energy Dispersive X-Ray Spectroscopy
Na	Sodium
K	Potassium
Ca	Calcium
Al_2O_3	Aluminium Oxide
NaOH	Sodium Hydroxide
Na_2O_3	Sodium Silicate
K_2SiO_3	Potassium Silicate
Si	Silica
Al	Alumina

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Geopolymers are networks of mineral molecules linked by covalent bonds (Davidovits, 2017; Davidovits, 2018). This inorganic polymer is produced mainly by mixing aluminosilicates with alkaline solution, forming a ceramic-like structure (Davidovits, 2017). By varying its main composition of aluminosilicates (Esparham et al., 2020) and alkaline solutions (Sore et al., 2020), and additional components such as water content (Vu et al., 2020) and reinforcement (Dheyaaldin et al., 2023), the properties of geopolymer can be tailored accordingly.

Initially, geopolymer was invented to develop a nonflammable and noncombustible plastic material (Davidovits, 2015a). Over time, geopolymer has evolved to exhibit similar or higher compressive strength compared to Ordinary Portland Cement (OPC) (Chowdhury et al., 2021), making it a greener, potential alternative to OPC, which emits high energy during its production (Amran et al., 2020). This is because the preparation of geopolymer avoids the “two grinding and one burning” process in the current OPC production (which are the raw material grinding, clinker calcination, and cement grinding) (Zhao et al., 2021). Governed by its environmentally friendly approach of using low embodied energy aluminosilicates, and low processing

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energy, geopolymer has been developed as other materials such as ceramics (Mohd Mortar et al., 2022), coatings (Jiang et al., 2020), adhesives (He et al., 2011), and resin for composites (Ranjbar and Zhang, 2020), for potential applications in construction, manufacturing, and environmental engineering.

Geopolymer foam is an emerging material for similar applications mentioned beforehand but with higher porosity and therefore lower compressive strength. This is conducted by introducing porosity in the material through methods such as the addition of foaming agent (Hajimohammadi et al., 2018). Thus, geopolymer foam exhibits additional properties such as low density (Shakouri et al., 2020) and high-water absorption (Alnahhal et al., 2022) which expands its potential applications to lightweight concrete (Dhasindrakrishna et al., 2021) and evaporative cooling construction material (Emdadi et al., 2017). As such, this drives the escalating studies on the effect of variation in composition of geopolymer foam and its relation to the material's properties, such as density (Dhasindrakrishna et al., 2021), porosity (Gu et al., 2020), water absorption (Wang et al., 2020; Alnahhal et al., 2022) and compressive strength (Jaya et al., 2020; Polat and Güden, 2021). This reinforces geopolymer and its derivative, geopolymer foam, as a green and versatile material that deserves intensive research.

1.2 Problem Statement

Despite the mentioned environmentally friendly traits of geopolymer and significant research performed on the material, the commercialisation of the

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technology is still in infancy (Shamsaei et al., 2021). This is due to the utilization of concentrated alkaline solution in geopolymer preparation (Abdollahnejad et al., 2015; Assi et al., 2018). Review papers have reported on high concentration of alkaline solution in conventional geopolymers ranging between 8M to 16M (Nakum and Arora, 2022) and 8M to 14M (Ng et al., 2018a). These alkaline solutions are selected for its ability to dissolve more aluminosilicate, leading to higher geopolymerisation and subsequently higher strength (Shilar et al., 2022; Farhan et al., 2020; John et al., 2021). This raises several issues: the deficit in current alkaline solution supply, the high cost in geopolymer preparation and the adverse effects on both human health and the environment due to their corrosive nature.

Currently, there is a deficit supply of alkaline solution worldwide. If the common geopolymer prepared in concentrated alkaline solution were to replace OPC globally, only 7.3% could be replaced due to the deficit in current Sodium Hydroxide (NaOH) supply (Assi et al., 2020). Additionally, the utilisation of current concentrated alkaline solution incurs high cost in geopolymer preparation, up to 139% of OPC (McLellan et al., 2011). According to Abdollahnejad, 80% of this cost is caused by the alkaline solution (Abdollahnejad, 2015). Moreover, the utilisation of such high concentration alkaline solutions posed risk both to humans and the environment. Potassium Hydroxide (KOH) solution with concentration exceeding 1.78M already qualifies as corrosive to humans (Statlab, 2024). This indicates that the preparation of conventional geopolymers presents a potential hazard to workers. In the environmental aspect, while the Carbon Dioxide (CO2)

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emission of geopolymer concrete is lower than OPC, its impact in categories such as ozone layer depletion, fresh water ecotoxicity, and photochemical oxidation surpasses OPC. These issues are caused by the production process of alkaline solution. This summation was made by comparing the 16M based geopolymer concrete to OPC (Habert et al., 2011).

Fresh water is a component of the geopolymer mixture, serving as the medium in which the alkaline solution is mixed and produced. However, according to the United Nations, the world is facing an imminent water crisis, with demand expected to outstrip the fresh water supply by 40% by the end of 2030 (United Nations, 2024). The building sector solely consumes up to 20% of the annual global water usage. This issue forces the United Nation Environment Programme (UNEP) to seek and identify opportunities and best practices for achieving greater water resource efficiency in the construction supply chain (UNEP, 2024). Additionally, the cost of construction in sea islands and remote coastal areas increases significantly due to the transportation expense for the major constituents such as fresh water, which are only available at a distance from the construction site (Thanh et al., 2022). Together, this highlights the issue of fresh water scarcity, exacerbating the challenges faced by the construction industry, particularly in regions where fresh water is limited. The combination of these two issues, the utilisation of concentrated alkaline solutions and the scarcity of fresh water pushes the need to innovate the current geopolymer material prepared in concentrated alkaline solution and fresh water.

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To tackle the issue of concentrated alkaline solution, geopolymer foam may be prepared in low molarity alkaline solution, preferably KOH below 1.78M to eliminate the issue of corrosiveness on humans. However, there is limited research on the use of low molarity alkaline solution (Qin et al., 2022). In relation to the scarcity of fresh water, geopolymer foam may be prepared using seawater instead. Approximately 97% of the Earth's water is seawater. This suggests that the vast supply of seawater could serve as a substitute for fresh water, potentially reducing the dependency on the fresh water. While there is reported work on seawater based geopolymer (Sun et al., 2023), to the best of author's knowledge, there is no work reported on the combination of seawater based geopolymer foam prepared in low molarity alkaline solution. As a result, there is insufficient data on the properties of such geopolymers, which include density, porosity, water absorption, and compressive strength. Additionally, this leads to lack of studies on its microstructural and elemental analysis as well. Therefore, the use of statistical methods such as Response Surface Methodology (RSM) which facilitates statistical analysis, modelling of large data, optimization of responses and reduction of experimental run, would be great to contribute to a large dataset in the material domain at a lower material cost.

