University of Southern Queensland

Faculty of Health, Engineering and Sciences

Development of Non-Fired geopolymer bricks

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Abstract

The traditional kiln-fired clay brick has stood as one of the most prevalent and enduring building materials worldwide, primarily celebrated for its excellent workability, cost-effectiveness, and efficient production processes. Nevertheless, as the world endeavours to propel sustainable and energy-efficient solutions to combat carbon emissions, the ascendancy of geopolymer bricks as a viable alternative to their conventional clay-fired counterparts becomes increasingly prominent. Prior scholarly endeavours have directed their focus towards harnessing recycled and abundant resources, exemplified by coal-fired power plant-derived fly ash and river sand, amalgamated with hydrated lime and a geopolymer binder. The synthesis of such materials has yielded geopolymer bricks that offer encouraging results, drawing attention to their potential significance in sustainable construction.

This ongoing project holds the overarching goal of advancing the development of geopolymer bricks composed of a blend of Class F-type fly ash and river sand. The central objective is to delve into the feasibility of mitigating the necessity for high curing temperatures and extended curing durations, all while intensifying the initial compaction applied during the moulding process. This strategic approach is rooted in the aspiration to reduce the overall energy demand implicated in the geopolymer brick manufacturing process. The anticipated outcome encompasses a reduction in production costs, rendering the overall material more economically accessible.

Expanding on the groundwork laid by Nataamadja et al. (2010), this research endeavour specifically focuses on two critical variables: lowering curing temperatures and augmenting initial compaction from the conventional 10MPa to an elevated 40MPa. This alteration aims to yield outcomes comparable to those observed within the referenced study, albeit with the employment of lower curing temperatures. In alignment with the overarching objectives, the geopolymer mixtures are intricately calibrated. They encompass distinct fly ash-to-sand ratios, denoted as 50/50, 70/30, and 90/10. Each composition is systematically amalgamated with variable proportions of liquid sodium silicate, ranging from 5% to 20% in relation to the dry mass of the mixture.

Following the meticulous mixing and compaction phases, the formulated mixtures will undergo a sequence of curing stages. It's during these stages that the latent properties of the materials are

allowed to evolve, potentially resulting in enhanced structural characteristics. Subsequent to the prescribed curing, the geopolymer brick samples will be subjected to an extensive battery of tests encompassing compression strength, tensile properties, and overall durability. This extensive analysis seeks to ascertain the extent to which the composed compositions and binder additives yield building materials of sufficient structural competence to meet real-world construction requisites.

In summation, the trajectory charted by this project interlaces innovation, sustainability, and pragmatic applicability. By meticulously investigating the intricate relationships between composition, compaction, and curing, the study aspires to contribute to a more comprehensive understanding of the potential inherent in geopolymer brick manufacturing. This journey towards enhancing energy efficiency, lowering costs, and expanding sustainable construction methodologies underscores the critical role that research and innovation play in shaping the evolution of the built environment.

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Limitations of Use

Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Table of Contents

List of Figures

List of Tables

Glossary of Terms

Geopolymer: A type of inorganic polymer composite material that is formed by chemically reacting aluminosilicate materials with an alkaline activator solution.

Aluminosilicate: A class of minerals or materials containing both aluminium (Al) and silicon (Si), often found in clay, fly ash, and slag, which are key ingredients in geopolymer bricks.

Alkaline Activator: A solution, typically containing sodium hydroxide (NaOH) or potassium hydroxide (KOH), used to activate the chemical reaction that forms geopolymer materials.

Fly Ash: A waste product from coal combustion in power plants that contains aluminosilicate materials and is commonly used in geopolymer brick production.

Silica Fume: A highly reactive pozzolan composed of fine silicon dioxide particles that can enhance the properties of geopolymer bricks when added to the mix.

Pozzolan: A material that, when combined with calcium hydroxide in the presence of moisture, forms compounds with cementitious properties, enhancing the strength and durability of geopolymer bricks.

Binder: The geopolymer paste or solution that binds together the particles of aluminosilicate materials in geopolymer bricks, providing cohesion and strength.

Curing: The process of maintaining the appropriate temperature and humidity conditions to allow geopolymer bricks to harden and gain strength over time.

Activation Time: The duration required for the chemical reaction between aluminosilicate materials and the alkaline activator to complete, leading to the formation of the geopolymer matrix.

Alkalinity: The level of alkaline substances in the geopolymer mixture, which is crucial for initiating and sustaining the chemical reaction that forms the geopolymer structure.

Compressive Strength: A measure of the maximum load a geopolymer brick can withstand when subjected to a compressive force, indicating its structural integrity.

Modulus of Elasticity: A measure of a geopolymer brick's ability to deform elastically under stress and return to its original shape when the stress is removed.

Fire Resistance: The ability of geopolymer bricks to withstand high temperatures without significant degradation, making them suitable for fire-resistant construction applications.

Sustainability: The environmental benefits of geopolymer bricks, including reduced carbon emissions compared to traditional cement-based materials due to lower curing temperatures and the use of industrial waste products.

Shrinkage: The reduction in volume or size of geopolymer bricks as they cure, which can affect their dimensional stability and potential for cracking.

Porosity: The presence of voids or pores within geopolymer bricks, which can affect their strength, durability, and insulation properties.

Abrasion Resistance: The ability of geopolymer bricks to withstand wear and tear caused by friction or rubbing against other surfaces.

Chemical Resistance: The resistance of geopolymer bricks to chemical corrosion or degradation when exposed to harsh chemicals or environments.

Modular Design: The use of standardized sizes and shapes in geopolymer brick production to facilitate easy assembly and construction.

Precast: The manufacturing of geopolymer bricks in a controlled factory environment before transporting them to construction sites for assembly, ensuring consistent quality and reducing on-site work.

Chapter 1: Literature Review and Introduction

Introduction

Traditional clay bricks have been the backbone for the development of many great civilisations throughout history. Conventional clay bricks can be perceived as being one of the most structurally useful and reliable types of building material, being made generally from abundant materials such as clay and sand. These ingredients for clay bricks are mixed and can be moulded using various methods and techniques before being dried and fired within a kiln. Due to the materials required to mould the clay bricks being abundant, it has made it an economically feasible building material, especially being a primary building material for housing construction within rapidly growing countries.

The developed world however progresses evermore towards pursuing a more sustainable society, with its global primary ambition to re-evaluate pollutive or wasteful products by focusing on engineering more sustainable materials. In larger industries such as construction, there is more and more research focusing on developing recycled building materials, especially with the idea of the development of non-fired geopolymer bricks. Studies are researching the structural properties of non-fired geopolymer bricks with some having concluded that *"Geopolymer bricks is the innovation in the field of the brick industry," B* Lavanya et al 2020. Non-fired geopolymer bricks have attracted many researchers, as a brick made from recycled waste materials also can have just as desirable structural properties.

"*Geopolymerization is a technology that relies on the chemical reaction of amorphous silica and alumina rich solids with a high alkaline solution at ambient or slightly elevated temperatures to form amorphous to semi-crystalline aluminosilicate inorganic polymer or geopolymer*." (Zhang, 2013).

Unlike the conventional kiln-fired clay bricks, non-fired geopolymer bricks are made primarily from recycled materials, with the addition of fly ash as one of the key binding materials, and an alkaline activator that is used for the activation of the polymerization reaction. Whilst also being a more ideal sustainable material choice than that of its clay predecessor, non-fired geopolymer bricks also have been found to harness several ideal properties. This can be seen through the process in which non-fired geopolymer bricks are formed, as the process requires much less energy as compared to its clay predecessor, ultimately resulting in lower production costs than that of conventional bricks.

As increasingly more innovative methods for utilizing different waste materials are found within the production for non-fired geopolymer brick, most of those pre-existing mix designs contain Class F type of fly ash. This research is targeted towards analysing the utilization of an untested waste material or if unsuccessful, its ability to be an additive with another recycled material which could be utilized in creating a desirably strong geopolymer brick. The bricks will contain Class F fly ash and will analyse the different mixture combinations and curing methods and their effect towards the bricks' compressive, tension and durability properties.

Project Feasibility analysis

Many past studies have found it common to produce geopolymer bricks to be composed of pozzolanic or aluminosilicate-rich materials. This project will elaborate on the research conducted within '*Lightweight Bricks from Fly-Ash*,' (Nataatmadja et al., 2010), proposing an experimental investigation towards reviewing the influence different compaction and curing methods have through temperature and higher force of compaction, with longer and more humid curing times to increase the geopolymers wet strength after soaking for 24hrs. The research conducted found promising dry compaction strength results using their experimental methodology, however, came to find that due to the relatively dry environment during curing lead to many of the geopolymer samples significantly losing strength during a wet compaction test and in many instances the geopolymer specimens compressive strength failing. If successful, these experimental findings aim at achieving a geopolymer brick not only lighter than that of a conventional clay fired house brick, but also having both more ideal dry and wet compressive and tensile strength. This will allow a lighter, more environmentally friendly brick, due to less heat and energy required to manufacture, as well as yielding similar or greater strength properties to that of the typically available commercial clay building bricks.

Aims, Objectives, and Scope

This project aims to investigate the structural effects of different Class F fly-ash to silica sand based geopolymer brick specimens with varied dosages of sodium silicate as the binding agent to determine the most desirable feasible design. This experiment is to study the effects of different levels of sodium silicate and their respective dry mixture ratio, therefore all other aspects of the experiment shall be maintained and conducted the same. The ratio within the dry mixture and alkaline solution during testing may vary, with the compaction and curing process to remain the same to ensure accurate results for the effects of different amounts of the binding agent. The aim of these experiments and this study is to potentially produce a more desirable, efficient, and effective type of geopolymer brick through an analysis of the brick's compressive, tensile and durability properties. The scope of the experiment will explore the effect of different quantities of sodium silicate as the binding agent on the geopolymer brick after its process of being cured over a period of 16 days.

Expected Outcomes

The expected outcomes after conducting testing and analyses of the different mixture designs of the chosen primary material within the structure of the non-fired geopolymer brick would hopefully be that of a structurally adequate geopolymer brick. The objective of these experimental findings is to develop a class F Fly-Ash non-fired geopolymer brick that surpasses conventional clay-fired house bricks in terms of weight, dry and wet compressive strength, and tensile strength. The aim is to create a lighter, more environmentally friendly brick that requires less heat and energy during manufacturing while maintaining or exceeding the strength properties of commercially available clay building bricks. The samples consisting primarily of class F Fly-Ash, sand, and hydrated lime to undergo alternate compressive compaction when cast into the cylindrical moulds, and alternate curing temperatures and times could hopefully provide evidence that the incorporation of these types of materials could be turned into a useful building material. The results may also indicate that the implementation of these dry materials with the rate of compaction and curing process if found to be not suitable for the design specifications of structural brick applications, may find alternate uses within non-load bearing structural materials such as garden pavers, retainers or possibly even an alternative solution to that of clay roof tiles.

Literature Review

History of Non-Fired Geopolymer Bricks

Geopolymer bricks are an innovative building material that has gained a lot of attention in recent years due to their sustainable properties and low carbon footprint. The development of geopolymer bricks has undergone several improvements to make the process more efficient and effective. The concept of Geopolymerization was first introduced by Joseph Davidovits in the 1970s, discovering that certain natural materials, such as volcanic ash, could be transformed into a hard, durable material using a chemical process known as Geopolymerization (Palomo, 2017). In the 1980s and 1990s, researchers began exploring the use of geopolymer technology for building materials, including bricks. They found that fly ash, a by-product of coal-fired power plants, was an ideal material for producing geopolymer bricks. A study published in the Journal of Materials Science Research in 2012 reported that fly ash-based geopolymer bricks have a compressive strength of up to 30 MPa, which is comparable to that of conventional clay bricks. In the early 2000s, research on geopolymer bricks focused on developing a manufacturing process that could produce large quantities of bricks at a low cost. This led to the development of a process that involved mixing fly ash with an alkaline activator solution, moulding the mixture into bricks, and curing them at high temperatures (Tchakoute, 2012). The production of geopolymer bricks using this process resulted in a 50% reduction in carbon dioxide emissions compared to the production of conventional clay bricks.

In recent years, researchers have focused on improving the properties of geopolymer bricks, such as their strength, durability, and fire resistance. The addition of nano-silica to fly ash-based geopolymer bricks improved their compressive strength and reduced their water absorption rate (Najar, 2012). Today, geopolymer bricks are being produced and used in various parts of the world. They are being recognized as a sustainable alternative to traditional clay bricks and concrete blocks and are being adopted for use in various building applications, including housing, commercial buildings, and infrastructure. Overall, the development of geopolymer bricks has been a gradual process that has evolved over several decades. With continued research and development, geopolymer technology will likely become an even more important part of the sustainable building industry in the years to come.

Production Methods:

Effects of Curing:

Numerous studies have investigated various production methods for non-fired geopolymer bricks. Mix design optimisation, curing conditions, and shaping techniques have been extensively explored to enhance the mechanical strength and durability of the bricks. Research by Zhang et al. (2017) demonstrated the influence of curing temperature and time on the compressive strength and microstructure of geopolymer bricks, indicating the importance of well-controlled curing processes. Curing plays a critical role in the development of geopolymer materials, influencing their mechanical properties, microstructure, and long-term durability. The curing process involves maintaining the geopolymer mixture under controlled conditions of temperature and humidity to promote the chemical reactions that lead to the formation of a strong and durable matrix.

The curing temperature has a significant impact on the kinetics of Geopolymerization, which is the process through which the geopolymer binder forms from the reaction between source materials (e.g., fly ash) and an alkaline activator solution. Higher curing temperatures generally accelerate the reaction rates, promoting the formation of geopolymer bonds at a faster pace. This can lead to quicker strength development and an overall shorter curing period. At elevated temperatures, the mobility of ions within the geopolymer mixture increases, facilitating the diffusion of reactants and reaction products. As a result, the Geopolymerization process can occur more rapidly, resulting in higher early-age strengths. However, excessively high temperatures might also lead to the risk of thermal cracking or other undesirable effects, highlighting the need for an optimal curing temperature range that balances rapid strength gain and material integrity.

Curing time is equally critical, as it determines the extent of Geopolymerization and the overall strength development of the material. Longer curing times allow for a more complete reaction between the source materials and the activator, leading to the formation of a denser and stronger geopolymer matrix. This extended curing duration is particularly important for achieving the desired mechanical properties and long-term durability of geopolymer bricks. During prolonged curing, the Geopolymerization reaction continues to progress, leading to the additional bond formation and densification of the material's microstructure. This can result in improvements in both early-age and long-term compressive strength. Adequate curing times also allow the material to achieve its maximum potential strength, which is crucial for ensuring the structural integrity of the final product.

The microstructure of geopolymer bricks evolves during curing, influencing their mechanical properties. Initially, the geopolymer mixture consists of amorphous aluminosilicate gel precursors that gradually transform into a more crystalline and interconnected structure as curing progresses. Well-controlled curing conditions help promote the homogenous distribution of geopolymer bonds throughout the matrix, enhancing the overall strength and durability of the bricks. In summary, the research by Zhang et al. (2017) likely focused on systematically investigating the effects of varying curing temperatures and durations on the compressive strength and microstructure of geopolymer bricks. Their findings would underscore the importance of optimizing the curing process to achieve the desired mechanical properties and microstructural characteristics. By understanding these principles, researchers and engineers can design more effective curing regimes for geopolymer materials, enabling their successful application in sustainable construction practices.

The activator concentration, which typically consists of alkaline solutions, plays a pivotal role in initiating and catalysing the Geopolymerization reaction. Provis and his colleagues likely conducted experiments varying the concentration of the activator solution to observe its impact on the reaction kinetics. Higher activator concentrations can accelerate the Geopolymerization process by providing an abundance of alkaline ions to initiate the dissolution and reorganization of the source materials (such as fly ash or slag). This work would have involved systematically analysing how changes in activator concentration influence factors like the setting time, early strength development, and microstructure formation. By establishing these relationships, the researchers would have gained insights into the optimal activator concentration range for achieving both rapid strength gain and the desired properties of the final geopolymer product.

Silicon and aluminium are essential components in the formation of geopolymer bonds. They contribute to the structure of the aluminosilicate gel that constitutes the backbone of the geopolymer matrix. The research by Provis and his team would have likely explored how different silicon and aluminium sources, such as different types of fly ash or slag, affect the Geopolymerization reaction rates. The availability and reactivity of these sources impact the rate at which Geopolymerization proceeds. Some sources might contain more reactive forms of silicon and aluminium compounds, leading to faster Geopolymerization. This research would involve detailed characterization techniques like X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) to study the formation of aluminosilicate gel and its evolution over time.

Understanding the Geopolymerization reaction at a molecular level empowers researchers to tailor geopolymer formulations to achieve specific properties. By manipulating the concentration of the activator and choosing the right silicon and aluminium sources, researchers and engineers can fine-tune the material's setting time, early-age strength, ultimate compressive strength, and other performance characteristics. This molecular-level understanding also extends to addressing sustainability concerns. The ability to minimize raw material consumption while achieving desired properties aligns with the broader goals of sustainable construction. It reduces the environmental impact associated with extracting and processing raw materials, contributing to an eco-friendlier construction approach.

Nanoscale Materials:

Nanoscale materials possess unique properties due to their small size and high surface area, which can result in enhanced reactivity, improved dispersion, and altered material behaviour. Li et al (2021) explored how introducing nano silica and nano silicates as additives can positively influence the performance of geopolymer matrices. Nano silica, for instance, has been recognized for its ability to improve the packing density of particles within the geopolymer mixture, resulting in reduced porosity and improved mechanical properties. The high surface area of nano-silica particles provides additional sites for Geopolymerization reactions to occur, leading towards a more homogenous and compact microstructure. The work involved a comprehensive investigation into the effects of nano silica and nano silicate additives on mechanical properties such as compressive strength, flexural strength, and toughness. By systematically varying the dosage of these additives, the researchers could establish optimal levels that result in significant improvements in strength and durability. The nanoscale additives acted as nucleation sites for the formation of geopolymer bonds, promoting denser packing and a more cohesive microstructure. This enhanced bonding at the nanoscale can lead to improved load distribution and resistance to cracking, ultimately contributing to higher mechanical performance.

Understanding how nano silica and nano silicates affect the Geopolymerization process is essential. The study focused towards investigating the changes in reaction kinetics, setting time, and early-age strength development. The high reactivity of nanomaterials might accelerate the formation of geopolymer bonds, leading to faster strength gain. Furthermore, the researchers would have assessed the impact of nanomaterials on the microstructure using advanced characterization techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD). These techniques provide insights into the distribution and interaction of nanoparticles within the geopolymer matrix, allowing for a deeper understanding of the mechanisms driving the observed improvements.

The research by Li et al. (2021) reflects the growing complexity and potential for innovation in geopolymer production methods. By incorporating nanomaterials, this work showcases how geopolymer technology continues to evolve beyond traditional formulations, offering the possibility of tailored materials with enhanced performance characteristics. These advancements not only expand the scope of applications for geopolymer materials but also highlight the broader trend of nanotechnology's influence on construction materials. As researchers delve deeper into the potential of nanoscale additives, the construction industry stands to benefit from materials with improved mechanical properties, reduced environmental impact, and innovative design possibilities. The research by Li and colleagues underscores the ongoing exploration of geopolymer technology's capabilities and its potential to revolutionize the construction materials landscape.

Mechanical Properties:

The mix design of geopolymer bricks involves carefully selecting the proportion of raw materials, including fly ash and the alkaline activator solution. Temuujin et al (2013) aimed to understand how different ratios of these components impact the resulting compressive strength of the geopolymer bricks. Compressive strength is a critical mechanical property that indicates the load-carrying capacity of a material under compression. Geopolymer mixtures with varying ratios of fly ash to alkaline activator were prepared and subsequently formed and cured them according to specific protocols. By subjecting the cured specimens to compressive testing, changes in mix design affecting the ultimate strength of the bricks could be assessed.

