



Waka Kotahi Hoe ki angitū - Innovation Fund

A Sustainable Method for Stabilisation of Pumice Soil in Road Construction using Waste Glass in an Alkali Activation Process

Auckland University of Technology

Roohollah Kalatehjari

PhD, MEngNZ, MNZGS, FHEA

Senior Lecturer in Geotechnical Engineering

Built Environment Engineering Department, School of Future Environments,
Auckland University of Technology, Auckland, New Zealand

Afshin Asadi

PhD, CMEngNZ, CPEng, FICE

Technical Advisor, EnvoGeotechnique Ltd, Auckland, New Zealand

Geotechnical Team Lead, Wilton Joubert Consulting Engineers, Auckland, New Zealand

Project Completion Date: 30 June 2023

Executive Summary: A Sustainable Method for Stabilisation of Pumice Soil in Road Construction using Waste Glass in an Alkali Activation Process

Introduction

In 2022 the research project was awarded \$80,420 by the Waka Kotahi NZ Transport Agency Hoe ki angitū Innovation Fund to investigate the use of waste glass in the alkali-activation process for stabilising pumice soils. The aim of this innovation research project was to deliver valuable insights and outcomes for sustainable soil stabilisation by utilising alkali-activated reclaimed glass as a soil stabiliser in road construction. The project focused on comparing the environmental impact of soil stabilisation using alkali-activation technology with waste/reclaimed glass against current soil stabilisation methods using cement and lime.

Objectives of the project

The primary objectives of the project were as follows:

- Examining the efficacy and performance of the alkali-activation process as a sustainable binder for stabilisation of pumice soils.
- Studying the underlying mechanisms of the stabilised soil using microstructural analysis.
- Conducting an experimental investigation on the strength characteristics of the stabilised soil.
- Conducting a life cycle assessment to compare the developed binder with the traditional stabilisers.

Key findings

This research explored the innovative use of alkali-activated waste/reclaimed glass for stabilising pumice soils. The findings, derived from systematic testing conducted to understand the microstructural, compositional, and mechanical aspects of pumice sand, reclaimed glass powder, alkali-activated binder, and stabilised soil, are summarised below:

- X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) Analysis: XRD testing revealed that pumice sand consists of glassy and crystalline structures, including Albite, Quartz, and Tridymite. In contrast, the reclaimed glass powder displayed an amorphous structure. The chemical composition of the pumice, as deduced from XRF analysis, indicated high levels of Si and the presence of Al. This finding is consistent with the pumice's dominant composition of Albite, Quartz, and Tridymite. Meanwhile, the crushed glass powder mainly comprises silicon dioxide. Notably, sodium oxide and calcium oxide are also present, pointing toward the makeup of soda-lime glass, which suggests its potential for alkali activation.
- Scanning Electron Microscope (SEM) and Energy Dispersive X-Ray Analysis (EDX): The SEM images highlighted pumice's inherent porous nature – a defining characteristic of the material. The EDX tests confirmed the predominant presence of silicon (Si) and oxygen (O) in pumice. In contrast, the crushed glass powder showed a blend of elements, with the dominant ones being oxygen (O), silicon (Si), and sodium (Na). Importantly, the presence of sodium (Na), potassium (K), and calcium (Ca) in the glass powder underscores its importance in the alkali-activation process.
- Compaction and Sieve Analysis: The compaction test results, using a standard proctor test device,

depicted a double-peaked compaction curve for both soils. Notably, the maximum dry unit weights were 8.3 kN/m³ for fine pumice sand and 7.2 kN/m³ for coarse pumice sand. Post-compaction sieve analysis shed light on the higher crushability effect on fine pumice sand compared to its coarser counterpart. Interestingly, the crushability rate did not correlate with the pumice sands' compaction moisture content, providing valuable insights into pumice sand's behaviour and potential applications in pavement design and soil stabilisation.