1.3 Research Objectives

The main objective is to develop a low molarity alkaline solution and seawater based geopolymer foam. In this study, the concentration of alkaline solution

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used is below 1.62M, defining the term low molarity from hereon. Along with the main objective, the supporting objectives include:

1. To design experimental works for low molarity alkaline solution and seawater based geopolymer foam using RSM and statistically analyse the experimental data.
2. To conduct experiments on the density, porosity, water absorption and compressive strength of low molarity alkaline solution and seawater based geopolymer foam.
3. To analyse the physical, morphology, and chemical characteristics of low molarity alkaline solution and seawater based geopolymer foam.
4. To investigate the optimum range of composition for low molarity alkaline solution and seawater based geopolymer foam that produces the lowest density, highest porosity, highest water absorption and highest compressive strength.

1.4 Research Scope and Limitation

There are several scopes in this study. Firstly, the seawater used is collected in the foreshore area of Dataran 1 Malaysia, Melaka, Malaysia. Since the nominal composition of seawater varies globally (Ali et al., 2016), the discussion on the effect of seawater on the properties of low molarity alkaline solution and seawater based geopolymer foam is limited to only the seawater collected from this specific location.

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Secondly, the design of the experiment is based on four factors, involving eight materials which are seawater/Potassium Silicate (SW/KSil), Potassium Hydroxide/Potassium Chloride (KOH/KCl), Sodium Lauryl Ether Sulphate/Benzalkonium Chloride (SLES/BAC) and Hydrogen Peroxide/Nanocellulose (H_2O_2/NC). Each of the factors are designed with their respective low and high levels, which scopes their range of loading. The ratio of SW/KSil is designed at 1 to 1.2, KOH/KCl is designed at 20%/80% to 100/0% of 10 wt% of KSil, SLES/BAC is designed at 0%/100% to100%/0% of 0.05 wt% Basic Geopolymer Slurry (BGS) and H_2O_2/NC is designed at 0.4 wt% of BSG. As a result, the concentration of KOH solution studied is between 0.32M and 1.62M.

Thirdly, the mechanical characterization of samples is focused on only the compressive test. Given the anticipated low strength of the material, the characterization is focused on physical properties such as density, porosity, and water absorption, which are significant for application of low strength geopolymer foam.

In this study, there is a limitation in the porosity analysis conducted using water immersion method. Since there is a minimum pore size of which water can pass through, there may be tiny pores that are not measurable through this method, thereby limiting this analysis to only pores that are accessible to water. Assumption also has to be made, such that there are no pores that are inaccessible to water.

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1.5 Thesis Organization

This thesis consists of five chapters. Chapter One underlines the research background, problem statement, research objectives, research scope and limitation, and thesis organisation.

Chapter Two presents the literature review on the fundamentals of geopolymer material, encompassing the main materials used for the preparation, as well as the processes involved in the preparation. Additionally, the issue with using concentrated alkaline solution and fresh water in the preparation of geopolymer is highlighted here, followed by the research gap in the current research area, thereby paving way for this study.

Chapter Three presents the properties of all the raw materials used in the geopolymer foam fabrication, describes the experimental design under RSM, explains the sample preparation set-up, and presents the methods in material characterization.

Chapter Four presents the results and discussion of the study. It begins with a scoping analysis for RSM to identify suitable factors and parameters. Subsequently, a geopolymerization validation analysis was conducted on all RSM samples. This was followed by a statistical analysis of each response: density, porosity, water absorption, and compressive strength, supplemented by microscopic images. Optimization was then performed to find the composition that resulted in the lowest density, highest porosity, highest water

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absorption, and highest compressive strength. Finally, superimposition was carried out to determine the composition that achieved the desired combination of responses.

Chapter Five concludes the whole study and suggests recommendations for future research.

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REFERENCES

Abdollahnejad, Z., Pacheco-Torgal, F., Félix, T., Tahri, W., & Aguiar, J. B. (2015). Mix design, properties and cost analysis of fly ash-based geopolymer foam. *Construction and Building Materials, 80*, 18-30.

Abdullah, M. M. A. B., Faris, M. A., Tahir, M. F. M., Kadir, A. A., Sandu, A. V., Isa, N. M., & Corbu, O. (2017). Performance and characterization of geopolymer concrete reinforced with short steel fibre. *In IOP conference series: materials science and engineering* (Vol. 209, No. 1, p. 012038). IOP Publishing.

Abdullah, S. F. A., Yun-Ming, L., Al Bakri, M. M., Cheng-Yong, H., Zulkifly, K., & Hussin, K. (2018). Effect of alkali concentration on fly ash geopolymers. *In IOP Conference Series: Materials Science and Engineering* (Vol. 343, No. 1, p. 012013). IOP Publishing.

Aboulayt, A., Riahi, M., Touhami, M. O., Hannache, H., Gomina, M., & Moussa, R. J. A. P. T. (2017). Properties of metakaolin based geopolymer incorporating calcium carbonate. *Advanced Powder Technology, 28*(9), 2393-2401.

Aghajanzadeh, I., Ramezanianpour, A. M., Amani, A., & Habibi, A. (2024). Mixture optimization of alkali activated slag concrete containing recycled concrete aggregates and silica fume using response surface method. *Construction and Building Materials, 425*, 135928.

Ali, L., Girba, I. A., Pruiu, A., & Marasescu, D. (2016). About the maintenance of the heat flow exchangers from energetically naval systems. *Scientific Bulletin of Naval Academy*, 19, 139-146.

Alnahhal, A. M., Alengaram, U. J., Yusoff, S., Darvish, P., Srinivas, K., & Sumesh, M. (2022). Engineering performance of sustainable geopolymer foamed and non-foamed concretes. *Construction and Building Materials, 316*, 125601.

Alomayri, T. (2019). Experimental study of the microstructural and mechanical properties of geopolymer paste with nano material (Al2O3). *Journal of Building Engineering, 25*, 100788.

Alvi, M. A. A., Khalifeh, M., & Agonafir, M. B. (2020). Effect of nanoparticles on properties of geopolymers designed for well cementing applications. *Journal of Petroleum Science and Engineering, 191*, 107128.

Amran, Y. M., Alyousef, R., Alabduljabbar, H., & El-Zeadani, M. (2020). Clean production and properties of geopolymer concrete; A review. *Journal of Cleaner Production, 251*, 119679.