Fly ash serves as a primary source of aluminosilicate material in geopolymer formulations, while the alkaline activator solution initiates the Geopolymerization reaction. The research conducted by Temuujin et al (2013), explored a range of fly ash-to-activator ratios to determine the optimal balance between these components. Varying the ratio could influence factors such as the degree of Geopolymerization, the formation of bonding phases, and the overall microstructure of the material. The study might have revealed that certain ratios result in higher compressive strengths due to the effective utilization of the fly ash particles and the activation of the Geopolymerization process. This information is crucial for establishing guidelines for mix design in practical applications, ensuring that the geopolymer bricks meet or exceed the desired strength requirements.

In addition to compressive strength, water absorption is another vital property that affects the durability and performance of construction materials. High water absorption can lead to increased vulnerability to weathering, freeze-thaw cycles, and other degradation mechanisms. Temuujin and colleagues likely explored how changes in mix design influenced the water absorption characteristics of geopolymer bricks. The study's findings would provide insights into the effects of different ratios on the porosity and permeability of the geopolymer matrix. By optimizing the mix design to minimize water absorption, the researchers could contribute to the development of geopolymer bricks that exhibit enhanced durability and resistance to environmental stressors.

Electron Microscopy and X-Ray Diffraction:

Research by Fernandez-Jimenez et al. (2010) employed scanning electron microscopy (SEM) and X-ray diffraction (XRD) to analyse the formation of geopolymers and the interlocking structure that contributes to enhanced mechanical properties. This microstructural understanding has informed the design of geopolymer formulations with improved strength and durability. The research conducted by Fernandez-Jimenez et al. (2010) is a significant contribution to the field of geopolymer technology, focusing on the microstructural characterization of geopolymer bricks and its profound implications for understanding the interplay between composition, porosity, and mechanical behaviour. This study delves into the intricate details of geopolymer matrices, employing advanced techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) to elucidate the formation of geopolymers and the underlying interlocking structure that contributes to their enhanced mechanical properties.

Scanning electron microscopy (SEM) and X-ray diffraction (XRD) are powerful tools in materials science that provide detailed insights into the microstructure and crystallography of materials. In the context of geopolymer bricks, these techniques allow researchers to visualize the arrangement and morphology of geopolymer phases at a microscopic level. Fernandez-Jimenez and colleagues would have prepared geopolymer samples and subjected them to SEM analysis to visualize the distribution of different phases, such as aluminosilicate gels and crystalline compounds. XRD would have been employed to identify the crystalline phases formed during the Geopolymerization process. The combination of these techniques provides a comprehensive picture of the microstructure, phase composition, and bond formation mechanisms within geopolymer matrices.

One of the key findings of this research likely centres around the interlocking structure that emerges within geopolymer matrices. The interlocking structure refers to the way in which different components of the geopolymer bind together, creating a cohesive and well-integrated material. This structure is crucial for enhancing mechanical properties such as compressive strength, flexural strength, and durability. The study by Fernandez-Jimenez et al. would have revealed how the Geopolymerization process results in the development of a network of interlocking bonds. These bonds create a three-dimensional framework that resists deformation and cracking under load. This interlocking structure allows stress to be distributed more evenly throughout the material, leading to enhanced mechanical performance.

The microstructural insights gained from this research have profound implications for the design of geopolymer formulations. Understanding how the composition, curing conditions, and precursor materials influence the microstructure enables researchers and engineers to tailor geopolymer mixes for improved strength and durability. By manipulating the microstructure through careful selection of source materials and optimization of curing conditions, geopolymer formulations can be designed to promote the formation of a dense and interlocking matrix. This leads to higher compressive strength, reduced porosity, and improved resistance to environmental stresses. The research findings likely laid the foundation for guidelines and strategies to achieve these desirable properties.

Geopolymer Brick Elastic and Acoustic Properties:

In terms of dynamic properties, researchers have investigated the elastic and acoustic properties of non-fired geopolymer bricks. Work by Provis et al. (2018) explored the relationship between porosity, density, and ultrasonic wave velocity, providing insights into the potential for using geopolymer bricks in acoustic insulation applications. These studies highlight the multifaceted nature of geopolymer materials and their relevance in diverse engineering contexts. The research conducted by Provis et al. (2018) represents a significant step towards understanding the dynamic properties of non-fired geopolymer bricks, particularly focusing on their elastic and acoustic characteristics. This study delves into the relationship between key material parameters, such as porosity, density, and ultrasonic wave velocity, shedding light on the potential applications of geopolymer bricks in fields beyond structural engineering, such as acoustic insulation.

The elastic properties of a material determine its ability to deform under load and return to its original shape when the load is removed. Elasticity is influenced by factors like porosity and density. Porosity refers to the volume fraction of void spaces within a material, which can significantly affect its mechanical behaviour. Provis and colleagues likely investigated how the porosity of non-fired geopolymer bricks impacts their elastic properties. The study might have revealed that higher porosity leads to lower elastic modulus, indicating that highly porous geopolymer bricks are more compliant and less stiff. This understanding is crucial for designing geopolymer materials that meet specific functional requirements, especially in applications where elasticity and deformation behaviour are significant factors.

Ultrasonic wave velocity is a measure of how quickly sound waves travel through a material. The research by Provis and his team would have explored how ultrasonic wave velocity correlates with porosity and density in non-fired geopolymer bricks. Higher porosity often leads to lower wave velocities due to the presence of air-filled voids that impede the propagation of sound waves. This finding has implications beyond structural engineering. The potential for using geopolymer bricks in acoustic insulation applications becomes evident. Lower ultrasonic wave velocities in porous geopolymer materials suggest their ability to attenuate sound transmission. This insight paves the way for geopolymer bricks to serve as effective sound barriers in architectural designs, contributing to enhanced indoor environmental quality.

The research underscores the multifaceted nature of geopolymer materials. Beyond their structural applications, geopolymer bricks exhibit properties that make them relevant in diverse engineering contexts. From mechanical strength to thermal conductivity, from acoustic insulation to fire resistance, geopolymer materials possess a range of characteristics that expand their potential uses. This broader relevance aligns with the growing demand for sustainable and high-performance materials in modern construction and engineering practices. By demonstrating the acoustic potential of geopolymer bricks, the work by Provis et al. (2018) showcases the adaptability of these materials to meet multifunctional needs in contemporary engineering challenges.

Geopolymer Brick Creep and Shrinkage:

Bullen et al (2022) conducted a series of long-term creep tests on geopolymer bricks to observe how they deform over extended periods under constant loads. This involved subjecting specimens to various stress levels and monitoring their deformation responses over months or even years. These tests provide insights into the creep behaviour and help in estimating factors like creep compliance, which quantifies the material's ability to deform under stress over time. In addition to experimental tests, the researchers employed finite element modelling (FEM) to simulate and predict the time-dependent behaviour of geopolymer bricks under different loading conditions. FEM involves breaking down complex structures into smaller elements and analysing their mechanical behaviour using computational methods. This approach enables researchers to simulate various loading scenarios and observe how creep and shrinkage influence structural responses.

The outcomes of this research shed light on how the geopolymer material responds to sustained loads over time. By combining the insights from long-term creep tests and FEM simulations, Bullen et al. developed a comprehensive understanding of the time-dependent behaviour of geopolymer bricks. This understanding is crucial for ensuring the safety, durability, and long-term performance of structures built using these materials. This has allowed them to be able to identify factors that influence creep and shrinkage in geopolymer materials, such as the composition, curing conditions, and mechanical properties of the matrix. This knowledge aids in optimizing the mix of design and construction practices to mitigate the effects of time-dependent deformations.

The findings of this research have direct implications for the design of geopolymer structures. By understanding the time-dependent behaviour of geopolymer materials, engineers can account for the gradual deformations that might occur under sustained loads. This is crucial for ensuring that structures maintain their integrity and functionality over their intended service life. The insights gained from the long-term creep tests and FEM simulations likely inform design codes and guidelines for using geopolymer materials in real-world applications. These guidelines consider the material's behaviour under different loading conditions and provide recommendations for factors such as allowable stresses, safety margins, and serviceability criteria.

Durability and Environmental Impact:

Acid Resilience:

Durability is a critical factor in the evaluation of construction materials, especially when considering their long-term performance in real-world applications. The ability of geopolymer bricks to resist deterioration from external factors, such as chemical exposure and environmental stresses, determines their lifespan and suitability for different contexts. Duxson et al.'s research addressed the durability aspect by specifically investigating how geopolymer bricks withstand acid attack. Acid attack refers to the degradation of materials caused by exposure to acidic substances. Duxson and his team subjected geopolymer bricks to various acid solutions to assess their performance under aggressive chemical conditions. This research would involve measuring factors like mass loss, surface degradation, and changes in mechanical properties after exposure to acids. The findings would have indicated the ability of geopolymer bricks to resist acid-induced deterioration. Compared to traditional fired bricks, which might be more vulnerable to acid attack due to their porous and heterogeneous nature, geopolymer bricks demonstrated superior resistance. This insight has practical implications for the use of geopolymer materials in environments where acid exposure is a concern, such as in industrial settings or urban areas with high pollution levels.

The study by Kani et al. (2016) complements the investigation into geopolymer brick durability by focusing on another critical aspect: freeze-thaw resistance. Freeze-thaw cycles occur when water within porous materials freezes and expands, causing mechanical stresses that can lead to cracking and degradation. Kani and colleagues likely subjected geopolymer bricks to a series of freeze-thaw cycles to evaluate their performance under harsh climatic conditions. The research would have provided insights into how geopolymer bricks respond to freeze-thaw stresses and whether they maintain their structural integrity. The results likely highlighted the potential of geopolymer materials to withstand such conditions, indicating their suitability for regions with cold climates where freeze-thaw cycles are a common occurrence. The durability studies by Duxson et al. and Kani et al. contribute to the broader narrative of geopolymer technology's sustainability and practical application. Geopolymer materials have the potential to offer extended service life, reduced maintenance requirements, and minimized environmental impact compared to conventional construction materials. Their resistance to acid attack and freeze-thaw conditions underscores their adaptability to a range of environments, enhancing their appeal as sustainable alternatives.

Life Cycle Assessment:

Life cycle assessment (LCA) studies have contributed valuable insights into the environmental benefits of using non-fired geopolymer bricks. The work of Habert et al. (2011) conducted a comprehensive LCA comparing the ecological footprint of geopolymer and traditional brick production. The study revealed that geopolymer technology significantly reduces carbon emissions and energy consumption, aligning with sustainable construction practices. The research conducted by Habert et al. (2011) represents a crucial step in understanding the environmental impact and sustainability benefits of non-fired geopolymer bricks through life cycle assessment (LCA). Life cycle assessment is a comprehensive approach that evaluates the environmental burdens associated with a product's entire life cycle, from raw material extraction to manufacturing, use, and disposal. Habert and colleagues undertook an LCA study to directly compare the ecological footprint of geopolymer brick production with that of traditional fired brick production. This research provides profound insights into the positive environmental effects of geopolymer technology, highlighting its potential to reduce carbon emissions and energy consumption, thus aligning with sustainable construction practices.

Life cycle assessment is a robust methodology that allows for a holistic evaluation of the environmental impacts of a product or process. It considers not only the direct emissions and resource consumption associated with manufacturing but also the upstream and downstream impacts, including material extraction, transportation, energy use, and waste management. LCA studies are pivotal in identifying opportunities for reducing environmental burdens and making informed decisions to minimize a product's overall environmental footprint. The research by Habert et al. (2011) focused on a comparative LCA study that directly contrasted the environmental performance of geopolymer brick production with that of traditional fired brick production. This study likely encompassed the entire life cycle of both materials, starting from the extraction of raw materials like clay and fly ash, through the manufacturing processes, transportation, and ending with the disposal or recycling of the bricks. The outcomes of the LCA study would have highlighted the significant environmental benefits of non-fired geopolymer bricks. Geopolymer technology, which relies on industrial byproducts like fly ash and uses lower firing temperatures compared to traditional brick production, has the potential to drastically reduce carbon emissions and energy consumption. The study's findings would likely show that geopolymer bricks emit fewer greenhouse gases and require less energy during manufacturing, contributing to a lower overall environmental impact. The research aligns with the broader goals of sustainable construction practices by providing empirical evidence of the positive environmental attributes of geopolymer technology. Sustainable construction aims to reduce the environmental burden associated with building materials, minimize energy consumption, and decrease reliance on non-renewable resources. The LCA study's findings reinforce the notion that geopolymer technology offers a pathway to achieving these goals.

Efflorescence and Long-Term Stability:

To address concerns related to efflorescence and long-term stability, researchers have explored the incorporation of supplementary cementitious materials and chemical additives in geopolymer formulations. Investigations by Provis et al. (2020) into the influence of calcium-rich precursors on mitigating efflorescence highlighted the potential for achieving improved aesthetics and durability in geopolymer brick products. Efflorescence refers to the migration of soluble salts to the surface of construction materials, often resulting in unsightly white deposits and potential long-term durability issues. To counter these challenges, Provis and colleagues explored innovative approaches by investigating the incorporation of calcium-rich precursors and chemical additives in geopolymer formulations. This research offers valuable insights into how these strategies can mitigate efflorescence and enhance the aesthetics and durability of geopolymer brick products. Efflorescence is a common concern in construction materials, particularly in masonry products such as bricks. It can mar the appearance of surfaces and, in severe cases, indicate potential durability issues. Geopolymer materials, despite their many advantages, can also be susceptible to efflorescence due to the presence of soluble salts within the matrix. Additionally, ensuring the long-term stability of geopolymer materials is crucial to their acceptance and practical application in construction.

One strategy explored by Provis et al. (2020) involves incorporating supplementary cementitious materials in geopolymer formulations. These materials, often derived from industrial byproducts like slag or fly ash, can enhance the properties of geopolymer matrices. In this context, the researchers likely investigated the influence of calcium-rich precursors, possibly including calcium-containing industrial wastes, on reducing efflorescence. The findings of this research would reveal how the inclusion of calcium-rich precursors impacts the formation and migration of soluble salts within the geopolymer matrix. The introduction of these precursors might lead to the formation of less soluble compounds that inhibit the movement of salts to the surface. This, in turn, could mitigate the occurrence of efflorescence and contribute to improved aesthetics by maintaining the appearance of geopolymer brick products over time.

Efflorescence is often an indicator of the potential for long-term durability issues. By investigating methods to mitigate efflorescence, the research by Provis and colleagues indirectly contributes to enhancing the long-term stability of geopolymer materials. The reduction of soluble salts at the surface can prevent the accumulation of detrimental substances that might compromise the material's structural integrity and resistance to environmental degradation. The insights gained from this research have practical implications for the formulation and design of geopolymer materials. By identifying strategies to mitigate efflorescence, researchers and engineers can develop geopolymer mixes that are less prone to surface discolouration and durability concerns. These findings are valuable for practitioners seeking to optimize geopolymer formulations for specific applications, ensuring that the materials meet aesthetic and performance requirements.

Marine and Industrial Applications:

Furthermore, ongoing research is investigating the durability of geopolymer bricks in aggressive environments, such as marine and industrial settings. The resistance of geopolymer materials to chloride penetration, sulphate attack, and alkali-silica reaction has gained attention, with studies like that of De Weerdt et al. (2018) providing insights into the mechanisms that govern degradation processes. These findings contribute to the ongoing refinement of geopolymer formulations for diverse applications. The ongoing research into the durability of geopolymer bricks in aggressive environments, particularly in marine and industrial settings, signifies a crucial aspect of geopolymer technology's development. Aggressive environments pose significant challenges to construction materials due to factors like high moisture levels, exposure to corrosive agents, and chemical reactions that can lead to deterioration. Researchers, such as De Weerdt et al. (2018), have been at the forefront of investigating the resilience of geopolymer materials under such conditions. This research aims to uncover the resistance of geopolymer materials to specific degradation processes, including chloride penetration, sulphate attack, and alkali-silica reaction, which are common issues in aggressive environments. The insights gained from these studies offer valuable information about the mechanisms governing degradation, enabling the ongoing refinement of geopolymer formulations for a wide range of applications.

Aggressive environments, such as marine and industrial settings, subject construction materials to harsh conditions that can accelerate degradation. Chloride ions, present in seawater and industrial pollutants, can lead to corrosion of reinforcing materials within concrete structures. A sulphate attack can cause the expansion and cracking of materials, and an alkali-silica reaction involves the interaction between alkalis in concrete and reactive silica in aggregates, resulting in expansion and cracking. Overcoming these challenges is crucial for ensuring the longevity and performance of construction materials.

Studies conducted by researchers like De Weerdt et al. (2018) delve into the mechanisms by which geopolymer materials resist degradation in aggressive environments. These investigations likely involve subjecting geopolymer specimens to simulated aggressive conditions in the laboratory and monitoring their behaviour over time. By analysing changes in material properties, microstructure, and chemical composition, researchers can uncover how geopolymer matrices react to different degradation mechanisms. The findings of these studies offer insights into the ways in which geopolymer materials interact with aggressive agents. For instance, research might reveal that the inherent chemical composition of geopolymer matrices leads to reduced chloride ion ingress, mitigating the risk of corrosion of embedded reinforcement. Understanding how geopolymer materials hinder sulphate attack and alkali-silica reactions can provide designers and engineers with the knowledge to select appropriate materials for specific environments and applications.

The insights gained from research on geopolymer durability in aggressive environments contribute to the continuous improvement of geopolymer formulations. As researchers better understand the mechanisms that enable geopolymer materials to resist degradation, they can adjust material compositions and processing parameters to enhance these protective mechanisms. This ongoing refinement ensures that geopolymer materials meet the demands of real-world applications, particularly in environments where traditional construction materials may struggle to perform effectively. The research by De Weerdt et al. (2018) and similar studies impact a variety of applications where geopolymer materials are considered, including infrastructure in marine environments, industrial structures, and even sustainable construction practices. By demonstrating the ability of geopolymer materials to withstand aggressive conditions, these studies reinforce the potential of geopolymer technology to contribute to durable, resilient, and sustainable construction solutions. The ongoing research into geopolymer durability in aggressive environments is an essential part of advancing geopolymer technology and its acceptance in the construction industry.

Recent Developments and Rational Method Concerns

Recent developments in the field of geopolymer brick design have focused on improving their properties and reducing their environmental impact. One such development is the use of waste materials as raw materials in the production of geopolymer bricks. Researchers have explored the use of waste materials such as fly ash, rice husk ash, and slag as alternatives to traditional raw materials, such as clay and cement, with the use of rice husk ash and slag as raw materials resulted in bricks with higher strength and lower porosity (Singh, 2020). Another area of development is the use of new binders such as calcium aluminate cement and curing techniques to improve the properties of geopolymer bricks. It was found within the study that the use of this binder improved the compressive strength and durability of the bricks. One of the key challenges in the design of geopolymer bricks is achieving consistent properties across different batches (Li, 2019). The effectiveness of the binder is influenced by a variety of factors, including the raw materials used, the mixing process, and the curing conditions. To address this concern, researchers have focused on developing standardized testing protocols and quality control measures to ensure that the geopolymer bricks meet specific performance requirements. Overall, recent developments in geopolymer brick design have focused on improving their properties and reducing their environmental impact, while method concerns have centred around achieving consistent properties and developing standardized testing protocols and quality control measures.

There is also further research targeted utilising high-calcium fly ash to develop desirable properties of geopolymer bricks. This is reflected with high-calcium fly ash used to produce fire-resistant applications within geopolymer bricks (Chindaprasirt, 2018). In addition to this, there are also many geopolymer studies applying different types of recycled materials and their respective mixtures to determine the effects of the bricks' properties for creating a structurally desirable geopolymer brick. Studies on the impact of material interaction within geopolymer design utilising overburden laterite from the aluminium industries as the primary material within the development of non-fired geopolymer bricks found that laterite non-fired geopolymer bricks had a lower density, water absorption and increased compressive strength compared to conventional clay bricks (Najar, 2021).