- **Particle Size Distribution and Alkali-Activation:** The need to adjust the reclaimed crushed glass powder's particle size and specific surface area was emphasised to serve effectively in the alkali-activation process. Through grinding experiments, the research aimed to produce glass particles similar in size to clay particles. These tests concluded that the ideal grinding specification involves a half-loaded jar with 16 steel grinding balls, each 15mm in diameter, operating for 20 minutes at 600 rpm. For the alkali activation to take place effectively, an activator is required, and based on the literature review, Potassium Hydroxide (KOH) with a molarity of 10 was chosen. This activator, combined with the ground glass powder, resulted in varying strength levels depending on the activator/precursor ratio.
- **Mortar Mix Design and EDX Test:** The mortar mix designs, especially those with an activator/precursor ratio greater than 0.3, showed impressive strengths exceeding 35 MPa. SEM images for these mixes depicted the presence of glass binder gels, while those with lower activator/precursor ratios showcased incomplete alkali activation due to an insufficient activator. The EDX test further emphasised the differences between samples with varying activator/precursor ratios in terms of the alkali activation process completion.
- **Particle Size, Soil Stabilization, and Strength Testing:** Experiments were conducted to determine the influence of particle size distribution of the glass precursor on the mortar's unconfined compressive strength. As particle size increased, a reduction in strength was observed. Further testing with pumice soil stabilisation highlighted the necessity of having a minimum precursor/aggregate ratio of 0.4 for proper cohesion. Additionally, the California Bearing Ratio (CBR) test emphasised the effect of compaction on soil strength and the significant role fine particles play in bolstering this strength. The CBR test results further demonstrated superior strength gain in samples stabilised using the proposed alkali-activation process, providing evidence of the effectiveness of this innovation for stabilising pumice sand in road subgrades.
- **Life Cycle Assessment (LCA):** Using the Waka Kotahi LCAP tool, a comparative life cycle assessment was undertaken. The assessment highlighted that the proposed soil stabilisation approach using reclaimed glass results in 21% and 15% lower carbon dioxide emissions than cement and lime. This finding paves the way for more environmentally friendly construction methods, although it is recognised that further research is needed for a comprehensive comparison in real-world settings.
- **Future Potential and Research Expansion:** This investigation unveiled a promising avenue for further research. The findings demonstrated potentials for scaling up to pilot field tests and other related opportunities. Such expansion would not only validate the preliminary results at a larger scale but would also provide comprehensive data beneficial to various construction sectors. This also opens up opportunities for further research initiatives in this field.

Environmental Impact:

The LCA study revealed that alkali-activated reclaimed glass soil stabilisation exhibited lower carbon dioxide emissions than cement and lime. Specifically, the carbon dioxide emissions of soil stabilisation using cement and lime were 21% and 15% higher than the proposed approach with reclaimed glass. The environmental benefits of alkali-activation technology stemmed from the reduced carbon footprint

of reclaimed glass compared to traditional cement production as well as utilising waste glass, which would otherwise be sent to landfills. It is important to note that the production of other alkali activators and techniques should also be considered to investigate their potential environmental benefits by contributing to the reduction of energy consumption and associated emissions.

Feasibility and Limitations:

The research highlighted the feasibility of utilising reclaimed glass as a cement substitute and soil stabiliser. However, limitations were acknowledged, including variations in materials and methods across studies and potential differences in environmental impacts at different scales of production. One primary challenge was the scarcity of comprehensive data regarding the environmental impact of diverse stabilisers, compounded by a lack of standardisation and varying reporting methodologies. From a regulatory perspective, the existing frameworks did not specifically include using alkali-activated materials as soil stabiliser. This regulatory void introduced complications, posing challenges to assessing the viability of our innovative technique. In addition, our laboratory tests, though rigorous, were limited by sample size. A larger sample size might have yielded more statistically substantial data to provide confidence for a comparable real-world application. The study emphasised the importance of addressing these limitations and conducting field tests and pilot projects to validate the laboratory findings under real-world conditions.

Recommendations:

Informed by our findings, we outline the following recommendations and potential directions for further research. We are emphasising the need for extended research timelines, broader environmental evaluations, and explorations into the real-world implications of our findings. A keen interest is in field testing and pilot projects to assess the real-world performance of the alkali-activated reclaimed glass. Collaboration is pivotal. We aim to join forces with industry stakeholders, regulatory bodies, and academic institutions, ensuring knowledge transfer and promoting the adoption of alkali-activated materials. Future studies and actions could include:

- Conducting field testing and validation to assess the performance of alkali-activated reclaimed glass in actual road construction scenarios.
- Expanding the scope of the life cycle assessment study to include a broader range of environmental impacts and indicators, such as water consumption and resource depletion.
- Performing sensitivity analysis to identify critical parameters and assumptions influencing the results and their variability.
- Exploring technological improvements in producing and applying alkali-activated materials to reduce environmental impacts further.