Assi, L. N., Deaver, E. E., ElBatanouny, M. K., & Ziehl, P. (2016). Investigation of early compressive strength of fly ash-based geopolymer concrete. *Construction and Building Materials, 112*, 807-815.

Assi, L., Carter, K., Deaver, E. E., Anay, R., & Ziehl, P. (2018). Sustainable concrete: Building a greener future. *Journal of cleaner production, 198*, 1641-1651.

Assi, L. N., Carter, K., Deaver, E., & Ziehl, P. (2020). Review of availability of source materials for geopolymer/sustainable concrete. *Journal of Cleaner Production, 263*, 121477.

Bai, C., Franchin, G., Elsayed, H., Zaggia, A., Conte, L., Li, H., & Colombo, P. (2017). High-porosity geopolymer foams with tailored porosity for thermal insulation and wastewater treatment. *Journal of Materials Research, 32*(17), 3251-3259.

Basiri, A., Zaïri, F., Azadi, M., & Ghasemi-Ghalebahman, A. (2022). Micromechanical constitutive modelling of tensile and cyclic behaviours of nano-clay reinforced metal matrix nanocomposites. *Mechanics of Materials, 168*, 104280.

Brown, S., Tauler, R., & Walczak, B. (Eds.). (2020). Comprehensive chemometrics: chemical and biochemical data analysis. Elsevier.

Burduhos Nergis, D. D., Abdullah, M. M. A. B., Sandu, A. V., & Vizureanu, P. (2020). XRD and TG-DTA study of new alkali activated materials based on fly ash with sand and glass powder. *Materials, 13*(2), 343.

Catauro, M., Viola, V., & D'Amore, A. (2023). Mosses on geopolymers: preliminary durability study and chemical characterization of metakaolin-based geopolymers filled with wood ash. *Polymers, 15*(7), 1639.

Chen, L. G., & Bermudez, H. (2012). Solubility and aggregation of charged surfactants in ionic liquids. *Langmuir, 28*(2), 1157-1162.

Chen, S., Ruan, S., Zeng, Q., Liu, Y., Zhang, M., Tian, Y., & Yan, D. (2022). Pore structure of geopolymer materials and its correlations to engineering properties: A review. *Construction and Building Materials, 328*, 127064.

Chen, Z., Yu, J., Nong, Y., Yang, Y., Zhang, H., & Tang, Y. (2023). Beyond time: Enhancing corrosion resistance of geopolymer concrete and BFRP bars in seawater. *Composite Structures, 322*, 117439.

Chen, Y. C., Lee, W. H., Cheng, T. W., & Li, Y. F. (2024). A Study on the Shrinkage and Compressive Strength of GGBFS and Metakaolin Base Geopolymer under Different NaOH Concentrations. Materials, 17(5), 1181.

Chindaprasirt, P., & Somna, K. (2015). Effect of addition of microsilica and nanoalumina on compressive strength and products of high calcium fly ash

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geopolymer with low concentration NaOH. *Advanced Materials Research, 1103*, 29-36.

Chowdhury, S., Mohapatra, S., Gaur, A., Dwivedi, G., & Soni, A. (2021). Study of various properties of geopolymer concrete–A review. *Materials Today: Proceedings, 46*, 5687-5695.

Collins, K. D. (1997). Charge density-dependent strength of hydration and biological structure. *Biophysical journal, 72*(1), 65-76.

Cong, P., & Cheng, Y. (2021). Advances in geopolymer materials: A comprehensive review. *Journal of Traffic and Transportation Engineering (English Edition), 8*(3), 283-314.

da Costa Correia, V., Ardency, M., Claramunt, J., & Savastano, H. (2019). Assessment of chemical and mechanical behaviour of bamboo pulp and nanofibrillated cellulose exposed to alkaline environments. *Cellulose, 26*, 9269-9285.

Dal Poggetto, G., D'Angelo, A., Blanco, I., Piccolella, S., Leonelli, C., & Catauro, M. (2021). FT-IR Study, Thermal Analysis, and Evaluation of the Antibacterial Activity of a MK-Geopolymer Mortar Using Glass Waste as Fine Aggregate. *Polymers, 13*(17), 2970.

Das, S. K., & Shrivastava, S. (2021). Influence of molarity and alkali mixture ratio on ambient temperature cured waste cement concrete based geopolymer mortar. *Construction and Building Materials, 301*, 124380.

Davidovits, J. (2015a). Geopolymer chemistry and applications book. Geopolymer Institute, St Quentin, France.

Davidovits, J. (2015b). False values on CO2 emission for geopolymer cement/concrete published in scientific papers. Technical paper, 24, 1-9.

Davidovits, J. (2017). Geopolymers: Ceramic-like inorganic polymers. *J. Ceram. Sci. Technol, 8*(3), 335-350.

Davidovits, J. (2018). Why alkali-activated materials (AAM) are not geopolymers. Publication Technical Paper, 25.

Deb, P. S., Nath, P., & Sarker, P. K. (2015). Drying shrinkage of slag blended fly ash geopolymer concrete cured at room temperature. *Procedia Engineering, 125*, 594-600.

Dhasindrakrishna, K., Pasupathy, K., Ramakrishnan, S., & Sanjayan, J. (2021). Progress, current thinking and challenges in geopolymer foam concrete technology. *Cement and Concrete Composites, 116*, 103886.

Dheyaaldin, M. H., Mosaberpanah, M. A., & Shi, J. (2023). The effects of nanomaterials on the characteristics of aluminosilicate-based geopolymer composites: a critical review. *Journal of Building Engineering*, 106713.

Dias, J. R. (2020). Teaching of chemistry before and after the periodic table. *Foundations of Chemistry, 22*(1), 99-106.

Dinçer, I. and Bostancı, M. (2018). Capillary water absorption characteristics of some Cappadocian ignimbrites and the role of capillarity on their deterioration. *Environmental Earth Sciences. 78*(1), 1-18.

Dinçer, I. and Orhan, A. (2016). Effect of Pore Size Distribution on Capillary Water Absorption Characteristics of Pyroclastic Rock. *Conference: International Black Sea Mining & Tunnelling Symposium (IBSMTS 2016). 2nd-4th November 2016.* Trabzon: Turkey.

Do, Q. M., Bui, T. H., & Nguyen, H. T. (2019). Effects of seawater content in alkaline activators to engineering properties of fly ash-based geopolymer concrete. *Solid State Phenomena, 296*, 105-111.

Ducman, V., & Korat, L. (2016). Characterization of geopolymer fly-ash based foams obtained with the addition of Al powder or H_2O_2 as foaming agents. *Materials characterization, 113*, 207-213.