Alternative research has also highlighted there have been very limited types of waste material which has been successfully utilized to produce geopolymer bricks. Zhang, (2013) highlighted the large quantity of different types of waste material which have not yet been proven to be an effective material to be used within non-fired geopolymer bricks. *"Geopolymer not only provides performance comparable to OPC in many applications, but has additional advantages, including abundant raw material resources, the rapid development of mechanical strength, good durability, superior resistance to chemical attack, ability to immobilize contaminants, and significantly reduced energy consumption and greenhouse gas emissions."* (Zhang, 2013). It was noted that most waste materials or by-products haven't been found to have desirable strength characteristics and material properties to produce structurally effective geopolymer bricks which can be used for commercial applications within construction.

Further literature highlights the implementation of recycled waste materials within the design mixtures of non-fired geopolymer bricks. This is reflected through an investigation towards alternate geo-polymerisation techniques containing three different combined industrial waste products acting as binders. These three binders were included with high-volume ladle furnace slag, class F fly ash, and ground granulated blast furnace slag to create non-fired geopolymer brick alternatives, The Australian Journal of Structural Engineering (2022). There was also similar research conducted focusing on the different material effects of fly ash brick production within the Turkish brick manufacturing industry. It analyzed the production of geopolymer bricks containing fly ash mixed with different types of heavy metal waste materials, (Cengizler, 2022). Similar results can be highlighted within studies investigating the possibility of utilising brick clay mill residue to produce non-fired geopolymer bricks. The geopolymer bricks consisted of brick clay mill residues with alkali activation and the samples' structural properties were measured through the compressive strength, linear shrinkage, bulk density, and microstructure of the non-fired geopolymer bricks containing brick clay mill residue with sodium hydroxide and sodium silicate solutions. Each sample's compressive strength was then determined using the Tecnotest-2000 to apply an increasing incremental load on a corresponding cross-sectional area until load failure. The results concluded that the utilisation of brick clay mill residues can be used to produce alkali-activated geopolymer bricks (Zhang, 2021).

There have also been extensive experimental investigations towards analysing the different types of properties within geopolymer bricks using class F fly ash, sodium silicate and sodium hydroxide solution (Arioz et al., 2003). The experiment consisted of class F fly ash geopolymer bricks being formed by undergoing 30 MPA forming pressure, whilst also being cured in an oven and steam undergoing various temperatures each at different time intervals. The compressive strength and density of the fly ash-based geopolymer bricks were recorded at one week, four weeks then again at 90 days. The experiment's findings highlighted the geopolymer bricks ranged with a compressive strength between 5MPa to 60MPa. It was also noted after a conclusive summary that there was no significant effect on the brick's density based on the temperature of the heat treatment and the varying durations.

Additional geopolymer studies review potential recycled coal-fired power station waste materials which can be utilised to be a suitable candidate for manufacturing structurally effective geopolymer bricks. The applications of class F fly ash along with sodium silicate solution as the alkali activator were used to investigate the feasibility of producing geopolymer bricks using recycled coal-fired power station waste. It was concluded that using sodium silicate solution as the alkali activator produced concrete-like building materials that can be produced from mixtures of fly ash and bottom ash (Freidin, 2007). Similar research results were also evaluated through experimental geopolymer material investigations containing fly ash. The behaviour and corresponding effects of the class F fly ash within the different geopolymer brick mixture designs were instigated to determine its effects on the bricks' durability (Subramani, 2016). Other papers analysed the influence of elevated temperatures during the curing process and its effect on phase composition, microstructure, and strength development of the class F fly ash geopolymer bricks. This is seen through different experimental investigations towards geopolymer materials prepared using different classes of fly ashes and elevated curing temperatures, (Bakharev, 2005), (Jiang, 2020). There have also been some studies towards interchanging recycled glass as an additive within the fly ash mixture, but also the implementation of recycled plastics within geopolymer brick mixtures. Geopolymer brick material studies investigating plastic-fly ash waste composites reinforced with carbon nanotubes, also saw a hybrid of waste plastic-fly ash composites which were also further reinforced by carbon nanotubes for the development of a structurally sound geopolymer brick (Makgabutlane, 2022).

Experimental investigations towards analysing the mechanical performances of fly ash-based geopolymer bricks due to the influence of pressure, temperature and time during the curing stages have produced promising results. The experiment was designed to review the performance of fly ash-based geopolymer bricks compacted under different compaction pressures, ranging from 0, 20, and 40MPa. These geopolymer samples were also exposed to both ambient and hot curing temperatures over a period of 7 and 28 days. The experimental findings concluded that the geopolymer samples exposed to a higher rate of compaction force yielded significantly increased strength properties due to the more densely compacted mixtures enabling a reduction in the samples' porosity and water absorption (Ahmad et al., 2021). The findings of the report indicated that due to the combined influences of pressure, temperature, and time produced geopolymer bricks with an increase of strength up to 600%.

Additional experimental investigations towards reviewing the feasibility of producing lightweight geopolymer bricks from class F fly ash as the major constituent in the mixture composition of the geopolymer brick samples. These class F fly-ash-based bricks are composed of varying proportions of fly-ash, sand, hydrated lime, sodium silicate, and water. The experiment focused on using three main fly-ash-to-sand ratios, ranging from 50/50, 70/30 and 90/10. The different fly-ash to sand mix geopolymer brick samples were also subjected to varying quantities of sodium silicate solution, with each type of dry mixture additionally having 5, 10, 15 and 20% respective to the sample's mass, with 5% hydrated lime content, (Nataatmadja et al., 2010). The findings indicate the feasibility of manufacturing lightweight fired bricks using fly ash that meet the requirements of engineering. Specifically, by carefully adjusting the proportions, these bricks can achieve compressive strengths and absorption properties on par with clay bricks. The optimal combination involved a ratio of 70% fly ash to 30% common sand, along with 15% sodium silicate and 5% lime (Nataatmadja et al., 2010). This geopolymer brick design demonstrated superior performance in terms of strength, moldability, and water absorption. Furthermore, in addition to possessing comparable characteristics to traditional clay bricks, the fly ash bricks exhibited a substantial weight reduction, approximately 50%, rendering them a viable alternative.

Other Models used in non-fired geopolymer brick design:

Several models have been used in non-fired geopolymer brick design. These models can help designers predict the properties of geopolymer bricks based on their composition and processing conditions.

The power-law model has been used to predict the rheological properties of geopolymer pastes, used as the binder in geopolymer brick production, (Provis, 2014). It is based on observations of how the paste behaves under shear stress and relates the stress and rate of deformation to the composition and processing conditions of the paste. This model is typically used to optimize the processing conditions of geopolymer pastes and ensure that they are suitable for use in geopolymer brick production.

The activation energy model can be used to predict the curing kinetics of geopolymer materials. The model relates the rate of reaction to the activation energy of the reaction, which can be determined through experiments. The activation energy model is used to predict the curing kinetics of geopolymer materials (Kuenzel, 2017). It is based on the Arrhenius equation, which relates the rate of reaction to the activation energy of the reaction. This model is typically used to optimize the curing conditions of geopolymer bricks and ensure that they achieve the desired properties in a reasonable amount of time.

Additionally, the empirical model approach can be utilised towards analysing the properties of geopolymer bricks. This model is based on experimental data which is used to predict specific properties of geopolymer bricks, such as their compressive strength or water absorption. These models typically relate the property of interest to the composition and processing conditions of the bricks (Fathifal, 2019). Empirical models are useful for predicting properties that are difficult to measure experimentally and for identifying trends in how different factors affect the properties of geopolymer bricks.

Artificial neural network models are machine learning models that are trained on a dataset of experimental data and can be used to predict the properties of new geopolymer mixture compositions. These models are useful for predicting complex relationships between the composition and properties of geopolymer bricks, and for identifying important factors that affect the properties of the bricks, (Luukkonen, 2017). Artificial neural network models are particularly useful for predicting properties that are difficult to measure experimentally and for optimizing the composition of geopolymer bricks for specific applications.

Another model which has been used when analysing the properties of geopolymer bricks is the finite element method. The finite element method models are used to simulate the mechanical behaviour of geopolymer bricks under different loading conditions (Habert, 2011). These models can be used to optimize the design of geopolymer bricks for specific applications, such as building facades or structural components. Finite element method models are particularly useful for predicting the behaviour of complex structures and for identifying design factors that affect the performance of geopolymer bricks.

Soil Compaction Theory and Literature

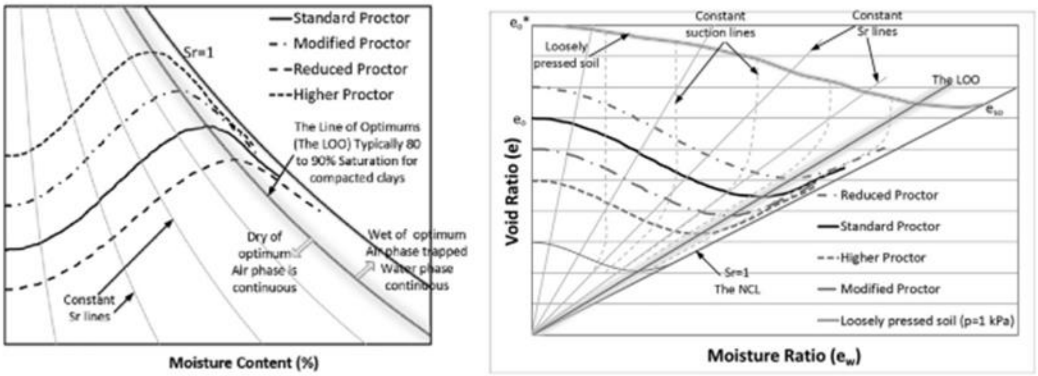
The theory of soil compaction resulting from dynamic pressure involves studying the compression and densification of soil when subjected to dynamic loads, such as those produced by heavy machinery, vehicles, or impact forces. Dynamic pressure refers to the pressure exerted on the soil surface by these dynamic loads. When a dynamic load is applied to the soil surface, it generates a stress wave that travels through the layers of soil. This stress wave causes the soil particles to rearrange and compact, leading to an increase in soil density.

The process of compaction is influenced by several factors, including the magnitude and duration of the dynamic load, soil type, moisture content, and initial density. The dynamic load applied to the soil surface generates a stress wave that propagates through the soil, with its velocity and magnitude depending on soil properties such as stiffness and damping characteristics. As the stress wave passes through the soil, it induces particle rearrangement and deformation. Consequently, the soil particles undergo compaction and realignment, increasing soil density. The extent of soil deformation and compaction is determined by the magnitude and duration of the dynamic load.

Various soil properties, including grain size distribution, moisture content, and initial density, influence the response of soil to dynamic pressure. Cohesive soils like clay tend to undergo more significant compaction compared to granular soils like sand. Moisture content plays a critical role in soil compaction due to dynamic pressure. Optimal moisture content is necessary to achieve maximum compaction and density, as excessive or insufficient moisture can adversely affect the compaction process. Compaction curves are used to depict the relationship between soil density and moisture content for a given dynamic load. These curves aid in determining the optimum moisture content required for maximum compaction.

Understanding the theory of soil compaction resulting from dynamic pressure is crucial in engineering and construction practices. It enables engineers to design suitable foundations, roadways, and structures capable of withstanding dynamic loads while minimizing soil settlement and deformation. By considering the factors that influence soil compaction, engineers can optimize construction processes and ensure the long-term stability and performance of built environments.

Soil compaction, achieved through densification, offers improvements to soil properties. It enhances soil strength, and bearing capacity, and diminishes compressibility and permeability (Kodikara et al., 2018). The introduction of the Proctor curve in 1933 revolutionized the compaction process, and the subsequent development of the California Bearing Ratio (CBR) further advanced this field. Compacted soil exhibits various behavioural patterns, including plastic deformation, such as swelling and collapse compression when wet, as well as cracking during drying. It can also experience changes in density due to wetting and drying cycles. These tests have been employed in laboratories to establish the relationship between dry density (γd) or void ratio (e) and moisture content (w) for a specific soil type under a given gross energy input (Kodikara et al., 2018). The energy is introduced by compacting moist soil in layers within a cylindrical mould using a hammer. This relationship generates a typical compaction curve in the γd-w plane, characterized by an inverted parabolic shape. This curve identifies the maximum dry density (γd max) and the corresponding optimum moisture content (w, opt) for that specific energy input.



(a) (b)

l. (a) Typical compaction curves and features; (b) Depiction of (unloaded) compaction curves in $e{-}e_w$plane (modified from Kodikara [43]).

Figure 1: (a) Typical compaction curves and features; (b) Depiction of (unloaded) compaction curves in e-ew plane (modified from Kodikara).

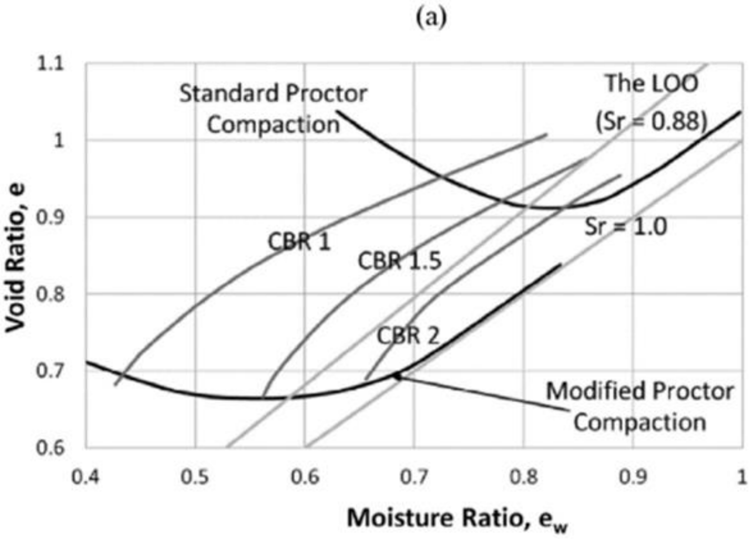


Figure 2: Contours of soaked CBR plotted against as-compacted (e, ew) for compacted basaltic clay soils (Kodikara et al., 2018).

The compaction water content (w) is determined by taking the average of three measurements obtained from the top, middle, and bottom parts of the mixture's mass. Once the water content is determined, the dry unit weight (γd) of the mixture is calculated using the following formula:

$$\gamma_d = \frac{W - W_m}{(1 + w) * V}$$

where: **W** = the weight of the mould and the mixture mass (kg)

W$_m$ = the weight of the mould (kg)

w = the water content of the mixture (%)

V = the volume of the mould (m^3)

This process should be repeated four more times, with selected water contents that are both lower and higher than the optimum value. It is recommended to have 1-2 of these points close to the optimum moisture content, ensuring a well-distributed range of values.

The resulting dry unit weights, along with their corresponding water contents, are then plotted on a diagram. This diagram also includes the zero-void curve, which represents the correlation between the dry unit weight and water content, assuming the soil is 100% saturated. It is important to note that no matter how much energy is applied to the sample during compaction, it cannot be compacted beyond this curve.

The calculation of the zero-void curve is carried out using the following method:

$$\gamma_d = \frac{G_S * \gamma_w}{1 + w * G_S}$$

where: **G_S** = specific gravity of soil particles (G_S~2.70)

γ_W = saturated unit weight of the soil (kN/m^3)

Below in Figure 1 illustrates the typical curves obtained from the Standard and Modified Proctor tests, along with the zero air voids curve.

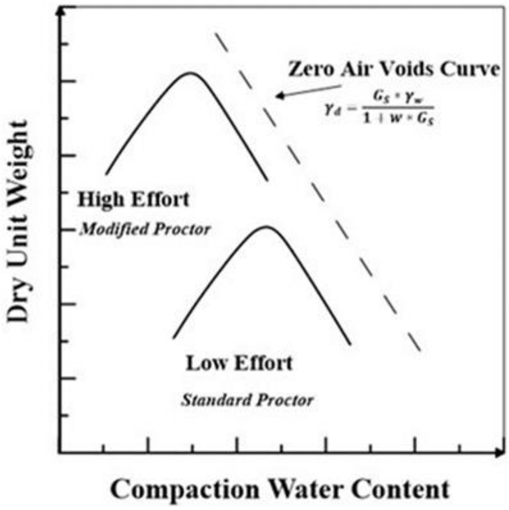


Figure 3: Compaction Water Content vs Dry unit weight graph.

The strength development of geopolymer materials during compaction is heavily influenced by temperature. Geopolymers are a type of cementitious material created by activating aluminosilicate materials with alkaline solutions. When temperature is applied during the compaction and curing process, it triggers various mechanisms that contribute to strength development. Alkaline activators, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) solutions, are commonly used in Geopolymerization reactions. These activators facilitate the dissolution of aluminosilicate precursors like fly ash or slag, promoting the formation of a polymeric gel network. Elevated temperatures accelerate the activation process, resulting in faster dissolution, enhanced chemical reactions, and improved polymerization. Consequently, the geopolymer matrix achieves higher strength in a shorter time. Temperature also affects the Geopolymerization process, which involves the formation of a three-dimensional aluminosilicate gel network. Higher temperatures expedite the formation of the gel, promoting crosslinking of polymer chains and creating a denser structure. This densification enhances interparticle bonding and increases strength. Geopolymers can also form crystalline phases like zeolites or calcium aluminosilicate hydrates, which contribute to strength development. Elevated temperatures facilitate the nucleation and growth of these crystals, improving mechanical properties.

However, it's important to note that while higher temperatures can accelerate strength development, there is an optimal temperature range. Excessive heat beyond this range can cause thermal degradation or undesired phase transformations, leading to reduced strength or other negative effects. The specific temperature conditions and curing duration for geopolymer materials depend on factors such as composition, activator type, and desired properties. Experimental studies and optimization techniques are employed to determine the appropriate temperature and curing regime to achieve the desired strength and durability of geopolymer-based products. Overall, controlling the temperature during compaction and curing significantly influences the strength development of geopolymer materials. By optimizing temperature conditions, it is possible to enhance chemical reactions, promote gel formation, and induce the growth of crystalline phases, ultimately resulting in higher-strength geopolymer products.

Geopolymer Brick Curing Literature

The relationship between heat and geopolymers, particularly concerning their strength development after curing, is a complex and crucial aspect that significantly influences the final properties of these materials. Geopolymers undergo a heat-driven chemical reaction known as geopolymerization, where aluminosilicate materials react with alkaline activators to form a three-dimensional network of polymeric bonds. This reaction is influenced by the Arrhenius equation, which describes how the rate of a chemical reaction increases with temperature.

$$k = A * e^{-\frac{Ea}{RT}}$$

Mathematically, the Arrhenius equation highlights the role of temperature (*T*) and activation energy (*Ea*) in influencing the reaction kinetics. In the case of geopolymers, higher temperatures accelerate the geopolymerization process by lowering the activation energy barrier, leading to faster bond formation and structural development. The effects of heat on geopolymers' strength after curing are multifaceted and interconnected with the geopolymerization process. As the temperature increases, the reaction kinetics become more favourable, resulting in faster development of the geopolymeric structure. This rapid bond formation leads to enhanced early-age strength, which is crucial for construction applications requiring quick setting times. Additionally, the elevated temperature promotes the densification of the geopolymeric matrix by facilitating the rearrangement and compaction of particles within the mixture. A denser matrix exhibits improved structural integrity and resistance to stress, contributing to better long-term strength.