Implementing these recommendations can achieve a more comprehensive and reliable assessment of the environmental benefits of alkali-activated reclaimed glass in soil stabilisation. This approach will also facilitate informed decision-making processes and promote the adoption of sustainable practices in the construction industry. The researchers acknowledge the need for future studies and actions to enhance the understanding and adoption of sustainable practices in the construction industry. While this project contributed valuable insights into the potential environmental benefits of alkali-activated reclaimed glass, we emphasise the need for further research and field testing to validate our laboratory findings.

Final Project Report: AUT – Soil Stabilisation with Glass Waste

Table of Contents

Introduction.....	2
Objectives of the project	2
Key findings.....	2
Environmental Impact:	3
Feasibility and Limitations:.....	4
Recommendations:	4
Table of Contents	5
1. A Sustainable Method for Stabilisation of Pumice Soil in Road Construction using Waste Glass in an Alkali Activation Process	6
1.1 Introduction.....	6
1.2 Objectives of the Project	8
1.3 Materials and Methods.....	8
1.3.1 Pumice Soil	8
1.3.2 Waste/Reclaimed Glass	10
1.3.3 Potassium Hydroxide.....	11
1.3.4 Test Plan and Analysis	11
1.4 Physical, Chemical, and Microstructural Analysis of the Materials.....	11
1.4.1 Particle Size Distribution and Soil Classification	11
1.4.2 Specific Surface Area and Volumetric Particle Size Analysis	14
1.4.3 Physical and Chemical Analysis.....	16
1.4.4 Microstructural and Elemental Analysis.....	19
1.5 Strength Characteristics and Performance of the Proposed Alkali-activated Binder in Stabilising Pumice Soil.....	24
1.5.1 Compaction Properties and Crushability of Pumice Sand.....	24
1.5.2 Design and Characterisation of Materials for Alkaline Activation Process.....	25
1.5.3 Design and Performance Analysis of the Alkali Activated Mortar	27
1.5.4 Strength Characteristics of the Stabilised Soil Using UCS Test	35
1.5.5 Strength Characteristics of the Stabilised Soil Using CBR Test	38
1.6 Life Cycle Assessment for Stabilisation of Pumice Soil Using the Proposed Alkali-Activated Binder Compared with Cement and Lime.....	41
2. What were some of the challenges you faced (e.g., regulatory barriers, access to data)?.....	46
3. What was the approach you took, and did you achieve your deliverables and milestones?.....	46
4. What worked well?.....	46
5. What didn't work well?.....	47
6. What would you do differently next time (e.g., how you allocated resources and funding)?.....	47
7. Has our support led to further opportunities (e.g., further funding, partnerships with other organisations)?.....	47
8. How will you accelerate your innovation from here (next steps)?	48
9. Highlights	48
10. Appendix	49
11. Reference List	49

1. A Sustainable Method for Stabilisation of Pumice Soil in Road Construction using Waste Glass in an Alkali Activation Process

1.1 Introduction

This report presents the process and findings of a novel alkali-activation method that utilises reclaimed glass to stabilise pumice soil in road subgrades. The primary objective of this innovation is to introduce a process that incorporates reclaimed glass into stabilising pumice soil, thereby reducing the overall carbon footprint of the road construction process. The test plan employed in this study follows the guidelines outlined in the NZTA Bog documents (NZTA, 2020a, 2020b), which provide a pilot specification for in-situ subgrade stabilisation. In addition, the design of the test plan incorporates supplementary resources, including the Australian Road Research Board's publications on best practice advice for the use of recycled materials in road and rail infrastructure (Hall, Grenfell, Pandelidi, Yaghoubi, Chaudry, et al., 2022; Hall, Grenfell, Pandelidi, Yaghoubi, Lyons, et al., 2022). By integrating these additional sources, the test plan and strategy are enriched, enhancing the overall comprehensiveness and effectiveness of the study.