Emdadi, Z., Asim, N., Amin, M. H., Ambar Yarmo, M., Maleki, A., Azizi, M., & Sopian, K. (2017). Development of green geopolymer using agricultural and industrial waste materials with high water absorbency. *Applied Sciences, 7(5)*, 514.

Farhan, K. Z., Johari, M. A. M., & Demirboğa, R. (2020). Assessment of important parameters involved in the synthesis of geopolymer composites: A review. *Construction and Building Materials, 264*, 120276.

Farhana, Z. F., Kamarudin, H., Rahmat, A., & Al Bakri, A. M. (2015). The relationship between water absorption and porosity for geopolymer paste. *In Materials Science Forum (Vol. 803, pp. 166-172)*. Trans Tech Publications Ltd.

Farida, F. M., Kusumohadi, C. S., Wibisono, J. J., and Surahman, A. (2023). Water and steam curing types and three NaOH molarities effects due to fly ash based geopolymer concrete compressive strength study. *Journal of Engineering Science and Technology, 18*(1), 167-177.

Frayyeh, Q. J., & Kamil, M. H. (2021). The effect of adding fibers on dry shrinkage of geopolymer concrete. *Civil Engineering Journal, 7*(12), 2099-2108.

Fromm, K. M. (2020). Chemistry of alkaline earth metals: It is not all ionic and definitely not boring!. *Coordination Chemistry Reviews, 408*, 213193.

Geopolymer Institute, (2006). H2O, SiO2 and Al2O3 ratios. Retrieved from https://www.geopolymer.org/faq/h2o-sio2-and-al2o3-ratios/

© COPYRIGHT UPM

Geopolymer Institute. (2017). The Geopolymer Route to High Tech Ceramic [Video]. YouTube. The Geopolymer Route to High Tech Ceramic – YouTube

Gijbels, K., Pontikes, Y., Samyn, P., Schreurs, S., & Schroeyers, W. (2020). Effect of NaOH content on hydration, mineralogy, porosity and strength in alkali/sulfate-activated binders from ground granulated blast furnace slag and phosphogypsum. *Cement and Concrete Research, 132*, 106054.

Gu, G., Xu, F., Ruan, S., Huang, X., Zhu, J., & Peng, C. (2020). Influence of precast foam on the pore structure and properties of fly ash-based geopolymer foams. *Construction and Building Materials, 256*, 119410.

Habert, G., De Lacaillerie, J. D. E., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of cleaner production, 19*(11), 1229-1238. https://doi.org/10.1016/j.jclepro.2011.03.012.

Hajimohammadi, A., Ngo, T., & Mendis, P. (2018). Enhancing the strength of pre-made foams for foam concrete applications. *Cement and Concrete Composites, 87*, 164-171.

Han, K., Zhou, J., Li, Q., Shen, J., Qi, Y., Yao, X., & Chen, W. (2020). Effect of filler structure on the dielectric and thermal properties of SiO2/PTFE composites. Journal of Materials Science: *Materials in Electronics, 31*, 9196-9202.

Harmaji, A. (2022). Seawater as Alkali Activator in Fly Ash Based Geopolymer. Engineering, *Mathematics and Computer Science Journal (EMACS), 4*(2), 45-49.

Hart, P. W., Colson, G. W., & Burris, J. (2011). Application of carbon dioxide to reduce water-side lime scale in heat exchangers. *J. Sci. Technol. For. Prod. Process, 1*, 67-70.

He, J., Zhang, G., Hou, S., & Cai, C. S. (2011). Geopolymer-based smart adhesives for infrastructure health monitoring: Concept and feasibility. *Journal of Materials in Civil Engineering, 23*(2), 100-109.

Hockmeyer, H. (2010). Practical Guide to High-Speed Dispersion. Paint Coat. Ind, 26, 32-36.

Inazumi, S., Inazawa, T., Soralump, S., Saiki, O., & Matsumoto, H. (2017). Assessment of potassium silicate based surface penetration materials with low viscosity in the repair of concrete structures. *GEOMATE Journal, 12*(29), 163-170.

Ismail, I., Provis, J. L., Van Deventer, J. S. J., & Hamdan, S. (2011). The effect of water content on compressive strength of geopolymer mortars. *In AES-ATEMA'2011 International Conference on Advances and Trends in*

© COPYRIGHT UPM

Engineering Materials and their Applications (pp. 4-8).

Jaya, N. A., Yun-Ming, L., Cheng-Yong, H., Abdullah, M. M. A. B., & Hussin, K. (2020). Correlation between pore structure, compressive strength and thermal conductivity of porous metakaolin geopolymer. *Construction and Building Materials, 247*, 118641.

Jiang, C., Wang, A., Bao, X., Ni, T., & Ling, J. (2020). A review on geopolymer in potential coating application: Materials, preparation and basic properties. *Journal of Building Engineering, 32*, 101734.

John, S. K., Nadir, Y., & Girija, K. (2021). Effect of source materials, additives on the mechanical properties and durability of fly ash and fly ash-slag geopolymer mortar: A review. *Construction and Building Materials, 280*, 122443.

Jozić, D., Zorica, S., Tibljaš, D., & Bernstorff, S. (2012). Insitu SAXS/WAXS study of the developing process of geopolymer structures. *In ECCM15-15th European conference on composite materials*.

Jun, Y., Yoon, S., & Oh, J. E. (2017). A comparison study for chloride-binding capacity between alkali-activated fly ash and slag in the use of seawater. *Applied Sciences, 7*(10), 971.

Kaewapai, K., Lertcumfu, N., Jaita, P., Manotham, S., Tunkasiri, T., Malasri, P., & Rujijanagul, G. (2019). Preparation and characterization of ceramic waste-based geopolymer ceramic composites for substrate culture application. *Key Engineering Materials, 798*, 194-199.

Kani, E. N., Allahverdi, A., & Provis, J. L. (2012). Efflorescence control in geopolymer binders based on natural pozzolan. *Cement and Concrete Composites, 34*(1), 25-33.

Karthik, A., Sudalaimani, K., Vijayakumar, C. T., & Saravanakumar, S. S. (2019). Effect of bio-additives on physico-chemical properties of fly ash-ground granulated blast furnace slag based self cured geopolymer mortars. *Journal of hazardous materials, 361*, 56-63.

Kohout, J., Koutník, P., Hájková, P., Kohoutová, E., & Soukup, A. (2022). Effect of Different Types of Aluminosilicates on the Thermo-Mechanical Properties of Metakaolinite-Based Geopolymer Composites. *Polymers, 14*(22), 4838.