However, the relationship between heat and geopolymers' strength is not linear. Excessive heat can lead to detrimental effects such as thermal cracking, excessive shrinkage, or even thermal degradation of the matrix. Therefore, finding the optimal curing temperature is crucial to balance the benefits of accelerated strength development with the potential risks associated with excessive heat. Previous research provides insights into this relationship. Provis and van Deventer (2014) highlight the significant impact of temperature on geopolymerization kinetics and the resulting strength development. Duxson et al. (2007) delve into the complexities of heat exposure during the curing process and its effects on the microstructure and mechanical properties of geopolymers. Fernandez-Jimenez and Palomo (2005) emphasize how heat accelerates the geopolymerization reaction, leading to enhanced early-age strength and densification of the matrix. In conclusion, the relationship between heat and geopolymers is a critical factor that shapes the strength development after curing. Properly controlled heat exposure can accelerate the geopolymerization process, promote densification, and optimize microstructural development, thereby enhancing both early-age and long-term strength. However, careful consideration is essential to avoid adverse effects associated with excessive heat.

Effects of Curing Temperature on Geopolymer Strength:

The curing temperature plays a pivotal role in influencing the strength development of geopolymer materials. Geopolymers are formed through a complex chemical reaction known as geopolymerization, where aluminosilicate materials react with alkaline activators to create a three-dimensional network of polymeric bonds. This process is sensitive to temperature, and understanding the effects of curing temperature on strength is crucial for tailoring geopolymer formulations to specific applications. Lower curing temperatures tend to slow down the geopolymerization reaction. This results in reduced bond formation and a more gradual development of the geopolymeric matrix. Consequently, the early-age strength of geopolymer specimens cured at lower temperatures is typically lower compared to those cured at higher temperatures. Research by Palomo et al. (1999) suggests that the lower reactivity of aluminosilicate materials at lower temperatures leads to less extensive network formation and weaker bonding within the matrix. Furthermore, the slow reaction kinetics at lower temperatures might hinder the complete utilization of available precursors, leading to a less dense and weaker microstructure. Studies by Davidovits (1994) indicate that lower curing temperatures can result in higher porosity due to incomplete geopolymerization, which subsequently compromises the mechanical strength of the material.

Conversely, higher curing temperatures accelerate the geopolymerization reaction. Increased thermal energy provides the activation energy required to overcome reaction barriers, leading to faster bond formation and more rapid development of the geopolymeric matrix. This acceleration results in higher early-age strength compared to specimens cured at lower temperatures. Research by Krivenko et al. (2007) highlights that higher temperatures promote the formation of a more ordered and denser geopolymer structure. The enhanced reaction kinetics at higher temperatures also lead to better utilization of precursors, resulting in a more complete geopolymerization and a stronger matrix. Studies by Duxson et al. (2007) emphasize that higher curing temperatures promote densification and microstructural rearrangement within the matrix, contributing to improved mechanical properties and higher long-term strength. While higher curing temperatures generally lead to improved strength due to faster reaction kinetics and enhanced densification, it's essential to strike a balance. Excessively high temperatures can cause thermal cracking, shrinkage, and even decomposition of the geopolymer matrix. Research by Fernandez-Jimenez and Palomo (2005) suggests that extreme temperatures can result in the degradation of bonds and a loss of mechanical strength.

Chapter 2: Materials and Methodology

Materials

The material composition of non-fired geopolymer bricks generally consists of a dry mixture containing Fly ash, sand, and hydrated lime. Additionally, the dry mixture will also require the addition of an Alkaline solution. The solution is made up of a commercially available chemical, sodium silicate with the inclusion of water. M. Najar's '*A study on the impact of material synergy in geopolymer adobe: Emphasis on utilizing overburden laterite of the aluminium industry,'* (2021), explains that sodium hydroxide was used as the major alkaline solution for the preparation of the Geopolymerization process of the brick structure. Sodium hydroxide is found to be preferred as the major alkaline solution due to its cost-effective, more accessible nature as compared to other alkali solutions. The commercially available sodium hydroxide can used alongside the sodium silicate to produce the activator. The molecular properties of both chemicals will be similar properties used within the various studies, primarily that of a sodium hydroxide containing 98% purity, Molarity of 40g/mol and a sodium hydroxide concentration between 8M to 10M. Najar and other studies during the preparation of the analytical reagents implemented double distilled water, with tap water then being further used during the preparation of the geopolymer moulds.

N. Youssef (2019), highlights that the general formula of the chemical composition with the geopolymer is:

$$\mathrm{M}_n^{+}[-(\mathrm{SiO}_2)_z-\mathrm{AlO}_2-]_n$$

Where M+ is an alkali cation (Na+ or K+); n is the degree of polymerization; and z is the Si/Al ratio.

Furthermore, the sand, fly ash, and hydrated lime, will be adequately sieved to the ideal properties in acceptance to Australian and New Zealand design requirements as part of material preparation before the mixture. These waste materials would require undergoing this process until the powdered dry mixture can be filtered through a number 100 mesh sieve to achieve a minimization of disproportional material mixture.

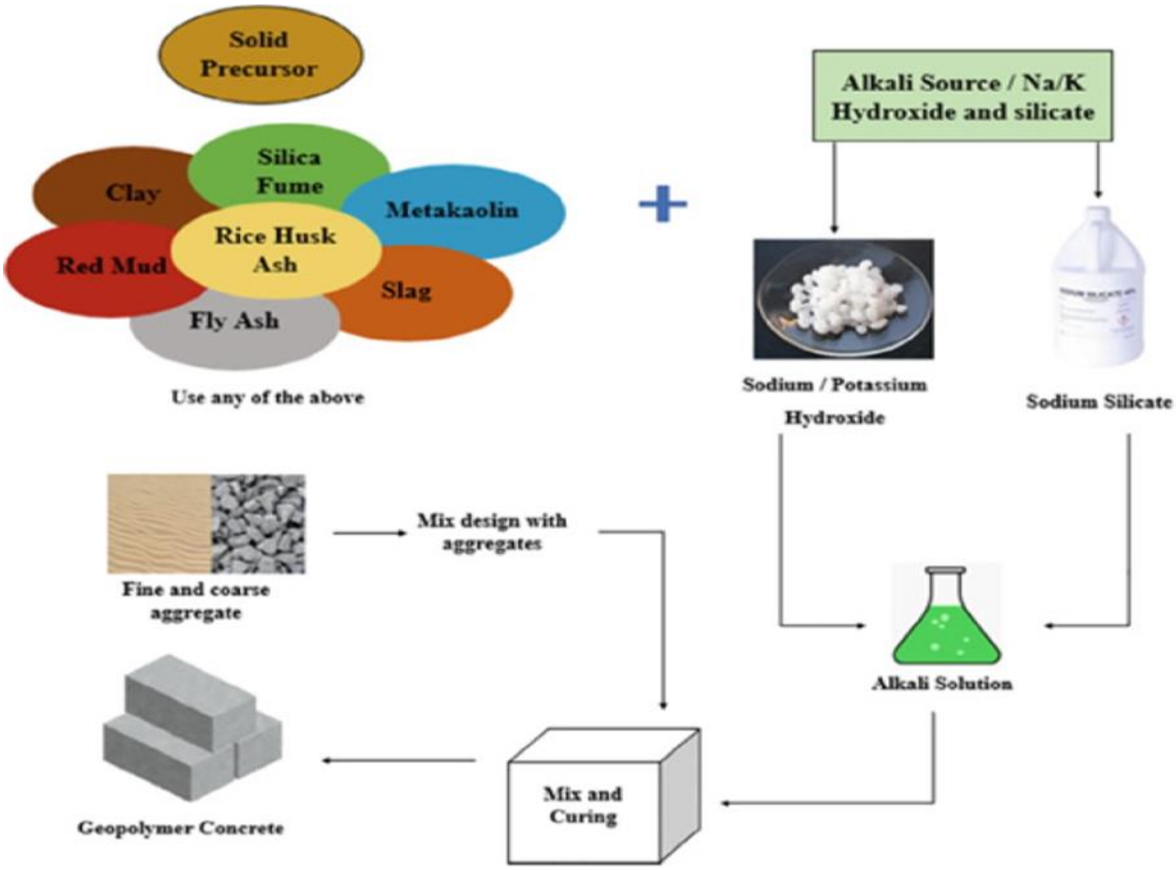


Figure 4: Flow diagram of geopolymer material mixture process. Tanu H.M., "*Utilization of industrial and agricultural waste materials for the development of geopolymer concrete*," (2022).

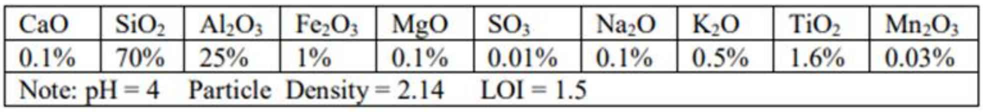
Fly Ash

Fly ashes are fine powders with a heterogeneous composition, mainly comprising rounded or spherical particles ranging from less than 1 µm to 150 µm in diameter. According to Australian Standards, fly ash is classified as "fine-grained" if it has a minimum of 75% passing through a 45 µm sieve and a maximum Loss on Ignition (LOI) of 4.0%. Conversely, "coarse-grained" fly ash allows for 40-70% to pass through the 45 µm sieve and has a maximum LOI of 12.0%.

These fly ashes are considered pozzolanic materials, meaning they react with water and lime (CaO) to form cementitious compounds. Some fly ashes contain enough "free lime" to exhibit self-cementing properties. However, the fly ash found in Queensland, known as class F fly ash, has a low CaO content (less than 4%) and therefore does not exhibit significant self-cementation behaviour. As mentioned earlier, the lower lime content of class F fly ash can be advantageous to produce fired bricks, as it reduces the occurrence of "scumming" during the firing process.

In this investigation, the primary component selected is a dry processed "fine-grained" ash from Queensland known as Tarong fly ash. This ash is characterized as a low iron mixture, with over 75% of its constituents consisting of silica and alumina oxides (refer to Table 1).

Table 1. Main Constituents and Properties of Tarong Fly-ash



CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	Mn_2O_3
0.1%	70%	25%	1%	0.1%	0.01%	0.1%	0.5%	1.6%	0.03%
Note: pH = 4 Particle Density = 2.14 LOI = 1.5									

Class F fly ash, a significant component in geopolymer mixtures, is classified based on the American Society for Testing and Materials (ASTM) standard, which categorizes fly ash according to its chemical composition and pozzolanic properties. Class F fly ash is characterized by its relatively low calcium oxide (CaO) content, high silica (SiO_2) and alumina (Al_2O_3) content, and its reactivity with alkaline activators. This composition renders it particularly suitable for geopolymerization reactions. Class F fly ash, often referred to as low-calcium fly ash, is prized for its pozzolanic characteristics, wherein it reacts with the alkaline activators in geopolymer mixtures to form a cementitious binder. The lower CaO content in Class F fly ash prevents the excessive formation of calcium-based compounds, which can impede the geopolymerization process. Instead, the high SiO_2 and Al_2O_3 content led to the formation of amorphous aluminosilicate gels that contribute to the development of a strong and durable geopolymeric matrix (Davidovits, 1994). In comparison to Class C fly ash, which contains higher levels of calcium and is derived from burning lignite or sub-bituminous coal, Class F fly ash is more desirable in geopolymer mixtures due to its distinct reactivity. The lower calcium content in Class F fly ash results in higher availability of reactive silica and alumina, facilitating a more efficient geopolymerization reaction (Kani et al., 2016). Class F fly ash's reactivity leads to faster setting times and higher early strength development, which can be advantageous in construction applications requiring rapid strength gain (Palomo et al., 1999).

Furthermore, Class F fly ash is environmentally advantageous due to its reduced carbon footprint. The lower CaO content results in fewer CO_2 emissions during the geopolymerization process compared to Class C fly ash (Provis & van Deventer, 2014). This aligns with sustainable construction practices that aim to minimize environmental impact. In conclusion, Class F fly ash's chemical composition and pozzolanic reactivity make it a preferred choice in geopolymer mixtures. Its high silica and alumina content, coupled with its low calcium content, contribute to efficient geopolymerization reactions and the formation of durable matrices. This underscores its significance in advancing sustainable construction practices and promoting the development of high-performance non-fired geopolymer materials.

Sand

The core focus of this research is an exhaustive exploration of non-fired geopolymer specimens, focusing on the incorporation of a ubiquitous construction material: river sand. River sand, being a widely employed component in concrete manufacturing, holds paramount importance due to its availability and typical utilization. The choice to integrate river sand into geopolymer mixtures aligns the investigation with established construction practices and materials, offering practical insights into the feasibility and potential enhancements of non-fired geopolymer bricks. In the context of river sand's incorporation into geopolymer mixtures, a critical consideration is the optimal particle size distribution that best supports the material's structural performance and overall characteristics. The particle size of aggregates, including sand, significantly influences the packing density, homogeneity, and microstructural development of the geopolymer matrix. This intricate interplay between particle sizes and material properties underscores the necessity for a balanced particle size distribution within the mixture. The most desirable size of river sand for geopolymer mixtures tends to span a range from fine to intermediate sizes. Research by Sata et al. (2001) highlights that a well-graded distribution aids in achieving a dense and compacted matrix, which is vital for ensuring optimal mechanical properties. Fine particles contribute to the cohesiveness of the mixture, facilitating strong interparticle bonding and promoting the geopolymerization reaction. On the other hand, intermediate-sized particles play a role in bridging gaps between fine particles, leading to enhanced packing density and further reinforcing the matrix.

However, a balance must be struck to prevent an excessive proportion of fine particles that might lead to an increase in porosity and reduced mechanical strength. Oversized particles can hinder the geopolymerization process and result in incomplete matrix formation. Therefore, a judicious combination of particle sizes that promotes efficient geopolymerization and optimizes the packing arrangement is paramount. The incorporation of river sand into non-fired geopolymer mixtures underscores its practical relevance within the construction industry. The ideal particle size distribution—spanning from fine to intermediate sizes—emerges as a critical factor influencing the homogeneity, packing density, and geopolymerization process. By adhering to this balance, the research endeavours to enhance our understanding of how river sand contributes to the mechanical properties and overall performance of non-fired geopolymer specimens.

Hydrated Lime

To enhance the strength and durability of the non-fired geopolymer bricks, commercial building lime, specifically hydrated lime, was utilized to initiate the pozzolanic reaction of the class F fly ash. Precautions were taken to prevent the occurrence of "scumming" during the manufacturing process. Through trial-and-error testing, it was determined that each fly ash brick could be prepared with a consistent amount of lime, equivalent to 5% of the total mass. Remarkably, the inclusion of this additional lime did not result in any observable "scumming" following the firing process.

Hydrated lime, also referred to as calcium hydroxide ($Ca(OH)_2$), is a chemical compound that emerges through the hydration process of quicklime (calcium oxide, CaO) with water. This transformation yields a finely powdered substance that finds applications across various industries due to its versatile properties. It is renowned for its alkaline character, high reactivity, and fine particle size, which contribute to its ease of incorporation into different materials. Sources such as Mindess et al. (2003) emphasize that the formation of hydrated lime occurs through an exothermic reaction, generating a white, powdery substance that readily reacts with water and carbon dioxide from the atmosphere. The alkaline nature of hydrated lime, with a pH value ranging from 12 to 13 when mixed with water, is central to its properties. Neville (2011) explains that its alkalinity influences the behaviour of materials it interacts with, affecting their chemical reactions and stability. Furthermore, the fineness of hydrated lime particles, often resulting from grinding, enhances its dispersibility and compatibility with other materials. Malhotra and Ramezanianpour (1994) note that this fine particle size contributes to its ability to efficiently interact with other compounds in mixtures, such as fly ash or geopolymer precursors.

Hydrated lime's role in enhancing workability is multifaceted, as elaborated by Mehta and Monteiro (2013). Its ultrafine particles facilitate lubrication between cementitious particles, thereby improving the flow and ease of placement during mixing. Sources such as ACI Committee 548 (2012) point out that this enhanced workability translates to reduced water demand for a given slump, contributing to improved density and durability of the final product. Furthermore, Neville and Brooks (2010) discuss how hydrated lime's ability to modify the rheology of mixtures reduces the permeability of concrete or geopolymer matrices. This reduction in permeability enhances the materials' resistance to moisture ingress, chemical attack, and other deleterious processes, thereby enhancing their service life.

The pozzolanic activity of hydrated lime underpins its role in strength enhancement and the mitigation of ASR, as highlighted by Provis and van Deventer (2014). When used in combination with other cementitious materials such as fly ash or slag, hydrated lime contributes to the formation of additional calcium silicate hydrate (C-S-H) gel, which reinforces the matrix and improves strength over time. Fernandez-Jimenez and Palomo (2003) discuss how hydrated lime's consumption of excess alkalis curtails ASR, a reaction that can result in damaging expansion and cracking in concrete. The interaction between hydrated lime and alkalis consumes reactive compounds, thereby reducing the potential for expansive reactions, improving the material's durability and minimizing the risk of damage in aggressive environments. Gourley and Myers (2019) elucidate how the addition of hydrated lime alongside pozzolanic materials such as fly ash or slag augments the pozzolanic reactions. The synergy between these materials enhances the formation of additional cementitious compounds, leading to improved microstructural development and material strength. Moreover, Mindess et al. (2003) underscore the role of hydrated lime in contributing to early strength development, which is crucial for projects with tight construction schedules. The reactivity of hydrated lime accelerates the initial stages of hydration, resulting in early strength gain and setting properties. This characteristic proves valuable in reducing construction timelines and improving project efficiency.

The ability to control the alkalinity and pH of mixtures is another facet of hydrated lime's significance, as emphasized by sources like Provis and van Deventer (2014). Engineers can manipulate the amount of hydrated lime added to regulate the material's chemical environment. This control impacts the kinetics of reactions, the solubility of ions, and the development of desired microstructures. These considerations have practical implications in optimizing the mechanical properties, durability, and overall performance of concrete or geopolymer mixtures tailored to specific applications.

Sodium Silicate/water glass

Sodium silicate, commonly referred to as water glass, is a chemical compound formed by the fusion of sodium carbonate (soda ash) and silica sand at high temperatures. The resulting glass-like material is soluble in water, leading to the term "water glass." The composition of sodium silicate varies depending on the ratio of sodium oxide (Na_2O) to silicon dioxide (SiO_2). This compound plays a vital role in geopolymer production due to its capacity to provide alkalinity, solubility, and silicon dioxide content. As highlighted by Davidovits (1994), sodium silicate acts as a precursor that contributes to the formation of geopolymeric networks. The alkaline nature of sodium silicate stands as a catalytic cornerstone in the initiation of the geopolymerization process, orchestrating a sequence of chemical reactions that bestow aluminosilicate materials with newfound strength and coherence. This phenomenon, driven by the interaction between sodium silicate and aluminosilicate precursors, such as fly ash or slag, is a prime example of the intrinsic synergy between chemistry and material science in the realm of geopolymer production. The pioneering research of Davidovits (1994) and subsequent studies elucidate the critical role played by the alkaline nature of sodium silicate. Upon mixing sodium silicate with aluminosilicate precursors, the solution becomes endowed with an alkaline pH, a fundamental condition for the hydrolysis and polycondensation reactions that characterize geopolymerization. These reactions lead to the transformation of the aluminosilicate constituents into a three-dimensional network of polymeric structures, a network that ultimately forms the basis of the hardened geopolymer material. The alkaline environment serves as a catalyst, expediting these reactions and fostering a dynamic interplay that triggers the hardening process.