This innovation aimed to utilise local glass waste in an environmentally friendly, sustainable method for stabilising pumice soil in road construction. The pumice soil used in this project is stabilised with an innovative method that uses glass waste in an alkali-activation process. This process is introduced as an alternative soil stabilisation technique to reduce the use of Portland Cement due to its environmental concerns and associated high CO₂ emissions. Despite recycling efforts, a considerable portion of glass waste is sent to landfills. Reusing this waste in the construction industry offers an efficient and beneficial solution. Alkali-activation process has been used to produce inorganic cement for over a century to valorise wastes derived from different human activities. This process is well-hypothesised in literature, where aluminosilicate sources from silica-rich materials are transformed under alkali conditions into highly reactive materials to form a well-structured aluminosilicate polymerised framework.

A review of the literature shows that alkali-activated materials show better performance in comparison to Portland cement in terms of durability in corrosive environments, much lower energy consumption in the production process, lower CO₂ emissions, and the utilisation of industrial waste (Alqaisi, Le, & Khabbaz, 2020; Habert, De Lacaillerie, & Roussel, 2011; Provis, Palomo, & Shi, 2015; Shi, Krivenko, & Roy, 2006; Teh, Wiedmann, Castel, & de Burgh, 2017). In response to the Climate Change Response (Zero-Carbon) Amendment Act 2019 and considerations concerning kaitiakitanga (guardianship), this innovation introduces an alternative binder in road construction to conventional soil stabilisers such as cement and lime. In addition, it provides an opportunity to accelerate the use of reclaimed glass.

Waste composition data of Class 1 landfills shows a 1.8% contribution from glass waste, equal to 65,150 tonnes in 2021 alone (Environment, 2022). Waste glass cullet can be used to produce new glass; however, the colour, composition, and contamination of wastes reduce the reused amount. The glass recycling process also has a waste stream as a fine powder collected by dust extraction units (Vinai & Soutsos, 2019). These glass wastes have been identified as a potential silicate source, comprising 70–75% of amorphous silica. Due to its chemistry and availability, waste glass is an excellent candidate to be used as a precursor in the proposed innovative method. Reusing waste glass as aggregate, precursors, and activators in preparing alkali-activated binders seems a viable path to efficiently utilising this solid waste and reducing the cost of the binder (Liu, Shi, Zhang, & Li, 2019).

Cement and concrete are essential parts of modern civilisation, with an annual production of over 10 billion tonnes worldwide (Aitcin, 2000). Concrete is the second most used material after water and is counted as the most used artificial material (Rodgers, 2018). Given the increase in traffic loads and the

deterioration of roads, the use of binders such as cement is inevitable as an additive for stabilising soft soils in road construction. These materials result from years of academic and industrial research to be durable against chemicals and maintain perfect quality under thermal and mechanical loads. Cement, as the vital component of concrete, has a massive carbon footprint, contributing to about 7% to 8% of global CO₂ emissions (Andrew, 2018; Olivier, Peters, & Janssens-Maenhout, 2012; Scrivener & Kirkpatrick, 2008; Provis & Van Deventer, 2013). The considerable amount of CO₂ emissions is due to the thermal decomposition of calcium carbonate to generate the primary form of Portland Cement (PC).

While cement makes up only a small percentage of the mix (around 5% by volume), it is almost exclusively responsible for the resulting CO₂ emissions. Cement is a significant contributor to global CO₂ emissions mainly because its production requires the high-temperature decomposition of limestone (calcium carbonate) to generate reactive calcium silicate and aluminate phases. Optimistic analyses show that CO₂ emissions from cement production could be reduced by 75% by 2050. However, only a small portion (around 20%) will come from operational advances (including using alternative fuels, optimised use of cement in concrete, recycling, and blending with pozzolans). At the same time, the remainder will need to come from technological innovation and new growth horizons (Provis & Van Deventer, 2013). Therefore, more innovative approaches, such as new technologies and alternative materials, will be necessary to achieve carbon-reduction targets by 2050 (McKinsey, 2022).