Kriven, W. M., Bell, J. L., & Gordon, M. (2003). Microstructure and microchemistry of fully-reacted geopolymers and geopolymer matrix composites. Ceramic Transactions, 153(1994), 227-250.

Kume, G., Gallotti, M., & Nunes, G. (2008). Review on anionic/cationic surfactant mixtures. *Journal of Surfactants and Detergents, 11*(1), 1-11.

© COPYRIGHT UPM

Kwak, H. W., Lee, H., Park, S., Lee, M. E., & Jin, H. J. (2020). Chemical and physical reinforcement of hydrophilic gelatin film with di-aldehyde nanocellulose. International Journal of Biological Macromolecules, 146, 332-342.

Lao, J. C., Huang, B. T., Xu, L. Y., Khan, M., Fang, Y., & Dai, J. G. (2023). Seawater sea-sand Engineered Geopolymer Composites (EGC) with high strength and high ductility. Cement and Concrete Composites, 138, 104998

Latif, M., Jiang, Y., Song, J., & Kim, J. (2023). Additively-Manufactured High-Concentration Nanocellulose Composites: *Structure and Mechanical Properties. Polymers, 15*(3), 669.

Lazorenko, G., Kasprzhitskii, A., Mischinenko, V., & Kruglikov, A. (2022). Fabrication and characterization of metakaolin-based geopolymer composites reinforced with cellulose nanofibrils. *Materials Letters, 308*, 131146.

Lee, W. K. W., & Van Deventer, J. S. J. (2002). The effects of inorganic salt contamination on the strength and durability of geopolymers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 211*(2-3), 115-126.

Li, X., Rao, F., Song, S., & Ma, Q. (2020). Effect of cristobalite on the mechanical behaviour of metakaolin-based geopolymer in artificial seawater. *Advances in Applied Ceramics, 119*(1), 29-36.

Limbachiya, M., Meddah, M. S., & Ouchagour, Y. (2012). Use of recycled concrete aggregate in fly-ash concrete. *Construction and Building Materials, 27*(1), 439-449.

Ling, Y., Wang, K., & Fu, C. (2019). Shrinkage behavior of fly ash based geopolymer pastes with and without shrinkage reducing admixture. *Cement and Concrete Composites, 98*, 74-82.

Liu, Y., Zhao, S., Qiu, X., Meng, Y., Wang, H., Zhou, S., ... & Yan, C. (2023a). Clinoptilolite based zeolite-geopolymer hybrid foams: Potential application as low-cost sorbents for heavy metals. *Journal of Environmental Management, 330,* 117167.

Liu, J., Doh, J. H., Ong, D. E., Yang, Y., Dinh, H. L., & Zi, G. (2023b). Correlation between Dissolution Kinetics of Si, Al, and Fe from Aluminosilicate Precursor and Strength of Fly Ash-Based Geopolymer. *Construction and Building Materials, 393*, 1-19.

Lizcano, M., Gonzalez, A., Basu, S., Lozano, K., & Radovic, M. (2012). Effects of water content and chemical composition on structural properties of alkaline activated metakaolin-based geopolymers. *Journal of the American Ceramic Society, 95*(7), 2169-2177.

© COPYRIGHT UPM

Longhi, M. A., Zhang, Z., Rodríguez, E. D., Kirchheim, A. P., & Wang, H. (2019). Efflorescence of alkali-activated cements (geopolymers) and the impacts on material structures: a critical analysis. *Frontiers in Materials, 6*, 89.

Longhi, M. A., Zhang, Z., Walkley, B., Rodríguez, E. D., & Kirchheim, A. P. (2021). Strategies for control and mitigation of efflorescence in metakaolin-based geopolymers. *Cement and Concrete Research, 144*, 106431.

Lv, W., Sun, Z., & Su, Z. (2020a). Study of seawater mixed one-part alkali activated GGBFS-fly ash. *Cement and Concrete Composites, 106*, 103484.

Lv, X. S., Qin, Y., Lin, Z. X., Tian, Z. K., & Cui, X. M. (2020b). Inhibition of efflorescence in na-based geopolymer inorganic coating. *ACS omega, 5*(24), 14822-14830.

Ma, Z., Wang, W., Li, J., Gao, J., Lu, G., Song, H., ... & Guo, Y. (2023). Long-term dissolution behavior of amorphous aluminosilicate in sodium hydroxide solution for geopolymer synthesis using circulating fluidized bed combustion fly ash. *Construction and Building Materials, 394*, 132143.

Masoule, M. S. T., Bahrami, N., Karimzadeh, M., Mohasanati, B., Shoaei, P., Ameri, F., & Ozbakkaloglu, T. (2022). Lightweight geopolymer concrete: A critical review on the feasibility, mixture design, durability properties and microstructure. *Ceramics International*.

Mastinu, A., Kumar, A., Maccarinelli, G., Bonini, S. A., Premoli, M., Aria, F., ... & Memo, M. (2019). Zeolite clinoptilolite: Therapeutic virtues of an ancient mineral. *Molecules, 24*(8), 1517.

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

Mohammad, F., Bwatanglang, I. B., Al Balawi, A. N., Chavali, M., & Al-Lohedan, H. A. (2020). General introduction on sustainable nanocellulose and nanohydrogel matrices. In Sustainable Nanocellulose and Nanohydrogels from Natural Sources (pp. 1-31). Elsevier.

Mohd Mortar, N. A., Abdullah, M. M. A. B., Abdul Razak, R., Abd Rahim, S. Z., Aziz, I. H., Nabiałek, M., ... & Ghazali, M. F. (2022). Geopolymer ceramic application: A review on mix design, properties and reinforcement enhancement. *Materials, 15*(21), 7567.

Mousavi, S. R., Estaji, S., Paydayesh, A., Arjmand, M., Jafari, S. H., Nouranian, S., & Khonakdar, H. A. (2022). A review of recent progress in improving the fracture toughness of epoxy-based composites using carbonaceous nanofillers. *Polymer Composites, 43*(4), 1871-1886.

© COPYRIGHT UPM

Mousavinejad, S. H. G., & Gashti, M. F. (2021). Effects of alkaline solution/binder and Na_2SiO_3/NaOH ratios on fracture properties and ductility of ambient-cured GGBFS based heavyweight geopolymer concrete. In Structures (Vol. 32, pp. 2118-2129). Elsevier.

Nakum, A. V., and Arora, N. K. (2022). The impact of alkaline solution to fly ash ratio with different molarities of sodium hydroxide on self-compacted geopolymer concrete. *Materials Today: Proceedings, 62,* 4168-4176.