To gain a comprehensive understanding, it is imperative to explore the broader research landscape. Provis and van Deventer (2014) delve into the intricate intricacies of the alkaline activation process, further substantiating the significance of the alkaline environment. Their exploration accentuates the role of alkalinity in driving the dissolution of silicon and aluminium species from the aluminosilicate precursor, leading to the formation of polymeric gels. These gels, created in the alkaline surroundings, ultimately consolidate into a robust network that imparts strength to the geopolymer material. The alkaline-driven polymeric structure formation is not merely an academic concept; it is a transformative process that shapes geopolymeric materials' mechanical and chemical properties, aligning with the pioneering observations of Davidovits (1994). The alkaline nature of sodium silicate emerges as a catalyst that ushers in the geopolymerization process, acting as the architectural foundation upon which polymeric structures are constructed. This fundamental principle, as articulated by Davidovits (1994) and further elucidated by Provis and van Deventer (2014), underscores the interplay between alkalinity, chemistry, and material formation. The alkaline environment serves as a medium through which geopolymeric materials achieve their mechanical strength and durability, a testament to the intricate dance between chemical reactivity and material transformation.

The solubility of sodium silicate stands as a crucial orchestrator in the delicate dance of geopolymer formation, paving the way for uniform mixing and the intricate interplay of vital constituents. This property, when coupled with the presence of silicon dioxide (SiO_2) within sodium silicate, sets the stage for network formation and underscores the material's structural integrity. As Palomo et al. (1999) illuminate, sodium silicate's soluble nature engenders not only comprehensive dispersion but also promotes effective interaction within the geopolymer mixture. The significance of sodium silicate's solubility is underscored by the work of Palomo et al. (1999). This property ensures that upon its introduction into the mixture, sodium silicate disperses evenly, enveloping the geopolymer constituents in a homogeneous solution. This uniform distribution plays a pivotal role in eliminating localized concentration variations, leading to a consistent and well-mixed composition. As a result, the interactions between sodium silicate and other precursors, such as aluminosilicate materials, are maximized, fostering a synergistic collaboration that culminates in the geopolymerization process.

Furthermore, the presence of silicon dioxide (SiO_2) within sodium silicate significantly shapes the geopolymerization process. As elucidated by Davidovits (1994), silicon dioxide is a fundamental building block for the formation of the geopolymeric matrix. This compound contributes to the network structure's stability and mechanical strength, making it an integral component in the geopolymerization process. The presence of silicon dioxide within sodium silicate provides a consistent and readily available source of this essential compound, streamlining the formation of the geopolymer network and ensuring the material's integrity. Additional sources like Provis and van Deventer (2014) corroborate the role of silicon dioxide as a cornerstone in geopolymerization. The comprehensive overview provided by these researchers emphasizes the intricate chemistry that underpins the formation of the geopolymeric matrix, with silicon dioxide acting as a linchpin in the intricate molecular interactions. This alignment of research underscores the collective understanding of the intricate role that sodium silicate's solubility and silicon dioxide presence play in the dynamic world of geopolymerization. Therefore, the solubility of sodium silicate operates as a catalyst for the harmonious mixing of geopolymer constituents, while the presence of silicon dioxide magnifies the material's structural foundation. The work of Palomo et al. (1999) and Provis and van Deventer (2014) provide a comprehensive view of these phenomena, emphasizing the significance of solubility in achieving homogeneity and the role of silicon dioxide in shaping the geopolymer network's stability.

The journey from liquid solution to solid structure in geopolymer production hinges on the remarkable adhesive properties of sodium silicate. This pivotal ingredient, when combined with water, orchestrates a transformative gel-like metamorphosis that intertwines particles and engenders the birth of a cohesive geopolymeric matrix. This intricate process, observed upon mixing sodium silicate with water, substantiates the adhesive prowess of this compound in holding together the geopolymeric framework, culminating in the development of a durable and resilient material. This phenomenon has been well-documented and further explored by various researchers, with a comprehensive understanding substantiated by additional sources. Palomo et al. (1999), in their research on alkali-activated fly ashes, underscore the gelation process as a critical juncture in geopolymerization. The mixing of sodium silicate with water sets the stage for hydrolysis and polycondensation reactions, creating a network of bonds that progressively build the geopolymeric structure. The subsequent formation of gel-like structures within the mixture is a direct manifestation of the adhesive nature of sodium silicate, as these structures function as molecular bridges, fusing particles and initiating the transformation from liquid to solid-like state.

Moreover, the adhesive properties of sodium silicate extend beyond mere physical binding. The alkaline environment catalysed by sodium silicate, as discussed by Provis and van Deventer (2014), contributes to the chemical interactions between silicate species and aluminosilicate precursors. This chemical bonding further solidifies the geopolymeric matrix, imbuing it with mechanical strength and durability. Provis and van Deventer's comprehensive insight underscores how sodium silicate's adhesive properties encompass a complex interplay of physical and chemical phenomena, enabling the development of a cohesive, load-bearing structure. In conclusion, the transition from a liquid solution to a cohesive geopolymer matrix is a testament to the adhesive prowess of sodium silicate. As a catalyst for hydrolysis, polycondensation, and the creation of gel-like structures, sodium silicate acts as the adhesive agent that binds particles together. This adhesive behaviour, as validated by sources like Palomo et al. (1999) and Provis and van Deventer (2014), is a driving force behind the solidification of geopolymeric material. It not only creates the physical framework but also facilitates chemical interactions, resulting in a geopolymer matrix characterized by its durability and strength.

In the realm of geopolymer production, sodium silicate emerges as a pivotal ingredient that catalyses the transformation of raw materials into a robust geopolymeric matrix. At the heart of its significance is the unique silicate activation process, as elucidated by Davidovits (1994), which defines how sodium silicate imparts its binding prowess to the Geopolymerization process. When sodium silicate is mixed with aluminosilicate precursors such as fly ash or slag, a cascade of reactions is set in motion, culminating in the establishment of a three-dimensional network of geopolymeric bonds. This intricate network lies at the core of the material's solidification, bestowing it with structural integrity and a range of desirable properties. Davidovits' explanation of the silicate activation process provides a profound insight into the intricate chemistry that underpins Geopolymerization. Sodium silicate acts as a multifunctional agent: it not only supplies silicon dioxide (SiO_2) for the formation of the geopolymeric matrix but also creates an alkaline environment crucial for catalysing the reaction. This alkaline milieu is pivotal in activating the aluminosilicate precursors, initiating the hydrolysis and polycondensation reactions that generate the geopolymer network. The cross-linking of silicate species through the hydroxyl (OH^-) groups in the alkaline medium contributes to the solidification of the material, effectively transitioning it from a liquid solution to a hardened matrix. Further underscoring the importance of this process are references such as Hardjito and Rangan (2005), who delve into the transformative potential of sodium silicate in geopolymer concrete. Their research corroborates Davidovits' insights, emphasizing that the interaction between sodium silicate and aluminosilicate precursors prompts the formation of geopolymeric gels. The unique interplay between alkalinity, silicon dioxide contribution, and cross-linking is a cornerstone in achieving the geopolymer's mechanical strength and durability.

Mixing

The experimental procedure concerning the preparation and mixing of materials for the geopolymer specimens holds pivotal importance, as evidenced by an array of prior literature studies that emphasize the profound impact of material ratios and thorough mixing techniques on the performance of non-fired geopolymer bricks. Notably, the research conducted by Nataatmadja serves as a notable case study. This research delved into the influence of curing design on the wet compressive strength of non-fired geopolymer bricks and employed various fly ash to silica sand ratios—50/50, 70/30, and 90/10. Integral to all these dry mixtures was a consistent inclusion of 5% hydrated lime concerning the dry mixture composition, a component acknowledged for its enhancing effects. The pivotal mixing phase involves the utilization of a mixer boasting a capacity of approximately 20 litres, chosen for its ability to facilitate effective mixing outcomes.

Figure 5: 20L Heavy Duty Mixer

The procedure begins with the meticulous blending of the dry materials, a process that holds the key to a well-bonded geopolymer matrix. The dry mixtures—comprising fly ash, silica sand, and the constant hydrated lime additive—are subjected to a rigorous mixing regimen within the chosen mixer. The blending unfolds over an initial duration of 3-5 minutes, a period meticulously chosen to ensure the attainment of a homogenized geopolymer binder that lays the foundation for subsequent interactions. Following this initial mixing phase, the alkaline solution is introduced to the dry mixture, marking a pivotal juncture. The combination undergoes continued mixing for an additional 6 minutes, a meticulous duration aimed at fostering the formation of a fully homogenous binder. This sequence of mixing steps is a delicate balance, orchestrated to yield a consistent and uniformly distributed mixture, the very cornerstone of a robust geopolymer matrix.

Adding another layer of intricacy, the experimentation extends to the variation of Liquid Sodium Silicate quantities—a parameter with the potential to significantly impact the final material's characteristics. Different proportions—5, 10, 15, and 20% relative to the dry mass—of Liquid Sodium Silicate are systematically introduced to each type of dry mixture ratio. This intricate exploration scrutinizes the effects of Liquid Sodium Silicate as a binder, investigating how its varying quantities influence the overall geopolymerization reaction and the properties of the resultant matrix. By systematically assessing these quantities, the research navigates the delicate balance between too little and too much, aiming to pinpoint the optimal range that bestows the geopolymer with the desired attributes. In essence, this segment of the experimental procedure unveils a meticulous dance of material ratios, mixing durations, and sodium silicate proportions—a symphony orchestrated to yield a harmonious and high-performing geopolymeric composition. This orchestration, informed by prior literature and guided by systematic experimentation, underscores the significance of precision and methodical consideration in crafting non-fired geopolymer bricks with enhanced mechanical properties.

Casting

The experimental procedure for casting geopolymer specimens is meticulously designed to address the specific challenges posed by the chemical properties of the alkaline binder, integral to the Geopolymerization process of non-fired geopolymer bricks. This phase of the research plays a pivotal role in shaping the final characteristics of the specimens, necessitating precise protocols and prudent material selections. Key among these is the careful choice of a mould that not only accommodates the geopolymer mixture but also resists the corrosive impact of the alkaline binder. This selection is a deliberate strategy, aimed at maintaining the integrity of the specimens throughout the casting process.

The selection of the mould material is predicated on its compatibility with the Geopolymerization process. A mould is chosen that demonstrates inherent resistance to the chemical properties of the alkaline binder—an agent central to the geopolymerization reaction's efficacy. This selection underscores the thoughtful consideration woven into the experimental design, ensuring that the mould's material characteristics do not compromise the desired chemical interactions that yield the geopolymer matrix. The geopolymer specimens are moulded into cylindrical casts, a form that aligns with the standardized procedures available at the Springfield Engineering Laboratory. Beyond their role as mere containers, these cylindrical casts serve as vessels for the transformation of geopolymer mixtures into tangible specimens. The specifics of this phase involve meticulously pouring the geopolymer mixture into the moulds arranged on a stable table. During this process, stringent care is taken to achieve uniform distribution, ensuring that every recess of the mould is thoroughly filled. This practice extends beyond mechanical action, embodying an attention to detail akin to the art of precision.

However, the intricacy of the procedure surpasses the act of pouring. It encompasses an acute awareness of the geopolymer mixture's behaviour—its tendency to overflow and its compaction requirements. As part of this meticulous approach, any excess mixture that spills over the brick mould is carefully removed, signifying a conscious effort to minimize wastage and emphasize precision. The casting sequence unfolds with an unswerving commitment to uniformity. Compaction becomes a universal mandate, aimed at ensuring the comprehensive compression of every particle in a consistent manner. This compaction process is accompanied by a judicious topping-up phase, contributing to the pursuit of uniformity and completeness. The phase culminates only when the entire mould is filled with the compacted mixture, a testament to the rigour and diligence inherent in the procedure.

Curing

Following the meticulous preparation of geopolymer mixtures and their subsequent casting into 100mm diameter x 200mm high cylindrical specimens, a judicious curing regimen is initiated to optimize the development of geopolymeric properties. Curing, a critical phase in the maturation of geopolymer materials, exerts a profound influence on their mechanical and structural attributes. The experimental procedure adopts a multi-stage curing approach, each phase calibrated to harness the geopolymerization reaction's potential for optimal results.

During the initial stage of curing, the freshly cast specimens are subjected to a controlled environment mimicking room conditions—approximately 23 degrees Celsius and a relative humidity of 80%. This environment is maintained by utilizing a saturated aqueous solution, ensuring that the curing environment remains uniformly moist. This approach aligns with established literature that emphasizes the importance of initial humid curing for the activation of geopolymerization reactions. By maintaining the specimens in such conditions for four days, a conducive setting is established for the initiation of the geopolymerization process. This phase serves as a foundational period, during which the first stages of chemical reactions are encouraged to unfold.

After the initial four-day humid curing phase, the specimens are transitioned into an oven environment at a temperature of 40 degrees Celsius. In this phase, the specimens are maintained at an elevated relative humidity of 80% for 12 days. The elevated temperature serves to accelerate the kinetics of the geopolymerization reaction, fostering the formation of the geopolymeric matrix with enhanced efficiency. The sustained elevated humidity, coupled with the controlled temperature, ensures that the geopolymerization process proceeds unhindered, promoting the development of the desired mechanical properties.

Figure 6: 150L Fan Forced High-Temperature Laboratory Oven

The final stage of the curing process introduces an incremental increase in temperature. The specimens are exposed to an elevated temperature of 110 degrees Celsius for 12 hours. This elevated temperature regimen serves as a capstone, finalizing the geopolymerization reaction and ensuring the attainment of the desired material characteristics. The controlled temperature not only hastens the maturation process but also contributes to the densification of the geopolymer matrix, potentially enhancing its mechanical strength and durability. Drawing insights from past literature, the chosen curing strategy aligns with the observed benefits of a prolonged humid curing process preceding the oven drying phase. This strategy has shown promise in expediting and augmenting the geopolymer binding process, a crucial precursor to subsequent oven drying and mechanical testing. By capitalizing on the advantages of a carefully staged curing process, the experimental procedure seeks to unlock the full potential of geopolymer materials, optimizing their attributes for superior performance.

Chapter 3: Testing and Results

The evaluation of non-fired geopolymer bricks is a thorough and multifaceted process, aiming to uncover essential material properties crucial for their use in construction. These tests are thoughtfully designed to mimic real-world scenarios and adhere to Australian standards. They delve into fundamental characteristics like overall compressive strength, tensile strength, and durability. This comprehensive assessment provides a holistic view of the proposed geopolymer brick samples, assessing their structural soundness and their ability to withstand diverse environmental conditions.

At the core of this evaluation is the determination of the non-fired geopolymer bricks' overall compressive strength. This property is critical as it forms the foundation for their load-bearing capacity and structural performance. The compressive strength test involves subjecting the specimens to increasing loads until they fail, offering valuable insights into the ultimate strength of the geopolymer bricks. This examination not only confirms the material's suitability for structural purposes but also sheds light on its behaviour under extreme loads.

In addition to compressive strength, the evaluation also includes an assessment of tensile strength. Tensile strength is a vital indicator of a material's ability to resist forces that pull or stretch it apart. By applying tensile stresses to the specimens, this test provides essential data for engineering considerations.

Durability, a crucial attribute for construction materials, plays a significant role in this evaluation. Recognizing the importance of designing bricks capable of withstanding various environmental conditions, the testing protocol includes subjecting the specimens to a wet compressive test after soaking. This test simulates the material's performance under prolonged exposure to moisture, resembling real-world conditions. The wet compressive test rigorously examines the material's resistance to degradation in moist conditions, complementing the information gathered from the water absorption test. This sequential approach contributes to a comprehensive understanding of the material's response to moisture infiltration and its implications for long-term performance.

Compression Test

Each individual geopolymer brick sample will undergo meticulous testing using a specialized Universal Testing Machine (UTM). This apparatus is precisely engineered to unravel a material's intricate relationship between strength and deformation when subjected to a compressive load. The UTM's significance in this context lies in its capacity to provide quantitative insights into a material's structural integrity and its response to compressive forces. The testing procedure unfolds with precision, beginning with the placement of the geopolymer brick sample within the embrace of the Universal Testing Machine. This apparatus ensures that the sample is firmly positioned for assessment, a fundamental prerequisite for accurate and reliable results. The secure positioning of the sample is further reinforced by utilizing locking clamps on opposing edges of the brick. These clamps immobilize the sample, mitigating any lateral movement that could compromise the precision of the test outcomes.

A critical facet of this testing methodology involves measuring the surface area of the hydraulic pin, a component that interfaces directly with the geopolymer brick sample during the testing process. This meticulous measurement contributes to the precision of the ensuing calculations, underpinning the accuracy of the derived results. The essence of the compressive strength assessment resides in the incremental application of failure load onto a corresponding cross-sectional area of the geopolymer brick. This gradual incrementation mirrors the stress conditions experienced by materials in real-world scenarios and provides a controlled environment to ascertain their behaviour under load. The ultimate objective is to gauge the point at which the material succumbs to failure—a moment that offers insights into its inherent strength and capacity to withstand compressive stresses. The quantification of compressive strength is achieved by relating the total force applied until failure or deformation to the surface area upon which the compressive force is exerted. This calculus of force relative to surface area encapsulates the material's ability to withstand compressive loads, yielding a metric that is invaluable for engineering considerations and structural design. This quantitative outcome reflects the geopolymer brick's capacity to endure compressive stresses and forms the basis for informed decision-making in construction applications.

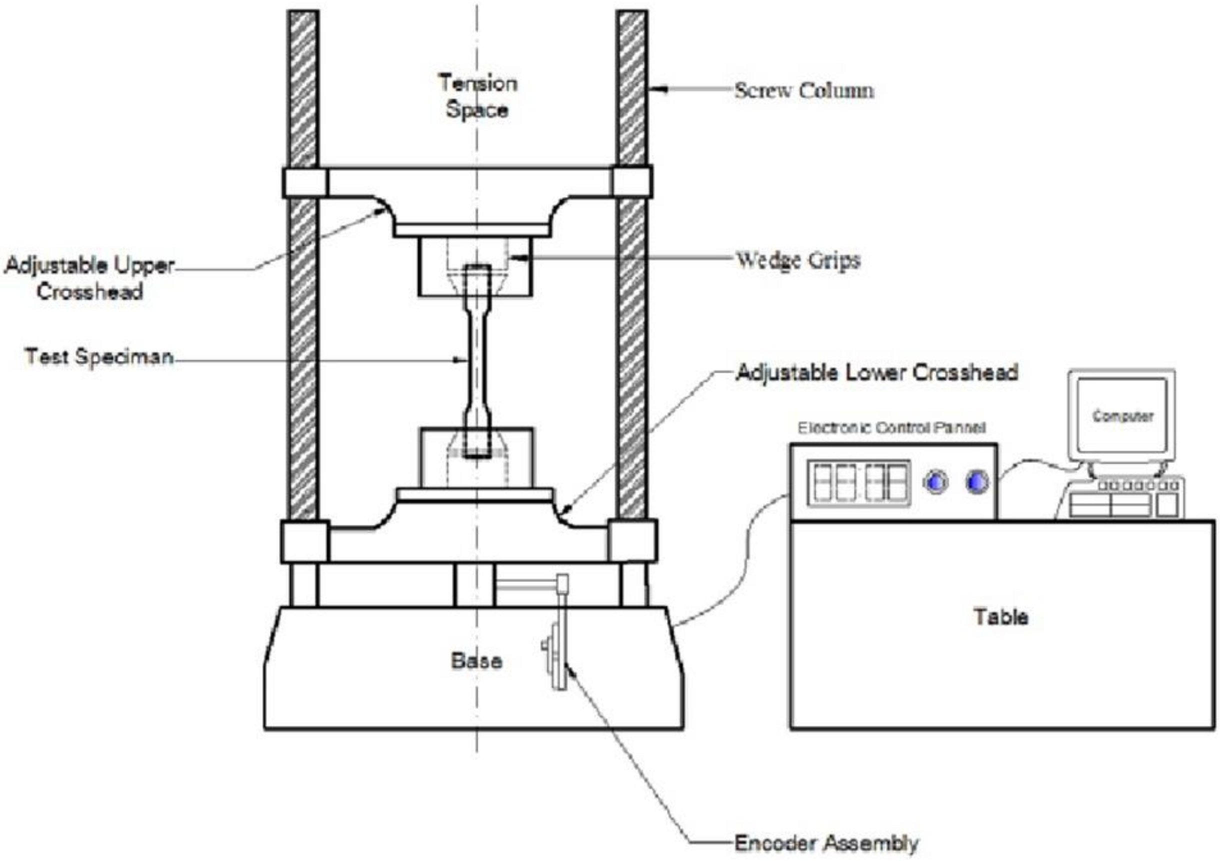


Figure 7: Diagram of Universal Test Machine (UTM).