Given the performance characteristics and the broad availability of cement, it will likely remain the material of choice for global construction. However, it could lose share to more sustainable alternative materials at a local level. One of the advantages of alkali-activated materials over traditional Portland cement is the much lower CO₂ emission associated with their production. Alkali-activated materials are among several alternative binders discussed to obtain environmental benefits for the construction industry. Discussions around the life-cycle analysis of alkali-activated binders have provided results that vary between mix designs and binder types. The estimated CO₂ savings (comparing alkali-activated materials to Portland cement) quoted in the literature from life-cycle studies range from 30% to 80% (Provis & Van Deventer, 2013).

Alkali-activated binders rely on the reaction of an aluminosilicate solid powder (precursor) with a concentrated aqueous alkali hydroxide (activator). There is extensive literature on potential activators. Among all the available options for activators (hydroxides, silicates, sulphates, carbonates, acidic solutions), the use of an alkali hydroxide (either sodium or potassium) combined with an alkali silicate (again either sodium or potassium) is favoured as it has been shown to give high compressive strengths when used with solid powder precursors, such as glass waste (Vinai & Soutsos, 2019).

Recent developments in ground improvement have highlighted the need for using pozzolans for partial or full replacement of Portland cement (Attom, Taqieddin, & Mubeideen, 2000; Aydilek & Arora, 2004; Pourakbar, Asadi, Huat, & Fasihnikoutalab, 2015). Both natural and artificial pozzolanic materials show pozzolanic activity and are used as supplementary cementitious materials. Artificial pozzolans can be produced deliberately, for instance, by thermal activation of kaolin clays to obtain metakaolin, or can be sourced from waste or by-products of high-temperature industrial processes, such as fly ash from coal-fired electricity production. Today, the most commonly used pozzolans come from industrial by-products. These include fly ash, silica fume produced during silicon smelting, and highly reactive metakaolin. In the innovative method presented, waste glass is repurposed as a substitute for these traditionally used pozzolans.

This innovation holds significance in multiple aspects, including sustainability, infrastructure development, waste management, and soil stabilisation. In an era of growing environmental concerns, sustainability in every field is necessary, and the construction industry is no exception. Alkali-activated binders could be employed as a substitution for cement as an additive to stabilise the soil, especially in road construction. The reduction of using raw materials for Portland cement, considering the Climate

Change Response Amendment Act 2019, through the reuse of waste glass and soil stabilisation in road construction projects, are some of the advantages of this technology. In addition, waste management is a significant concern today. Despite recycling efforts, a considerable portion of glass waste remains in landfills. Reusing this waste in the construction industry offers an efficient and beneficial solution. Although there is ongoing research on alkali-activated materials, and some are focused on waste glass, the intersection of this technology for road construction, especially on stabilising pumice soil, has not been studied before. This report presents the findings of state-of-the-art research conducted to explore this connection.

1.2 Objectives of the Project

The main objectives of this project include the following:

- Examining the efficacy and performance of the alkali-activation process as a sustainable binder for stabilisation of pumice soils.
- Studying the underlying mechanisms of the stabilisation of soil using microstructural analysis.
- Conducting an experimental investigation on the strength characteristics of the stabilised soil.
- Conducting a life cycle assessment to compare the developed binder with the traditional stabilisers.

1.3 Materials and Methods

In road construction, the subgrade layer is the foundation for the pavement. Ensuring that the subgrade has adequate bearing capacity to support the pavement and the traffic load is essential. In some areas with soft or loose soils, such as expansive clays or silty or sandy soils, soil stabilisation may be required for all road construction projects. However, soil stabilisation may be used less frequently in regions with more stable soils. Pumiceous soils can be found in a large area of New Zealand, especially North Island along the lower Waikato River valley and in parts of the Bay of Plenty (L Wesley, 2003). These soils usually show a low strength and are prone to erosion when in a loose state. When facing these soils, stabilising the subgrade is crucial to improving their bearing capacity. If properly stabilised, these soils can improve the bearing capacity of the pavement and reduce the potential for pavement failure (Mesfun, Quezon, & Geremew, 2019). Waka Kotahi provides guidelines for stabilising subgrade soil in road construction projects in New Zealand. These guidelines provide best practices for selecting stabilising materials, testing procedures, and construction methods. The guidelines also provide recommendations for the pavement structure design based on the stabilised subgrade (Gray, 2017). Based on the scope of this project, three essential materials, including pumice soil, reclaimed glass (crushed glass powder), and potassium hydroxide, were sourced from local suppliers, which are introduced in the following subsections.