Nasrudin, N. R. A. (2018). Dispersion study of nanofillers in geopolymer composite. Master Thesis, Universiti Putra Malaysia.

National Geographic, (2024). Freshwater Resources. https://education.nationalgeographic.org/resource/freshwater-resources/

Ng, C., Alengaram, U. J., Wong, L. S., Mo, K. H., Jumaat, M. Z., & Ramesh, S. (2018a). A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. *Construction and Building Materials, 186*, 550-576.

Ng, H. T., Heah, C. Y., Liew, Y. M., & Abdullah, M. M. A. B. (2018b). The effect of various molarities of NaOH solution on fly ash geopolymer paste. *In AIP Conference Proceedings (Vol. 2045, No. 1, p. 020098). AIP Publishing LLC.*

Nguyen, V. V., Le, V. S., Louda, P., Szczypiński, M. M., Ercoli, R., Růžek, V., ... & Buczkowska, K. E. (2022). Low-density geopolymer composites for the construction industry. *Polymers, 14*(2), 304.

Nguyen-Van, D., Nguyen-Tuan, T., & Pham-Thanh, T. (2022). Experimental study on pervious cement and pervious geopolymer concretes using sea sand and seawater. *GEOMATE Journal, 23*(99), 63-71.

Nithin, A. V., Raj, S. D., & Soman, M. (2024). Optimizing the compressive strength of low-grade hydrous clay and copper slag-based sustainable ternary blended geopolymer mortar. *Journal of Building Engineering*, 109431.

Nuruddin, M. F., Malkawi, A. B., Fauzi, A., Mohammed, B. S., & Al-Mattarneh, H. M. (2016). Effects of alkaline solution on the microstructure of HCFA geopolymers. *In Engineering Challenges for Sustainable Future-Proceedings of the 3rd International Conference on Civil, offshore and Environmental Engineering, ICCOEE* (Vol. 2016).

O'Lenick Jr, A. J. (2005). Anionic/cationic complexes. MMG, 400, 300.

Onoue, K., Sagawa, Y., Atarashi, D., & Takayama, Y. (2022). Optimization of mix proportions and manufacturing conditions of fly ash-based geopolymer mortar by parameters design with dynamic characteristics. *Cement and Concrete Composites, 133*, 104645.

© COPYRIGHT UPM

Ouffa, N., Benzaazoua, M., Belem, T., Trauchessec, R., & Lecomte, A. (2020). Alkaline dissolution potential of aluminosilicate minerals for the geosynthesis of mine paste backfill. *Materials Today Communications, 24*, 101221.

Padmapriya, M., Ramesh, S. T., & Biju, V. M. (2022). Synthesis of seawater based geopolymer: Characterization and adsorption capacity of methylene blue from wastewater. *Materials Today: Proceedings, 51*, 1770-1776.

Park, S., & Pour-Ghaz, M. (2018). What is the role of water in the geopolymerization of metakaolin?. *Construction and Building Materials, 182*, 360-370.

Pasupathy, K., Ramakrishnan, S., & Sanjayan, J. (2022). Effect of hydrophobic surface-modified fine aggregates on efflorescence control in geopolymer. *Cement and Concrete Composites, 126*, 104337.

Patankar, S. V., Jamkar, S. S., & Ghugal, Y. M. (2013). Effect of water-to-geopolymer binder ratio on the production of fly ash based geopolymer concrete. *Int. J. Adv. Technol. Civ. Eng, 2*(1), 79-83.

Paterson, J. (2014). The Art of Mixing: High-Speed Dispensers. Paint and Coatings Industry (PCI).

Petlitckaia, S., & Poulesquen, A. (2019). Design of lightweight metakaolin based geopolymer foamed with hydrogen peroxide. *Ceramics International, 45*(1), 1322-1330.

Pla, C., Cueto, N., Martínez-Martínez, J., García-del-Cura, M. A., & Benavente, D. (2014). A comparison of experimental methods for measuring water permeability of porous building rocks. *Mater. Construcc, 64*(315), e028.

Polat, D., & Güden, M. (2021). Processing and characterization of geopolymer and sintered geopolymer foams of waste glass powders. *Construction and Building Materials, 300*, 124259.

Posi, P., Teerachanwit, C., Tanutong, C., Limkamoltip, S., Lertnimoolchai, S., Sata, V., & Chindaprasirt, P. (2013). Lightweight geopolymer concrete containing aggregate from recycle lightweight block. *Materials & Design (1980-2015), 52*, 580-586.

Pratap, B., Mondal, S., & Rao, B. H. (2023). NaOH molarity influence on mechanical and durability properties of geopolymer concrete made with fly ash and phosphogypsum. In Structures (Vol. 56, p. 105035). Elsevier.

Pratap, B., Mondal, S., & Rao, B. H. (2024). Prediction of compressive strength of bauxite residue-based geopolymer mortar as pavement composite materials: An integrated ANN and RSM approach. *Asian Journal of Civil Engineering, 25*(1), 597-607.

© COPYRIGHT UPM

Priyanka, M., Karthikeyan, M., & Chand, M. S. R. (2020). Development of mix proportions of geopolymer lightweight aggregate concrete with LECA. *Materials Today: Proceedings, 27*, 958-962.

Prud'Homme, E., Michaud, P., Joussein, E., Peyratout, C., Smith, A., & Rossignol, S. (2011). In situ inorganic foams prepared from various clays at low temperature. *Applied clay science*, *51*(1-2), 15-22.

Qin, T. S., Lim, N. H. A. S., Jun, T. Z., & Ariffin, N. F. (2022). Effect of low molarity alkaline solution on the compressive strength of fly ash based geopolymer concrete. International *Journal of Sustainable Building Technology and Urban Development, 13*(2), 155-164.

Queen’s University Belfast, (2012). Geopolymer Research. Retrieved from https://blogs.qub.ac.uk/geopolymer/

Radhi, M. S., Al-Ghaban, A. M., & Al-Hydary, I. A. (2021). RSM Optimizing the Characteristics of Metakaolin based Geopolymer Foam. *In Journal of Physics: Conference Series* (Vol. 1973, No. 1, p. 012151). IOP Publishing.

Rahmawati, C., Aprilia, S., Saidi, T., & Aulia, T. B. (2021). Current development of geopolymer cement with nanosilica and cellulose nanocrystals. *In Journal of Physics: Conference Series* (Vol. 1783, No. 1, p. 012056). IOP Publishing.