Figure 8: Photo of Uni-Axial compressive testing machine

Compressive strength is the primary mechanical property considered in standard brick specifications. It measures the stress at which a brick fails when subjected to vertical compression perpendicular to its bed face. This is because most brickwork primarily experiences vertical compressive loads resulting from the self-weight of the structure and bearing loads (Nataatmadja et al., 2008). To ensure quality, three samples from each batch of bricks are tested in accordance with AS/NZS4456.4-1997.

Compressive Strength Results:		
	% LSS by mass	Failure Load (kN)
50/50	5	44.17
	5	62.28
	5	63.48
	10	104.04
	10	146.73
	10	149.41
	15	176.85
	15	249.39
	15	253.91
	20	146.45
	20	206.51
	20	210.30
70/30	5	71.24
	5	100.53
	5	102.38
	10	86.67
	10	122.15
	10	124.37
	15	187.57
	15	264.45
	15	269.25
	20	158.74
	20	223.88
	20	227.95
90/10	5	122.06
	5	172.05
	5	175.19
	10	142.11
	10	200.42
	10	204.11
	15	201.99
	15	284.78
	15	289.95
	20	170.11
	20	239.87
	20	244.21

Table 2: Maximum Failure loads recorded from Uni-Axial Compressive Test Results of all geopolymer samples.

From this raw data collected from the investigation, as apart of Australian standards 3 compressive tests must be conducted per specimen type, however the average of the three results can be recorded as the final compressive strength of each sample.

The failure load for each tested specimen was tested and recorded, to estimate the geopolymer brick specimens’ compressive strengths using Equation (1):

$\sigma c = Ka(1000P/A)$ (1)

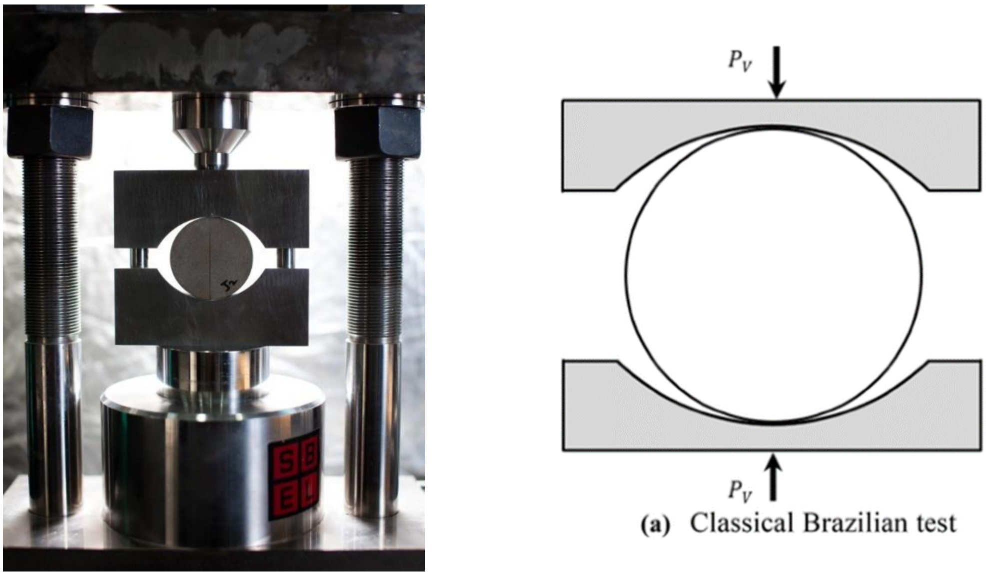
Where σc = uniaxial compressive strength (MPa),
P = failure load (kN),
A = net cross-sectional area (mm2), and
Ka = aspect ratio factor (to allow for height-to-thickness
ratio), in this case 0.85.

Compressive Strength Results:			
Fly Ash to Sand	% LSS by mass	Failure Load (kN)	σc (MPa)
50/50	5	44.17	4.78
	5	62.28	6.74
	5	63.48	6.87
	10	104.04	11.26
	10	146.73	15.88
	10	149.41	16.17
	15	176.85	19.14
	15	249.39	26.99
	15	253.91	27.48
	20	146.45	15.85
	20	206.51	22.35
	20	210.30	22.76
70/30	5	71.24	7.71
	5	100.53	10.88
	5	102.38	11.08
	10	86.67	9.38
	10	122.15	13.22
	10	124.37	13.46
	15	187.57	20.3
	15	264.45	28.62
	15	269.25	29.14
	20	158.74	17.18
	20	223.88	24.23
	20	227.95	24.67
90/10	5	122.06	13.21
	5	172.05	18.62
	5	175.19	18.96
	10	142.11	15.38
	10	200.42	21.69
	10	204.11	22.09
	15	201.99	21.86
	15	284.78	30.82
	15	289.95	31.38
	20	170.11	18.41
	20	239.87	25.96
	20	244.21	26.43

Table 3: Uni-Axial Compressive Strength Results of geopolymer samples.

Tensile Test

For this study, whilst not being the most important required test, testing for the bricks' tensile strength can help provide a better insight into the brick's structural behaviour in addition to compressive strength. The non-fired geopolymer brick samples' tensile properties can be determined through the indirect tensile test. The indirect split-tensile test is a diametric compression applied to a circular disk specimen (Zhou et al., 2007). The Brazilian tensile strength test apparatus is commonly utilized for conducting indirect tensile strength tests. This apparatus consists of a testing machine equipped with two parallel platens or loading points. The specimen, typically in the form of a cylindrical or disc shape, is positioned between these platens. During the test, compressive forces are applied to the specimen by the platens, resulting in indirect tensile stress. The load is gradually increased until the specimen fractures along the diametrical plane. The force required to cause the fracture is carefully measured and utilized to calculate the specimen's indirect tensile strength. The Brazilian tensile strength test apparatus is specifically designed to conduct indirect tensile strength tests and is suitable for a wide range of materials allowing for the determination of tensile strength indirectly, without directly subjecting the specimen to a tensile force. The significance of tensile strength in bricks is relatively lower compared to other parameters. However, tensile strength becomes an important factor when constructing brickwork with openings, spans, arches, and special courses like header and soldier courses.



(a) Classical Brazilian test

Figure 9: Photo of Tensile Test apparatus with sample and diagram depiction of forces acting against test sample.

Indirect Tensile Strength (Brazilian Test) Results			
FLY ASH TO SAND RATIO	% LSS by mass	Fs (kN)	Fs (N)
50/50	5	19.48	19480.4
	5	27.65	27649.6
	5	27.96	27963.8
	10	47.76	47758.4
	10	67.24	67238.8
	10	68.50	68495.6
	15	72.27	72266.0
	15	101.80	101800.8
	15	103.69	103686.0
	20	64.73	64725.2
	20	91.12	91118.0
	20	93.00	93003.2
70/30	5	0.00	0.0
	5	38.65	38646.6
	5	17.60	17595.2
	10	36.76	36761.4
	10	51.84	51843.0
	10	52.79	52785.6
	15	88.92	88918.6
	15	125.37	125365.8
	15	127.88	127879.4
	20	68.18	68181.4
	20	95.83	95831.0
	20	97.72	97716.2
90/10	5	63.15	63154.2
	5	88.92	88918.6
	5	90.49	90489.6
	10	68.50	68495.6
	10	96.77	96773.6
	10	98.66	98658.8
	15	96.15	96145.2
	15	135.73	135734.4
	15	137.93	137933.8
	20	78.55	78550.0
	20	110.91	110912.6
	20	112.80	112797.8

Table 4: Maximum Failure Load recorded during Indirect Tensile Strength Tests (Brazilian Test Method).

The indirect tensile test method was conducted is in accordance with AS/NZS4456.14-1997. The test simply involves applying a line load to a brick, supported by a linear reaction in the plane of linear loading to cause the brick to fail/split. As stated within the standards, the tensile strength will be determined through three specimens being test per sample type. The failure load is indirectly related to the tensile strength of the brick (Equation 2).

$f_s = 2F_s/(3.142bh)$ (2)

Where f_s = tensile strength (MPa),

F_s = maximum splitting load (N),

b = width of chosen cross-section (mm), (the length of the specimen = 200mm)

h = height of chosen cross-section (mm), (the diameter of the specimens = 100mm)

The overall tensile strength of each geopolymer sample is calculated by converting the maximum failure loads recorded through equation 1 outlined above.

Indirect Tensile Strength (Brazilian Test) Results		
FLY ASH TO SAND RATIO	% LSS by mass	fs (MPa)
50/50	5	0.62
	5	0.88
	5	0.89
	10	1.52
	10	2.14
	10	2.18
	15	2.3
	15	3.24
	15	3.3
	20	2.06
	20	2.9
	20	2.96
70/30	5	0
	5	1.23
	5	0.56
	10	1.17
	10	1.65
	10	1.68
	15	2.83
	15	3.99
	15	4.07
	20	2.17
	20	3.05
	20	3.11
90/10	5	2.01
	5	2.83
	5	2.88
	10	2.18
	10	3.08
	10	3.14
	15	3.06
	15	4.32
	15	4.39
	20	2.5
	20	3.53
	20	3.59

Table 5: Indirect Tensile Strength Results using the Brazilian Test Apparatus.

Durability Test

There are several methods and tests to measure the different durability properties of the geopolymer brick specimens. However, the most important durability test for geopolymer bricks is to conduct a water absorption test. Water absorption is a very important durability test especially when evaluating the structural properties of geopolymer bricks. It is conducted to determine the overall moisture the brick absorbs when the specimen is exposed to weathering such as rain. It also can act as a potential indicator of desirable durability properties such as quality, fire resistance, and the specimen's behaviour within weathering. The initial specimen weight is recorded and is then submerged in water at roughly 27 Degrees for 24 hours. The test then removes the specimen from the water and is wiped clean to remove any surface moisture or water. Following this, the specimen's new weight after conducting the test is recorded, and the water absorbed by the specimen can be calculated using the formula:

$$W = \frac{M_2 - M_1}{M_1} X\ 100$$

Where:

$M_2 = Mass\ after\ water\ absorbtion\ test$

$M_1 = Mass\ before\ water\ absorbtion\ test$

Cold Water Absorption Results				
FLY ASH TO SAND RATIO	% LSS	Dry Weight (g)	Wet Weight (g)	Cold Water Absorption %
50/50	5	1808	2138	18.23
50/50	10	1909	2282	19.53
50/50	15	2201	2663	21.02
50/50	20	2016	2362	17.14
70/30	5	1529	1907	24.73
70/30	10	1615	2000	23.89
70/30	15	1861	2181	17.18
70/30	20	1705	1965	15.27
90/10	5	1250	1601	28.04
90/10	10	1320	1642	24.37
90/10	15	1521	1743	14.58
90/10	20	1394	1563	12.16

Table 6: Cold Water Absorption Results

Boiling Water Absorption Results				
FLY ASH TO SAND RATIO	% LSS	Dry Weight (g)	Wet Weight (g)	Boiling Water Absorption %
50/50	5	1808	2138	17.69
50/50	10	1909	2282	17.47
50/50	15	2201	2663	15.93
50/50	20	2016	2362	12.34
70/30	5	1529	1907	26.88
70/30	10	1615	2000	23.54
70/30	15	1861	2181	13.34
70/30	20	1705	1965	11.73
90/10	5	1250	1601	29.22
90/10	10	1320	1642	26.18
90/10	15	1521	1743	21.62
90/10	20	1394	1563	20.32

Table 7: Boiling Water Absorption Results

Chapter 4: Discussion

Previous Research

In the initial stages of the study, the research employed by Nataatmadja et al., (2010) focused on utilising Tarong fly ash, a Class F fly ash alongside two different types of sand. This study focused on researching and comparing the differentiating structural properties of geopolymer bricks produced by both river sand and silica sand serving as the two primary raw materials for the experimentation. These combinations were crafted in fly ash-to-sand ratios of 50/50, 70/30, and 90/10, each representing a unique proportion of the two essential constituents. To further enhance the formulation, Liquid Sodium Silicate was introduced into the mixture at varying concentrations of 5%, 10%, 15%, and 20%. Additionally, a complementary element, hydrated lime, was integrated into the concoction at a consistent 5% content. The specific quantities of these additives were meticulously calculated by multiplying the percentages enclosed within parentheses by the cumulative mass of the primary raw materials.

This systematic approach to crafting different blends and introducing additives embodies a comprehensive strategy to investigate how varying compositions impact the resulting material properties. By systematically altering the fly ash-to-sand ratios and introducing different percentages of Liquid Sodium Silicate and hydrated lime, the researchers delve into the intricate interplay between these components. The choice of ratios and additives reflects a keen desire to comprehensively explore the potential for enhancing the overall quality and performance of the resulting material. This methodology holds the potential to unveil nuanced relationships between composition and material behaviour. As the percentages of Sodium Silicate and hydrated lime are carefully scaled in proportion to the primary raw materials, the investigation seeks to identify optimal formulations that not only contribute to the material's structural integrity but also potentially align with sustainable and cost-effective production practices. The systematic nature of these manipulations fosters a more profound understanding of how the ingredients interact at various levels, contributing to the broader scientific understanding of material science and its practical implications.

The study conducted by Nataamadja et al. (2010) delves deeply into the intricacies of geopolymer brick composition and their subsequent behaviour during firing and testing. One crucial observation made in their investigation pertains to the impact of moisture content on brick integrity. It was noted that bricks characterized by elevated moisture content values often displayed subtle hairline surface cracks subsequent to the firing process. The researchers highlight that excessive moisture levels were closely associated with a phenomenon known as gross shrinkage, a key precursor to the development of severe cracks and the consequential loss of structural strength. As a strategic measure, the research team opted to maintain moisture content levels well below 30% to circumvent these detrimental effects. This emphasis on managing moisture content underscores its pivotal role in ensuring the overall durability and performance of the produced bricks.

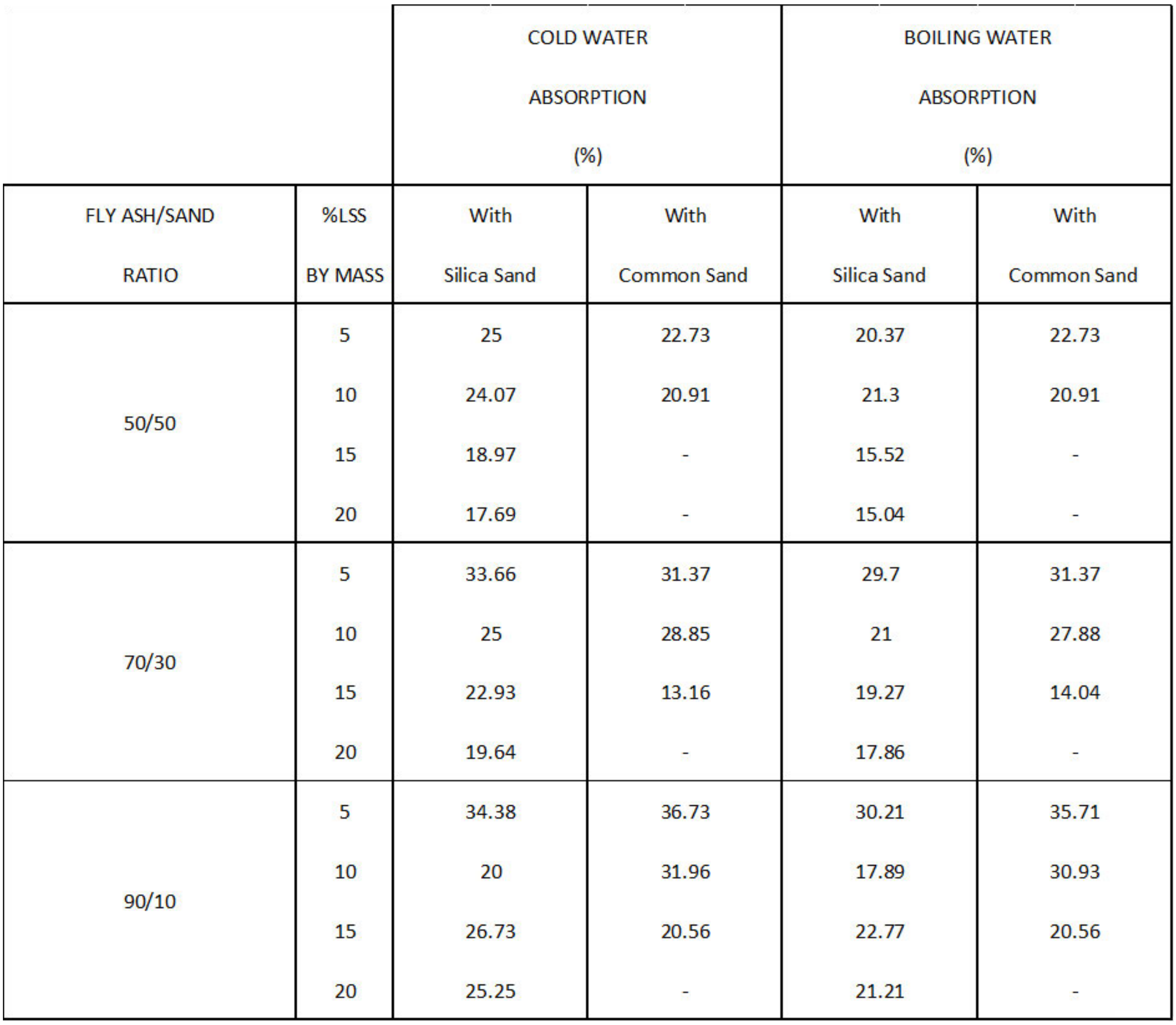
Furthermore, the study sheds light on the intricate relationship between the dry density of green bricks and the composition of their constituents, as well as the moulding pressure employed in their formation. Notably, a moulding pressure of 10 MPa was utilized, mirroring industry standards prevalent in clay brick production. This practice yielded green brick specimens with dry densities spanning a spectrum from approximately 1.15 t/m^3 to 1.65 t/m^3. However, the research findings emphasize that attaining optimum performance necessitates specific dry densities. For instance, bricks formulated from a mixture of fly ash and silica sand would ideally possess a dry density of around 1.40 t/m^3, while those composed of fly ash and common sand would ideally target a dry density of approximately 1.60 t/m^3. Remarkably, when contrasted with the significantly denser clay bricks with dry densities ranging from 2.25 t/m^3 to 2.8 t/m^3, the proposed fly ash bricks demonstrate a remarkable lightweight characteristic, indicating potential advantages in construction applications.

Of utmost significance in assessing brick quality and suitability for practical use is compressive strength. This mechanical property, serving as a cornerstone in standard brick specifications, quantifies the ability of the brick to withstand vertical compressive loads. As highlighted in the study, each batch of bricks was subjected to rigorous testing in accordance with AS/NZS4456.4 standards, involving the evaluation of three specimens. This systematic and standardized approach ensures a comprehensive understanding of how these fly ash bricks perform under compressive stress, thereby contributing to the robustness of the research's conclusions. In conclusion, the research conducted by Nataamadja et al. (2010) offers a nuanced exploration of various factors that intricately influence the properties and performance of fly ash bricks. From managing moisture content to optimizing dry density and comprehensively evaluating compressive strength, their investigation underscores the multidimensional nature of brick behaviour. These findings have profound implications for the field of construction, potentially paving the way for more sustainable and lightweight alternatives to traditional clay bricks.