1.3.1 Pumice Soil

The soil to be stabilised in this project is pumice sand sourced from Daltons[®], a local manufacturer and supplier of landscape products. The selected pumice sand, a by-product of their sand processing operation in Matamata, undergoes washing, screening, and grading to ensure its quality. Therefore, this pumice sand was selected for its consistency, ensuring repeatability in our testing process.

Pumice is a light and porous volcanic rock commonly found in New Zealand. Pumice soils, covering approximately 16% of North Island, are primarily composed of loose rhyolitic pumice, rich in silica, deposited by the Taupo eruption (AD 232 ± 10) and the Kaharoa eruption (AD 1314 ± 12) from Mt Tarawera. Additional areas of Pumice soils originate from 3500-year-old Waimihia pumice deposits and fluviially reworked pumice along rivers. Figure 1 illustrates the distribution of pumice soils in the central North Island of New Zealand, as Selby & Hosking (1973) identified. These soils consist of sandy

to gravelly pumice materials, exhibiting weak weathering with low clay content (Hewitt et al., 2021). Pumice soils are widely used for improving soil drainage and aeration and as lightweight concrete aggregate (Wilson, 1949).

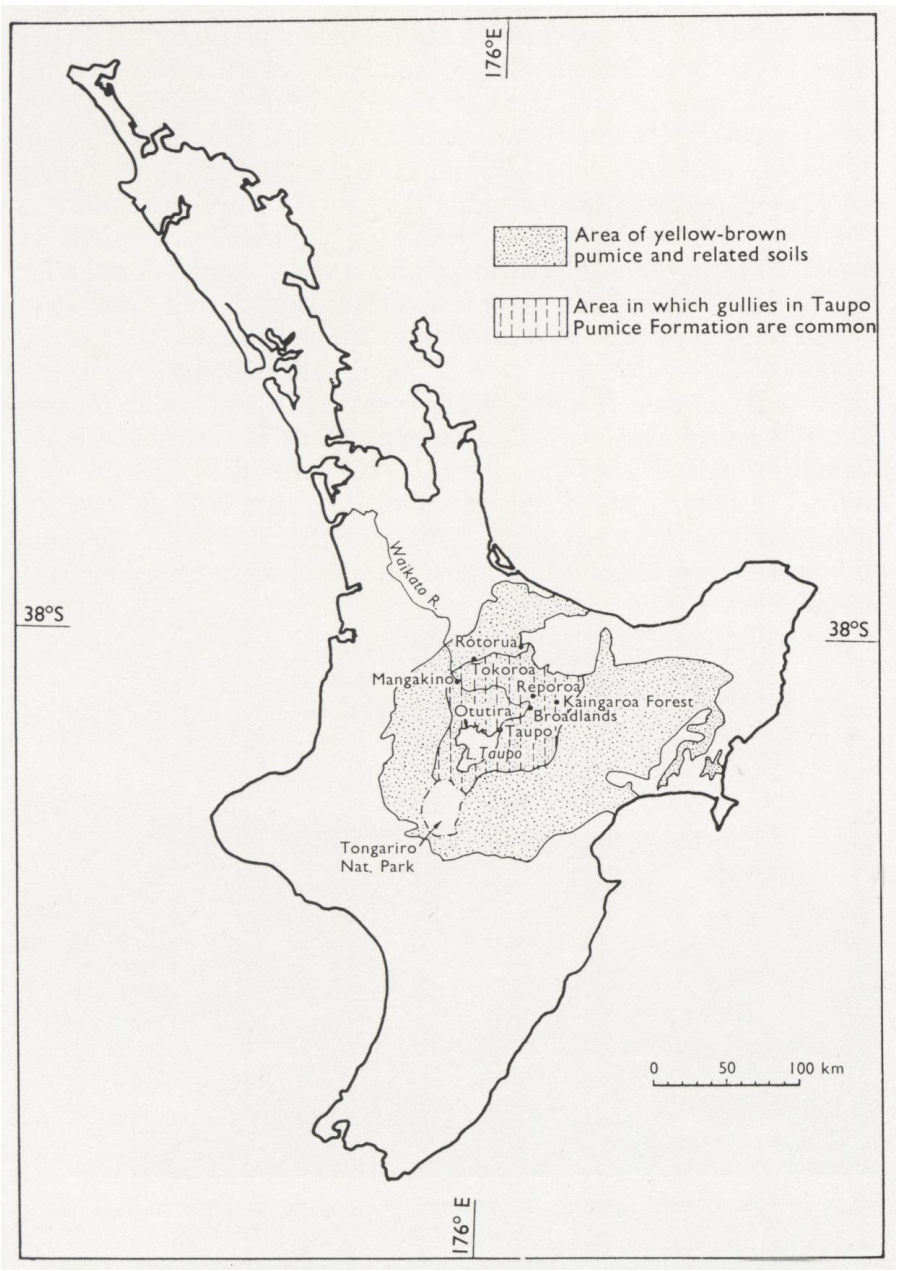


Figure 1. Common areas with pumice soils in the central North Island, New Zealand (Selby & Hosking, 1973).

One of the primary issues related to pumice soils is their low strength, which means they may be unable to support heavy loads, leading to excessive settlement and pavement damage. The crushing strength of pumice particles is found to increase as particle size decreases. Still, the crushing strength of pumice as soil is significantly lower than that of hard-grained soils, indicating its high crushability (Orense, Pender, Hyodo, & Nakata, 2013). Another issue with pumice soil is its susceptibility to erosion, which can lead to the loss of soil particles and reduce the stability of the pavement. These soils are susceptible to erosion by water, and if not protected, heavy rainstorms can result in severe erosion (Hewitt et al., 2021).

1.3.2 Waste/Reclaimed Glass