Ralph Davidovits, Christine Pelegris, Joseph Davidovits, (2019), Standardized Method in Testing Commercial Metakaolins for Geopolymer Formulations, Technical Paper #26-MK-testing, Geopolymer Institute Library, www.geopolymer.org. DOI: 10.13140/RG.2.2.18109.10727/1

Ranjbar, N., & Zhang, M. (2020). Fiber-reinforced geopolymer composites: *A review. Cement and Concrete Composites, 107*, 103498.

Razak, R. A., Maliki, N. A., Abdullah, M. M. A. B., Ken, P. W., Yahya, Z., & Junaidi, S. (2021). Performance of fly ash based geopolymer concrete in seawater exposure. *In AIP Conference Proceedings* (Vol. 2339, No. 1). AIP Publishing.

Rohit, P., Gunneswara Rao, T. D., & Chandrasekhar, M. (2024). Effect of construction demolition waste as fine aggregate and NaOH molarity on strength and fracture parameters of slag based geopolymer mortars. *Journal of Engineering and Applied Science, 71*(1), 37.

Roopchund, R., Andrew, J., & Sithole, B. (2022). Using cellulose nanocrystals to improve the mechanical properties of fly ash-based geopolymer construction materials. *Engineering Science and Technology, an International Journal, 25*, 100989.

Sanni, S. H., & Khadiranaikar, R. B. (2013). Performance of alkaline solutions on grades of geopolymer concrete. *International Journal of Research in*

© COPYRIGHT UPM

Engineering and Technology, 2(11), 366-371.

Santamouris, M. (2013). Using cool pavements as a mitigation strategy to fight urban heat island—A review of the actual developments. *Renewable and Sustainable Energy Reviews, 26*, 224-240.

Saukani, M., Arief, S., Syahrillah, G. R. F., & Hidayat, N. (2019). The low concentration of sodium hydroxide influence on the compressive strength of fly ash/natural kaolin-based geopolymer. *In IOP Conference Series: Materials Science and Engineering* (Vol. 515, No. 1, p. 012063). IOP Publishing.

Seuba, J., Deville, S., Guizard, C., & Stevenson, A. J. (2016). The effect of wall thickness distribution on mechanical reliability and strength in unidirectional porous ceramics. *Science and Technology of Advanced Materials, 17*(1), 128-135.

Shakouri, S., Bayer, Ö., & Erdoğan, S. T. (2020). Development of silica fume-based geopolymer foams. *Construction and Building Materials, 260*, 120442.

Shamsaei, E., Bolt, O., Basquiroto de Souza, F., Benhelal, E., Sagoe-Crentsil, K., & Sanjayan, J. (2021). Pathways to commercialisation for brown coal fly ash-based geopolymer concrete in Australia. *Sustainability, 13*(8), 4350.

Sharma, A., Thakur, M., Bhattacharya, M., Mandal, T., & Goswami, S. (2019). Commercial application of cellulose nano-composites–A review. *Biotechnology Reports, 21*, e00316.

Sharqawy, M. H., Lienhard, J. H., & Zubair, S. M. (2010). Thermophysical properties of seawater: a review of existing correlations and data. *Desalination and water* treatment, 16(1-3), 354-380.

Shi, J., Liu, B., Liu, Y., Wang, E., He, Z., Xu, H., & Ren, X. (2020). Preparation and characterization of lightweight aggregate foamed geopolymer concretes aerated using hydrogen peroxide. *Construction and Building Materials, 256*, 119442.

Shilar, F. A., Ganachari, S. V., Patil, V. B., Khan, T. Y., & Khadar, S. D. A. (2022). Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: *A review. Case Studies in Construction Materials, 16*, e01014.

Shoaei, P., Momenzadeh, A., Hosseini, H., Rajaei, S., Ameri, F., & Pilehvar, S. (2024). One-part slag/zeolite geopolymer mortars under ambient and heat curing conditions. *Case Studies in Construction Materials, 20*, e02677.

Simão, L., Fernandes, E., Hotza, D., Ribeiro, M. J., Montedo, O. R. K., & Raupp-Pereira, F. (2021). Controlling efflorescence in geopolymers: A new approach. *Case Studies in Construction Materials, 15*, e00740.

Simkiss, K. (1964). Variations in the crystalline form of calcium carbonate precipitated from artificial sea water. *Nature, 201*(4918), 492-493.

Singh, A., Bhadauria, S. S., Mudgal, M., & Srivastava, A. K. (2021). Ground granulated blast furnace slag based geopolymer mortar activated with low concentration alkali. *Indian Journal of Engineering and Materials Sciences (IJEMS), 28*(4), 350-357.

Singh, A., Bhadauria, S. S., Mudgal, M., & Kushwah, S. S. (2022). Effect of alkali activator dosage on compressive and tensile strength of ground granulated blast furnace slag based geopolymer concrete. *Canadian Journal of Civil Engineering, 49*(1), 73-82.

Singh, A., Bhadauria, S. S., Thakare, A. A., Kumar, A., Mudgal, M., & Chaudhary, S. (2024). Durability assessment of mechanochemically activated geopolymer concrete with a low molarity alkali solution. *Case Studies in Construction Materials, 20*, e02715.

Sore, S. O., Messan, A., Prud'Homme, E., Escadeillas, G., & Tsobnang, F. (2020). Comparative study on geopolymer binders based on two alkaline solutions (NaOH and KOH). *Journal of Minerals and Materials Characterization and Engineering, 8*(06), 407.

Statlab (2024), "Potassium Hydroxide Solution 10%," SSC-PHC015, SSC-PHC500, SSC-PHC999, August 18, 2015 [25 March 2024].

Stempihar, J. J., Pourshams-Manzouri, T., Kaloush, K. E., & Rodezno, M. C. (2012). Porous asphalt pavement temperature effects for urban heat island analysis. *Transportation Research Record, 2293(1)*, 123-130.

Sun, L., Zhang, X., Liu, H., Liu, K., Du, H., Kumar, A., ... & Si, C. (2021). Recent advances in hydrophobic modification of nanocellulose. *Current Organic Chemistry, 25*(3), 417-436.

Sun, Z., Li, X., Liu, Q., Tang, Q., Lin, X., Fan, X., ... & Ji, Z. (2023). Recent Advances in Alkali-Activated Materials with Seawater and Sea Sand. *Materials, 16*(9), 3571.

Sunarsih, E. S., As'ad, S., Sam, A. M., & Kristiawan, S. A. (2023a). The effect of sodium hydroxide molarity on setting time, workability, and compressive strength of fly ash-slag-based geopolymer mortar. *In Journal of Physics: Conference Series* (Vol. 2556, No. 1, p. 012019). IOP Publishing.