Table 8: Fired Geopolymer Bricks Uniaxial Compressive Strength (Andreas et Al., 2010)

	COMPRESSIVE STRENGTH, σc (MPa)	
% LSS by mass	WITH SILICA SAND	WITH COMMON SAND
50/50 FLY ASH/SAND		
5%	8.57	9.37
10%	7.55	15.41
15%	23.49	30.82
20%	12.29	-
70/30 FLY ASH/SAND		
5%	8.25	8.11
10%	11.4	11.72
15%	26.98	25.91
20%	24.31	-
90/10 FLY ASH/SAND		
5%	10.01	7.56
10%	16.66	12.72
15%	24.29	24.1
20%	27.81	-

Table 9: Fired Geopolymer Bricks Water Absorption Results (Andreas et al., 2010)



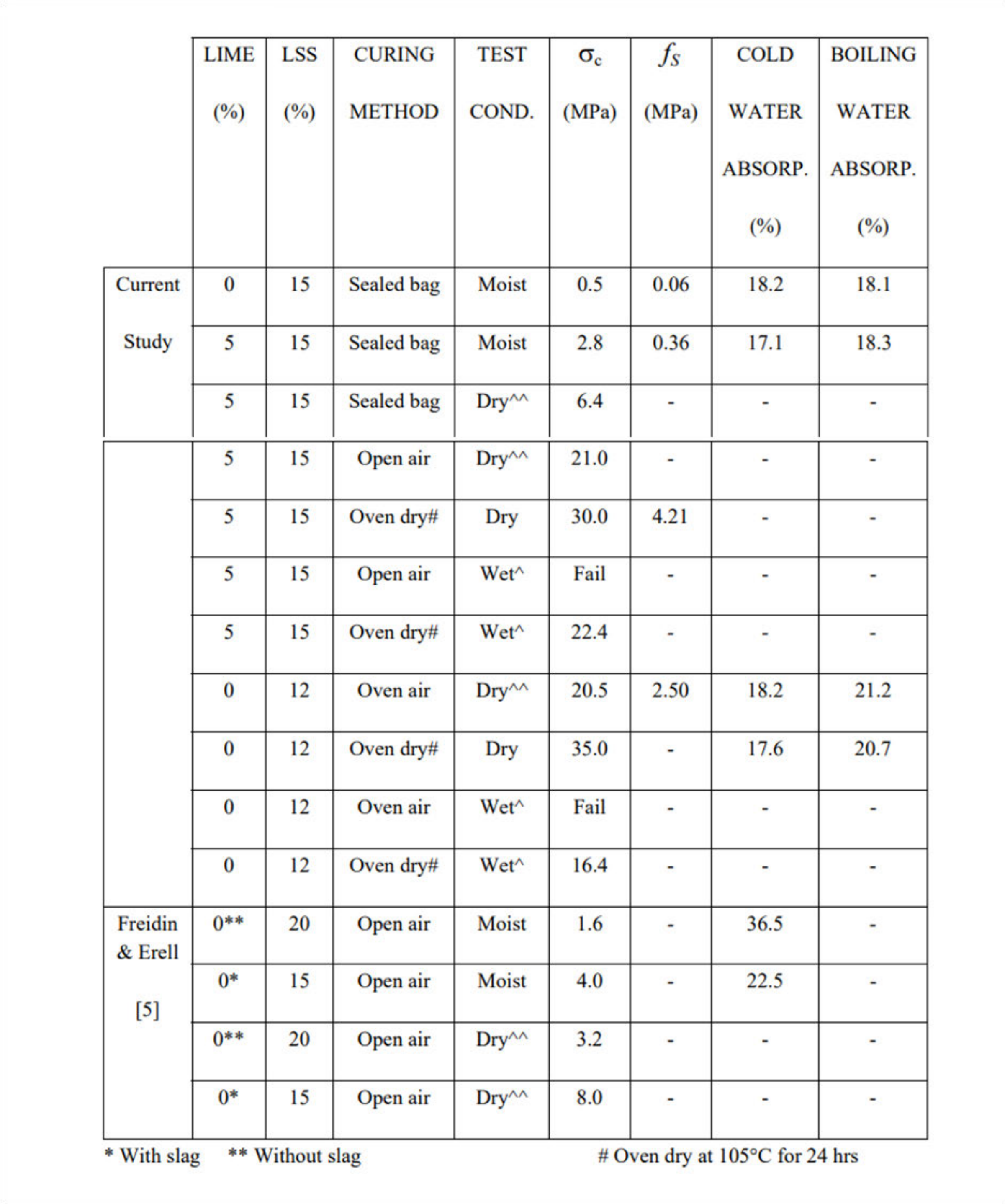
		COLD WATER ABSORPTION (%)		BOILING WATER ABSORPTION (%)	
FLY ASH/SAND RATIO	%LSS BY MASS	With Silica Sand	With Common Sand	With Silica Sand	With Common Sand
50/50	5	25	22.73	20.37	22.73
	10	24.07	20.91	21.3	20.91
	15	18.97	-	15.52	-
	20	17.69	-	15.04	-
70/30	5	33.66	31.37	29.7	31.37
	10	25	28.85	21	27.88
	15	22.93	13.16	19.27	14.04
	20	19.64	-	17.86	-
90/10	5	34.38	36.73	30.21	35.71
	10	20	31.96	17.89	30.93
	15	26.73	20.56	22.77	20.56
	20	25.25	-	21.21	-

As previously discussed, a significant study authored by Nataamadja et al. (2010) unveiled the outcomes of a meticulous experiment focused on the creation of air-cured bricks. This innovative approach harnessed a blend of fly ash, slag, and water glass as the fundamental components for crafting these bricks. The inherent potential of air-cured bricks to deliver commendable performance presents an enticing avenue for cost-effective construction solutions. Drawing inspiration from these encouraging findings, the ongoing investigation embarks on a journey to explore the realm of non-fired bricks, meticulously formulated with a balanced 70/30 proportion of fly ash to sand. Within the framework of this study, the spotlight falls upon the exclusive utilization of conventional sand. This sand is ingeniously combined with varying ratios of lime content, ranging precisely from 0% to 5%. Additionally, the experimentation introduces distinct concentrations of sodium silicate, finely tuned at either 12% or 15%. It's of paramount importance to emphasize that the comprehensive results showcased in Table 5 encompass an intricate tapestry of findings stemming from both air-cured and oven-cured bricks. The experimental testing protocols span a spectrum of environmental conditions, encompassing scenarios of moisture-laden, dry, and wet contexts. Moreover, these results are thoughtfully contextualized through meticulous comparison with the insights previously laid out in the seminal work by Nataamadja et al. (2010).

Upon meticulous analysis, an intriguing congruence emerges between the revelations unveiled by the present investigation and the pioneering study by Nataamadja et al. (2010). Noteworthy among the findings is the performance discrepancy observed between bricks subjected to the curing process within a sealed bag and those tested under moisture-rich conditions. Remarkably, the exposure of bricks to an open-air curing regimen spanning 28 days yielded a remarkable enhancement in terms of performance. This positive trend was notably highlighted when the bricks underwent a subsequent controlled oven-drying process, meticulously set at a temperature of 105°C. This deliberate procedure aimed to stabilize the bricks at a consistent mass before initiating the testing phase. However, the pinnacle of performance was attained through a distinct approach: freshly moulded, or "green," bricks underwent a carefully orchestrated 24-hour curing interval within an oven set at 105°C. Astonishingly, the outcomes of this strategy demonstrated parity, if not superiority, compared to the traditionally fired bricks.

Furthermore, the strategic introduction of lime as an additive emerged as a defining element, amplifying the holistic performance of the bricks. This additive proved to possess a discernible capacity to fortify the mechanical properties and overall durability of the bricks. However, a nuanced observation must be highlighted: while bricks subjected to open-air curing exhibited commendable dry compressive strength, this strength experienced a complete dissolution after a mere 48-hour immersion in water. The comprehensive findings from this endeavour resonate with the profound significance of nuanced curing methodologies and the judicious incorporation of additives in steering the trajectory of performance for non-fired bricks. The implications of these findings reverberate into the practical domain, particularly in contexts characterized by diverse and formidable environmental challenges.

Table 10: Non-Fired Geopolymer Bricks Previous Results (Nataamadja et al., 2010)



	LIME (%)	LSS (%)	CURING METHOD	TEST COND.	σ_c (MPa)	f_S (MPa)	COLD WATER ABSORP. (%)	BOILING WATER ABSORP. (%)
Current Study	0	15	Sealed bag	Moist	0.5	0.06	18.2	18.1
	5	15	Sealed bag	Moist	2.8	0.36	17.1	18.3
	5	15	Sealed bag	Dry^^	6.4	-	-	-
	5	15	Open air	Dry^^	21.0	-	-	-
	5	15	Oven dry#	Dry	30.0	4.21	-	-
	5	15	Open air	Wet^	Fail	-	-	-
	5	15	Oven dry#	Wet^	22.4	-	-	-
	0	12	Oven air	Dry^^	20.5	2.50	18.2	21.2
	0	12	Oven dry#	Dry	35.0	-	17.6	20.7
	0	12	Oven air	Wet^	Fail	-	-	-
	0	12	Oven dry#	Wet^	16.4	-	-	-
Freidin & Erell [5]	0**	20	Open air	Moist	1.6	-	36.5	-
	0*	15	Open air	Moist	4.0	-	22.5	-
	0**	20	Open air	Dry^^	3.2	-	-	-
	0*	15	Open air	Dry^^	8.0	-	-	-

* With slag ** Without slag # Oven dry at 105°C for 24 hrs

Results from the current investigation

Specimen properties post-curing

Following de-casting and the curing processes, a comprehensive examination of the various geopolymer samples revealed remarkable uniformity in their physical attributes. These samples exhibited consistent compositions, displaying minimal to no observable signs of segregation, voids, or notable disparities in aggregate distribution. To maintain the integrity of each sample, meticulous care was taken during the moulding process. The samples were compacted systematically in incremental layers, ensuring the absence of voids, deformities, and the attainment of a thoroughly compacted specimen. Additionally, special attention was paid to the specimen's ends, ensuring they were flush with the top of the concrete cast. This meticulous approach was adopted to guarantee a smooth testing surface devoid of any loose materials, which could potentially introduce inaccuracies into the various tests or alter the characteristics of the geopolymer specimens.

Consequently, the specimens exhibited straight alignment, devoid of any bends or curvature. This straightness proved crucial as it facilitated precise placement within the testing apparatus, thereby eliminating potential sources of error during the testing phase.

Figure 10: Photo of 15% LSS and 70/30 Fly Ash to Sand geopolymer specimen from current investigation.

Upon retrieval of the specimens from the fan-forced oven, a thorough examination revealed minimal to no indications of cracks, delamination, or any other visible defects within the core. This absence of structural defects held significant importance in ensuring the sound structural integrity of the specimens. The absence of cracks, in particular, was of paramount importance, as the presence of excessive moisture or rapid drying within the specimens during the oven-drying process could lead to cracking. Such cracks would not only compromise the reliability of the samples but could also impact the accuracy of the test results. In summary, the meticulous attention to detail throughout the entire process, from moulding to curing and drying, ensured that the geopolymer samples maintained their structural integrity, thereby enhancing the reliability and accuracy of subsequent tests and analyses.

Uniaxial Compressive Strength Results

COMPRESSIVE STRENGTH, σc (MPa)		
FLY ASH TO SAND RATIO	% LSS by mass	σc (MPa)
50/50	5	6.13
	10	14.44
	15	24.54
	20	20.32
70/30	5	9.89
	10	12.02
	15	26.02
	20	22.03
90/10	5	16.93
	10	19.72
	15	28.02
	20	23.6

Table 11. Uni-Axial Compressive Strength Results Table.

The dataset featuring compressive strength values of geopolymer samples at various fly ash to sand ratios and percentages of low-calcium fly ash (LSS) by mass provides a significant foundation for comprehending the performance and behaviour of these materials under diverse conditions.

Upon closer examination of the results from the 50/50 fly ash to sand ratio, a compelling trend emerges. It becomes evident that as the percentage of low-calcium fly ash (LSS) by mass increases, the compressive strength experiences a notable ascent. This phenomenon is articulated through a gradual rise in strength values, ranging from 6.13 MPa at 5% LSS to a substantial 24.54 MPa at 15%

LSS. However, intriguingly, a marginal dip in strength to 20.32 MPa manifests itself at the 20% LSS mark. This nuanced deviation piques our curiosity and prompts an exploration of potential causal factors. We must consider the possibility that this dip may be attributed to a multitude of influences, including variations in the composition of the geopolymer matrix, alterations in curing conditions, or complex interactions among the matrix's components.

In a parallel fashion to the 50/50 ratio, the 70/30 ratio showcases a trend of escalating compressive strength as the LSS percentage advances. This pattern is delineated by a spectrum of strength values that traverse from 9.89 MPa at 5% LSS to an impressive 26.02 MPa at 15% LSS. Echoing the previous ratio, a modest decline in strength is observed at 20% LSS, marking a value of 22.03 MPa. This consistent trend underscores the presence of an intriguing phenomenon—a distinctive optimal LSS percentage seemingly exists within this range. It hints at the prospect that meticulous selection of LSS content can serve as a potent lever for optimizing compressive strength in geopolymer compositions.

The 90/10 fly ash to sand ratio emerges as a standout performer, boasting the highest compressive strengths among the ratios in the dataset. The strength values follow a steady and robust ascent, initiating at a respectable 16.93 MPa at 5% LSS and culminating in an impressive 28.02 MPa at 15% LSS. Nonetheless, mirroring the trends identified in the previous ratios, we once again detect a noticeable dip in strength, this time clocking in at 23.6 MPa at the 20% LSS juncture. This dip aligns harmoniously with the patterns observed in the other ratios and further underscores the intriguing presence of an optimal LSS percentage range.

Water Absorption Results

WATER ABSORPTION RESULTS			
FLY ASH TO SAND RATIO	% LSS by mass	COLD WATER ABSORPTION %	BOILING WATER ABSORPTION %
50/50	5	18.23	17.69
	10	19.53	17.47
	15	21.02	15.93
	20	17.14	12.34
70/30	5	24.73	26.88
	10	23.89	23.54
	15	17.18	13.34
	20	15.27	11.73
90/10	5	28.04	29.22
	10	24.37	26.18
	15	14.58	21.62
	20	12.16	20.32

Table 12: Cold and Boiling Water Absorption Results Table.

Cold water absorption is a crucial parameter to evaluate the permeability and water retention properties of geopolymer samples. It provides insights into how these materials may behave when exposed to moisture during their service life. At the 50/50 fly ash to sand ratio, there appears to be a relationship between LSS content and cold-water absorption. As the percentage of LSS by mass increases, cold water absorption generally rises. For instance, at 5% LSS, the absorption is 18.23%, while at 15% LSS, it reaches 21.02%. However, the trend becomes less clear at 20% liquid sodium silicate, where the absorption drops to 17.14%. This deviation suggests that while LSS content plays a role, other factors may influence cold water absorption. In the 70/30 ratio, the trend in cold water absorption is less consistent. The absorption decreases from 24.73% at 5% LSS to 23.89% at 10% LSS but then experiences a significant drop to 17.18% at 15% LSS before further decreasing to 15.27% at 20% LSS. This fluctuation indicates that the relationship between LSS content and cold-water absorption is multifaceted and may be influenced by various factors beyond LSS alone. The 90/10 ratio demonstrates a similar trend with fluctuations in cold water absorption. It increases from 28.04% at 5% LSS to 24.37% at 10% LSS, decreases to 14.58% at 15% LSS, and stabilizes at 20% LSS with 12.16% absorption. Overall, reflecting upon the cold-water absorption results, the data suggests that the impact of liquid sodium silicate content on cold water absorption is not straightforward and may be influenced by the specific fly ash to sand ratio. While higher LSS content generally correlates with increased cold-water absorption, the fluctuations at certain LSS percentages indicate that additional factors, such as the overall mixture composition or curing conditions, may contribute to water absorption properties.

Boiling water absorption is another critical parameter as it simulates extreme conditions, assessing how geopolymer samples may respond to high-temperature exposure and moisture. Boiling water absorption at the 50/50 fly ash to sand ratio generally follows a pattern similar to cold water absorption. Higher LSS content is associated with increased absorption, ranging from 17.69% at 5% LSS to 12.34% at 20% LSS. In the 70/30 ratio, boiling water absorption exhibits a more consistent and linear increase as LSS content rises. It ranges from 11.73% at 20% LSS to 26.88% at 5% LSS. The 90/10 ratio's boiling water absorption pattern mirrors the trend observed in cold water absorption. It increases from 29.22% at 5% LSS to 20.32% at 20% LSS. After conducting the boiling water absorption test, the boiling water absorption appears to be more closely linked to liquid sodium silicate content compared to cold water absorption, particularly in the 70/30 and 90/10 ratios. The consistent rise in absorption with higher LSS content in boiling water suggests that LSS may have a more pronounced impact under extreme temperature conditions.

The insights derived from the water absorption data for geopolymer samples are both intricate and far-reaching, offering a profound understanding of how various factors influence the material's behaviour in the context of moisture exposure. These findings illuminate a complex interplay between two key factors: the fly ash to sand ratio and the proportion of low-calcium fly ash (LSS) content. Notably, a discernible trend emerges wherein higher LSS content consistently correlates with elevated water absorption rates. This observation raises pertinent questions about the long-term durability and performance of geopolymer-based products, especially when deployed in moisture-prone environments. The non-linear relationship between LSS content and water absorption introduces a layer of complexity, suggesting that additional influential factors are at play. These factors could encompass the intricate chemistry of the geopolymer matrix, curing conditions, and potential interactions among various components within the material as well as the initial compaction.

The promise lies in the potential for optimizing geopolymer formulations tailored to precise applications. By conducting systematic investigations into the interplay of variables, engineers and researchers can fine-tune geopolymer compositions to meet specific performance criteria. This optimization process hinges on meticulous mixture design and stringent quality control protocols. Ultimately, the wealth of information embedded in the provided water absorption data serves as an invaluable asset. It equips materials scientists and engineers with the knowledge needed to engineer geopolymer materials with finely tuned water absorption properties, ensuring their suitability for a wide spectrum of environmental conditions, whether they be standard or extreme. This underscores the paramount importance of precision in both the composition of geopolymer mixes and the rigor of curing procedures, paving the way for innovative and resilient construction materials.

Tensile Test Results:

TENSILE STRENGTH, fs (Mpa)		
FLY ASH TO SAND RATIO	% LSS by mass	fs (MPa)
50/50	5	0.797
	10	1.949
	15	2.945
	20	2.639
70/30	5	-
	10	1.503
	15	3.63
	20	2.776
90/10	5	2.574
	10	2.801
	15	3.923
	20	3.209

Table 13: Indirect Tensile Strength Test Results Table.

The provided data presents the outcomes of the Indirect Tensile Testing (Brazilian Test) conducted on samples comprising different combinations of fly ash to sand ratios and varying percentages of Liquid Sodium Silicate (LSS). A noteworthy observation from the results is the consistent positive correlation between the percentage of LSS by mass and the indirect tensile strength (fs) of the samples. In the case of a 50/50 fly ash to sand ratio, as the LSS content increased from 5% to 20%, the tensile strength improved progressively, reaching a peak value of approximately 2.945 MPa at 15% LSS content. This trend demonstrates the reinforcing effect of LSS on this particular mixture. Similarly, for the 70/30 and 90/10 fly ash to sand ratios, higher LSS percentages generally resulted in enhanced tensile strengths, supporting the notion that LSS contributes positively to the overall strength of the mixture. However, it's worth noting that data is missing for the 70/30 ratio at a 5% LSS content, which may require further investigation to understand the underlying reasons.

Comparing the different fly ash to sand ratios at the same LSS content (e.g., 10% LSS), a noticeable trend emerges. The 90/10 ratio consistently outperforms the 50/50 and 70/30 ratios, suggesting that this mixture is less sensitive to variations in LSS content while maintaining higher strengths. This finding implies that the 90/10 ratio could be a more robust choice when aiming to achieve a balance between strength and material efficiency. In terms of identifying an optimal mix proportion, the data suggests that a 90/10 fly ash to sand ratio with 15% LSS content yields the highest tensile strength of approximately 3.923 MPa, which could be considered a favorable mix for applications requiring high strength. However, it's important to acknowledge that these findings may exhibit some variability, especially at the 20% LSS content level, and should be further validated through additional experiments. These results hold significance for applications in construction and geotechnical engineering, where the use of fly ash, sand, and LSS mixtures may find practical utility. Nonetheless, it's crucial to recognize that these findings are based on a limited dataset, and future research should encompass a broader scope, taking into account various factors like curing conditions, material properties, and sample preparation methodologies, to establish more comprehensive and robust conclusions.

Chapter 5: Summary and Conclusions

The results of our tests exploring the relationship between lower curing temperatures and higher compaction pressure revealed that although they did not achieve higher compressive and tensile strength values, this method significantly reduced the time and energy required to produce these bricks while maintaining satisfactory properties. While the best-performing non-fired geopolymer brick samples did not reach the Uniaxial Compressive Strength of 30 or 35MPa from the previous study, the sample with 15% LSS and a 90/10 fly ash to sand ratio achieved a Uniaxial Compressive Strength of 28MPa, and the 15% LSS and 70/30 Fly ash to sand sample reached 26MPa. These two specimens, however, exhibited similar water absorption characteristics, both in cold and boiling water, compared to the previous study. Specifically, the 15% LSS and 90/10 fly ash to sand specimen had a cold-water absorption of 15% and a boiling-water absorption of 22%. Meanwhile, the 70/30 Fly ash to sand sample showed values of 17% and 13% for cold and boiling water absorption, respectively.

In comparison to the previous study, when testing the two geopolymer samples exposed to lower curing temperatures and higher compaction for indirect tensile strength, it was observed that the tensile strength, similar to compressive strength, decreased overall. The 70/30 sample withstood an indirect tensile stress of 3.6MPa, while the 90/10 sample withstood 3.9MPa. This was lower than the previous method's 70/30 fly ash to sand sample with 15% LSS, which yielded 4.2MPa in terms of indirect tensile strength. While our study did not replicate the exceptionally high Uniaxial Compressive Strength values of the previous work, it did demonstrate that by optimizing the compaction process and lowering curing temperatures, we could significantly reduce production time and energy consumption while maintaining satisfactory properties.

Our best-performing non-fired geopolymer brick samples achieved Uniaxial Compressive Strength values of 28MPa and 26MPa, with similar water absorption characteristics to the previous study. These results suggest that a balance between strength and energy efficiency can be struck in the production of geopolymer bricks. Additionally, the findings indicate that the reduction in curing temperature and increase in compaction pressure, while impacting tensile strength negatively, can be a viable approach for practical applications of geopolymer brick production. Overall, this research builds upon the foundation laid by Nataatmadja et al. and provides valuable insights into improving the sustainability and efficiency of geopolymer brick manufacturing.

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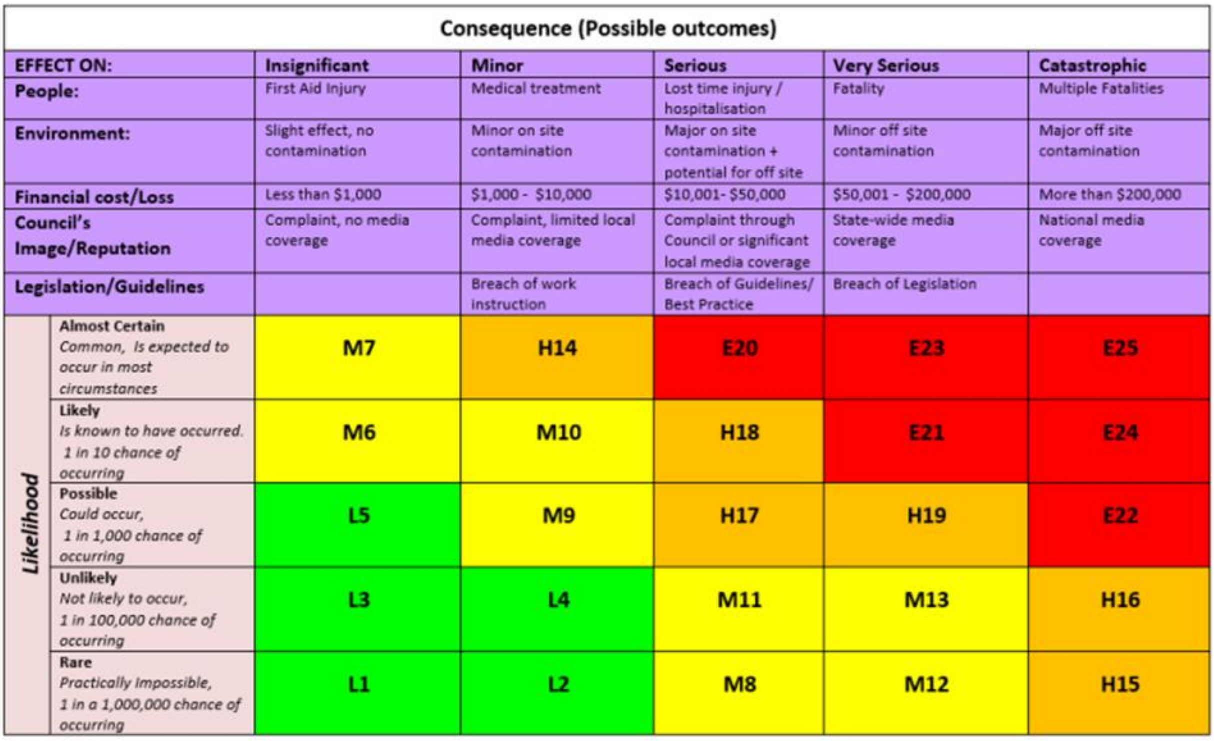
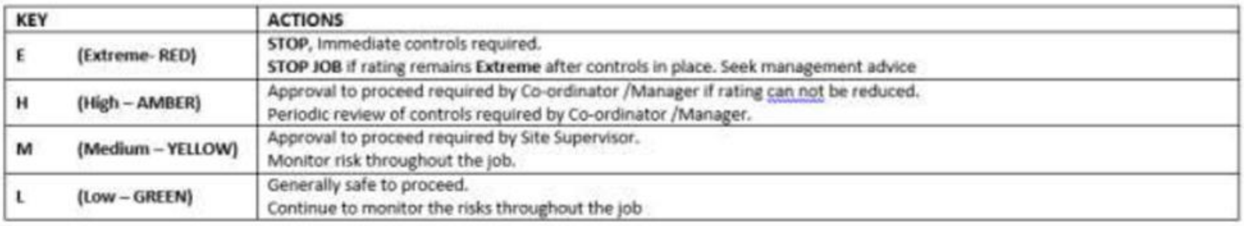
Appendix

Appendix A: Risk Assessment

The risk assessment in this project has been adapted from ESC's Risk Assessment Form, which is a widely used tool for evaluating risks (Eurobodalla Shire Council, 2014). This form considers various aspects such as risks to people, the environment, financial aspects, image/reputation, and adherence to legislation/guidelines. By utilizing this form, the assessment aims to identify potential hazards, assess the associated risks, and propose control measures to eliminate or mitigate the hazards. In the context of this project, the risk assessment will focus on evaluating risks related to personal safety and ensuring the timely completion of the project.



		Consequence (Possible outcomes)				
	EFFECT ON:	**Insignificant**	**Minor**	**Serious**	**Very Serious**	**Catastrophic**
	People:	First Aid Injury	Medical treatment	Lost time injury / hospitalisation	Fatality	Multiple Fatalities
	Environment:	Slight effect, no contamination	Minor on site contamination	Major on site contamination + potential for off site	Minor off site contamination	Major off site contamination
	Financial cost/Loss	Less than $1,000	$1,000 - $10,000	$10,001- $50,000	$50,001 - $200,000	More than $200,000
	Council's Image/Reputation	Complaint, no media coverage	Complaint, limited local media coverage	Complaint through Council or significant local media coverage	State-wide media coverage	National media coverage
	Legislation/Guidelines		Breach of work instruction	Breach of Guidelines/ Best Practice	Breach of Legislation	
Likelihood	**Almost Certain** *Common, Is expected to occur in most circumstances*	**M7**	**H14**	**E20**	**E23**	**E25**
	Likely *Is known to have occurred. 1 in 10 chance of occurring*	**M6**	**M10**	**H18**	**E21**	**E24**
	Possible *Could occur, 1 in 1,000 chance of occurring*	**L5**	**M9**	**H17**	**H19**	**E22**
	Unlikely *Not likely to occur, 1 in 100,000 chance of occurring*	**L3**	**L4**	**M11**	**M13**	**H16**
	Rare *Practically Impossible, 1 in a 1,000,000 chance of occurring*	**L1**	**L2**	**M8**	**M12**	**H15**



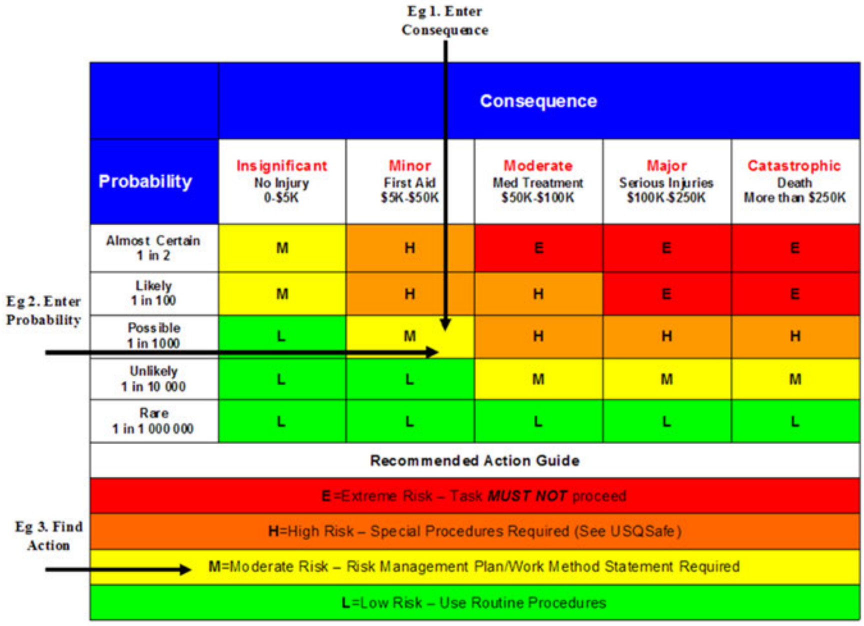
KEY		**ACTIONS**
E	**(Extreme- RED)**	**STOP**, Immediate controls required. **STOP JOB** if rating remains **Extreme** after controls in place. Seek management advice
H	**(High – AMBER)**	Approval to proceed required by Co-ordinator /Manager if rating can not be reduced. Periodic review of controls required by Co-ordinator /Manager.
M	**(Medium – YELLOW)**	Approval to proceed required by Site Supervisor. Monitor risk throughout the job.
L	**(Low – GREEN)**	Generally safe to proceed. Continue to monitor the risks throughout the job

Hierarchy of Controls

When putting controls in place for a hazard you **MUST** first attempt to eliminate the hazard. Where this is not possible then minimise the risk using the hierarchy of controls in the order listed.

Eliminate	Put a control in place that removes the hazard altogether
Substitute	Replace the hazard with something less hazardous
Isolate	Put a barrier between personnel and the hazard by space or time
Engineer	Manufacture a guard or use machinery
Administration	Signs, WMS's, Procedures, verbal or written direction, Training etc
PPE	Last line of defence – must be fit for purpose, serviceable and maintained

NOTE: More than one control may be needed to reduce a hazard to a reasonable level.



Probability	**Consequence** **Insignificant** No Injury 0-$5K	 **Minor** First Aid $5K-$50K	 **Moderate** Med Treatment $50K-$100K	 **Major** Serious Injuries $100K-$250K	 **Catastrophic** Death More than $250K
Almost Certain 1 in 2	M	H	E	E	E
Likely 1 in 100	M	H	H	E	E
Possible 1 in 1000	L	M	H	H	H
Unlikely 1 in 10 000	L	L	M	M	M
Rare 1 in 1 000 000	L	L	L	L	L

Recommended Action Guide

E =Extreme Risk – Task ***MUST NOT*** proceed

H=High Risk – Special Procedures Required (See USQSafe)

M=Moderate Risk – Risk Management Plan/Work Method Statement Required

L=Low Risk – Use Routine Procedures

Risk/Hazard Description	Risk Mitigation Measures	Probability Risk will occur	Consequence	Level of Risk
Inhaling potentially harmful dust particles of a dry mixture	Wearing a dust mask/appropriate PPE	Possible	Insignificant Injury	Low Risk
Acid chemicals irritating skin	Wearing gloves and other appropriate PPE	Possible	Insignificant Injury	Low Risk
Acid chemicals splashing when pouring into mixture irritating eyes	Wearing safety goggles and other appropriate	Possible	Minor Injury	Low Risk
Body/ clothing/ hair getting caught in a mixer	Keep hands away from the bowl of the mixer when operating. If have long hair, have it tied up.	Possible	Insignificant Injury	Low Risk
Hand getting caught in UTM	Stay behind machine protective guards when operating the machine, as marked generally on the floor of the lab.	Unlikely	Moderate Injury	Low Risk
Fragments of the specimen being flung whilst breaking under pressure using UTM	Stay behind machine protective guards when operating the machine, as marked generally on the floor of the lab.	Unlikely	Moderate Injury	Low Risk
Accidentally burning body parts when retrieving samples from oven	Use specified PPE, especially gloves suitable for high temperatures.	Possible	Minor Injury	Low Risk
Fragments of the specimen being flung whilst breaking under pressure from the Compressive Test.	Stay behind machine protective guards when operating the machine, as marked generally on the floor of the lab.	Unlikely	Moderate Injury	Low Risk

Appendix B: Results from Current Study

Compressive Strength Results:		
	% LSS by mass	Failure Load (kN)
50/50	5	44.17
	5	62.28
	5	63.48
	10	104.04
	10	146.73
	10	149.41
	15	176.85
	15	249.39
	15	253.91
	20	146.45
	20	206.51
	20	210.30
70/30	5	71.24
	5	100.53
	5	102.38
	10	86.67
	10	122.15
	10	124.37
	15	187.57
	15	264.45
	15	269.25
	20	158.74
	20	223.88
	20	227.95
90/10	5	122.06
	5	172.05
	5	175.19
	10	142.11
	10	200.42
	10	204.11
	15	201.99
	15	284.78
	15	289.95
	20	170.11
	20	239.87
	20	244.21

Indirect Tensile Strength (Brazilian Test) Results			
FLY ASH TO SAND RATIO	% LSS by mass	Fs (kN)	Fs (N)
50/50	5	19.48	19480.4
	5	27.65	27649.6
	5	27.96	27963.8
	10	47.76	47758.4
	10	67.24	67238.8
	10	68.50	68495.6
	15	72.27	72266.0
	15	101.80	101800.8
	15	103.69	103686.0
	20	64.73	64725.2
	20	91.12	91118.0
	20	93.00	93003.2
70/30	5	0.00	0.0
	5	38.65	38646.6
	5	17.60	17595.2
	10	36.76	36761.4
	10	51.84	51843.0
	10	52.79	52785.6
	15	88.92	88918.6
	15	125.37	125365.8
	15	127.88	127879.4
	20	68.18	68181.4
	20	95.83	95831.0
	20	97.72	97716.2
90/10	5	63.15	63154.2
	5	88.92	88918.6
	5	90.49	90489.6
	10	68.50	68495.6
	10	96.77	96773.6
	10	98.66	98658.8
	15	96.15	96145.2
	15	135.73	135734.4
	15	137.93	137933.8
	20	78.55	78550.0
	20	110.91	110912.6
	20	112.80	112797.8

Cold Water Absorption Results

FLY ASH TO SAND RATIO	% LSS	Dry Weight (g)	Wet Weight (g)	Cold Water Absorption %
50/50	5	1808	2138	18.23
50/50	10	1909	2282	19.53
50/50	15	2201	2663	21.02
50/50	20	2016	2362	17.14
70/30	5	1529	1907	24.73
70/30	10	1615	2000	23.89
70/30	15	1861	2181	17.18
70/30	20	1705	1965	15.27
90/10	5	1250	1601	28.04
90/10	10	1320	1642	24.37
90/10	15	1521	1743	14.58
90/10	20	1394	1563	12.16

Boiling Water Absorption Results

FLY ASH TO SAND RATIO	% LSS	Dry Weight (g)	Wet Weight (g)	Boiling Water Absorption %
50/50	5	1808	2138	17.69
50/50	10	1909	2282	17.47
50/50	15	2201	2663	15.93
50/50	20	2016	2362	12.34
70/30	5	1529	1907	26.88
70/30	10	1615	2000	23.54
70/30	15	1861	2181	13.34
70/30	20	1705	1965	11.73
90/10	5	1250	1601	29.22
90/10	10	1320	1642	26.18
90/10	15	1521	1743	21.62
90/10	20	1394	1563	20.32

Uniaxial Compressive Strength Test Results			Indirect Tensile Strength (Brazilian Test) Results		
FLY ASH TO SAND RATIO	% LSS by mass	σc (MPa)	FLY ASH TO SAND RATIO	% LSS by mass	fs (MPa)
50/50	5	4.78	50/50	5	0.62
	5	6.74		5	0.88
	5	6.87		5	0.89
	10	11.26		10	1.52
	10	15.88		10	2.14
	10	16.17		10	2.18
	15	19.14		15	2.30
	15	26.99		15	3.24
	15	27.48		15	3.30
	20	15.85		20	2.06
	20	22.35		20	2.90
	20	22.76		20	2.96
70/30	5	7.71	70/30	5	0.00
	5	10.88		5	1.23
	5	11.08		5	0.56
	10	9.38		10	1.17
	10	13.22		10	1.65
	10	13.46		10	1.68
	15	20.30		15	2.83
	15	28.62		15	3.99
	15	29.14		15	4.07
	20	17.18		20	2.17
	20	24.23		20	3.05
	20	24.67		20	3.11
90/10	5	13.21	90/10	5	2.01
	5	18.62		5	2.83
	5	18.96		5	2.88
	10	15.38		10	2.18
	10	21.69		10	3.08
	10	22.09		10	3.14
	15	21.86		15	3.06
	15	30.82		15	4.32
	15	31.38		15	4.39
	20	18.41		20	2.50

	20	25.96		20	3.53
	20	26.43		20	3.59

WATER ABSORPTION RESULTS			
FLY ASH TO SAND RATIO	% LSS by mass	COLD WATER ABSORPTION %	BOILING WATER ABSORPTION %
50/50	5	18.23	17.69
	10	19.53	17.47
	15	21.02	15.93
	20	17.14	12.34
70/30	5	24.73	26.88
	10	23.89	23.54
	15	17.18	13.34
	20	15.27	11.73
90/10	5	28.04	29.22
	10	24.37	26.18
	15	14.58	21.62
	20	12.16	20.32