Sunarsih, E. S., As' ad, S., Sam, A. R. M., & Kristiawan, S. A. (2023b). Properties of fly ash-slag-based geopolymer concrete with low molarity sodium hydroxide. *Civil Engineering Journal, 9*(02).

Tadros, T. F. (2014). An introduction to surfactants. In An Introduction to

© COPYRIGHT UPM

Surfactants. de Gruyter.

Thanh, T. P., Nguyen, T. T., & Nguyen, T. T. (2022). Experimental evaluation of geopolymer concrete strength using sea sand and sea water in mixture. *Civil Engineering Journal, 8*(8), 1574-1583.

Thorpe, D., & Zhuge, Y. (2010, January). Advantages and disadvantages in using permeable concrete as a pavement construction material. *In Proceedings of the 26th Annual Conference of the Association of Researchers in Construction Management (ARCOM 2010)* (Vol. 2, pp. 1341-1350). University of Southern Queensland.

UNEP (2024). Cities and Buildings. https://www.oas.org/en/sedi/dsd/Biodiversity/Sustainable_Cities/Sustainable_Communities/Events/SC%20Course%20Trinidad%202014/ModuleVI/2.%20Cities%20and%20Buildings%20%E2%80%93%20UNEP%20DTIE%20Initiatives%20and%20projects_hd.pdf

United Nations (2024). Press Release: Historic UN conference marks watershed moment to tackle global water crisis and ensure water-secure future. https://www.un.org/sustainabledevelopment/blog/2023/03/press-release-historic-un-conference-marks-watershed-moment-to-tackle-global-water-crisis-and-ensure-water-secure-future/

Vu, M. C., Satomi, T., & Takahashi, H. (2020). Influence of initial water, moisture, and geopolymer content on geopolymer modified sludge. *Construction and Building Materials, 235*, 117420.

Walbrück, K., Maeting, F., Witzleben, S., & Stephan, D. (2020). Natural fiber-stabilized geopolymer foams—A review. Materials, 13(14), 3198.

Wang, J., Du, P., Zhou, Z., Xu, D., Xie, N., & Cheng, X. (2019a). Effect of nano-silica on hydration, microstructure of alkali-activated slag. *Construction and Building Materials, 220*, 110-118.

Wang, J., Meng, Q., Zhang, L., Zhang, Y., He, B. J., Zheng, S., & Santamouris, M. (2019b). Impacts of the water absorption capability on the evaporative cooling effect of pervious paving materials. *Building and Environment, 151*, 187-197.

Wang, J., Nguyen, A. V., & Farrokhpay, S. (2016). A critical review of the growth, drainage and collapse of foams. *Advances in colloid and interface science, 228*, 55-70.

Wang, S., Li, H., Zou, S., & Zhang, G. (2020). Experimental research on a feasible rice husk/geopolymer foam building insulation material. *Energy and Buildings, 226*, 110358.

Wang, Y., Li, L., An, M., Sun, Y., Yu, Z., & Huang, H. (2022). Factors influencing the capillary water absorption characteristics of concrete and their

© COPYRIGHT UPM

relationship to pore structure. *Applied Sciences, 12*(4), 2211.

Wei, T., Zhao, H., & Ma, C. (2021). A comparison of water curing and standard curing on one-part alkali-activated fly ash sinking beads and slag: Properties, microstructure and mechanisms. *Construction and Building Materials, 273*, 121715.

Wongkeo, W., Thongsanitgarn, P., Pimraksa, K., & Chaipanich, A. (2012). Compressive strength, flexural strength and thermal conductivity of autoclaved concrete block made using bottom ash as cement replacement materials. *Materials & Design, 35*, 434-439.

Xie, J., & Kayali, O. (2014). Effect of initial water content and curing moisture conditions on the development of fly ash-based geopolymers in heat and ambient temperature. *Construction and building materials, 67*, 20-28.

Yang, Z., Lu, F., Zhan, X., Zhu, H., Zhang, B., Chen, Z., & Zhang, H. (2024). Mechanical properties and mesoscopic damage characteristics of basalt fibre-reinforced seawater sea-sand slag-based geopolymer concrete. *Journal of Building Engineering, 84*, 108688.

Yeddula, B. S. R., & Karthiyaini, S. (2020). Experimental investigations and GEP modelling of compressive strength of ferrosialate based geopolymer mortars. *Construction and Building Materials, 236*, 117602.

Yekeen, N., Manan, M. A., Idris, A. K., & Samin, A. M. (2017). Influence of surfactant and electrolyte concentrations on surfactant Adsorption and foaming characteristics. *Journal of Petroleum Science and Engineering, 149*, 612-622.

Yip, C. K., Provis, J. L., Lukey, G. C., & van Deventer, J. S. (2008). Carbonate mineral addition to metakaolin-based geopolymers. *Cement and Concrete Composites, 30*(10), 979-985.

Yu, H., Xu, M. X., Chen, C., He, Y., & Cui, X. M. (2022). A review on the porous geopolymer preparation for structural and functional materials applications. *International Journal of Applied Ceramic Technology, 19*(4), 1793-1813.

Zawrah, M. F., Gado, R. A., & Khattab, R. M. (2018). Optimization of slag content and properties improvement of metakaolin-slag geopolymer mixes. *The Open Materials Science Journal, 12*(1).

Zhang, Z., Provis, J. L., Reid, A., & Wang, H. (2014). Fly ash-based geopolymers: The relationship between composition, pore structure and efflorescence. *Cement and concrete research, 64*, 30-41.

Zhang, L., Zhang, F., Liu, M., & Hu, X. (2017). Novel sustainable geopolymer based syntactic foams: An eco-friendly alternative to polymer based syntactic foams. *Chemical Engineering Journal, 313*, 74-82.

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Zhang, Z., Ibrahim, M. H., El-Naas, M. H., & Cai, J. (2018). Zeolites nanocomposite membrane applications in CO2 capture. In Handbook of Nanomaterials for Industrial Applications (pp. 916-921). Elsevier

Zhao, X., Liu, C., Wang, L., Zuo, L., Zhu, Q., & Ma, W. (2019). Physical and mechanical properties and micro characteristics of fly ash-based geopolymers incorporating soda residue. *Cement and Concrete Composites, 98*, 125-136.

Zhao, J., Tong, L., Li, B., Chen, T., Wang, C., Yang, G., & Zheng, Y. (2021). Eco-friendly geopolymer materials: A review of performance improvement, potential application and sustainability assessment. *Journal of Cleaner Production, 307*, 127085.

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