The proposed stabilisation process uses waste/reclaimed glass sourced from a local supplier as the main stabilising material. Using reclaimed glass in construction projects is beneficial as it helps reduce waste and conserve natural resources. The application of reclaimed glass in road layers is a relatively new concept gaining attention as a sustainable alternative to traditional stabilisation materials. Glass can be recycled and reused as a construction material, making it a viable option for stabilising road subgrades. Reclaimed crushed glass application in asphalt dates to the 1970s, and commercial products with up to 30% recycled crushed glass are already available on the market in several countries (Alqaisi et al., 2020).

Some studies have been conducted to investigate the effectiveness of using waste or reclaimed glass in stabilising the subgrade of roads. In the Australian Road Research Board's Best Practice Advice on Recycled Material Use in Road and Rail Infrastructure (Hall, Grenfell, Pandelidi, Yaghoubi, Chaudry, et al., 2022), reclaimed crushed glass is introduced as a favourable material to be employed in the construction of embankments, structural and non-structural fill, retaining wall backfill and drainage, with several specifications in place to support its use. Using glass in road pavements and as a replacement for virgin sand in some rail applications is also introduced as an emerging opportunity. While the application of recycled crushed glass might be helpful in asphalt, crushed rock supplement, sand replacement, footpaths, kerbs, drainage, and fences, they only rely on the mechanical properties of glass grains and do not take advantage of their valuable chemical potential.

In the proposed soil stabilisation process, glass has the potential to replace traditional stabilisation materials such as lime, cement, or fly ash. Conventionally, glass is crushed into small particles and mixed with the soil to improve its strength, stiffness, and durability. The glass particles fill the voids in the soil, resulting in a denser and more stable subgrade. Reclaimed crushed glass, generally processed to pass the 4.75 mm sieve, is a product of manufacturing and consumer mixed glass waste. It is sourced mainly from food and beverage glass containers and may be colourless or coloured, with different particle sizes depending on the method of production and chemical composition (Perera et al., 2021).

If used in sand size and solely for its superior mechanical characteristics, the glass would not create any primary concerns related to its chemical composition. However, once the focus shifts to chemical reactivity, understanding the chemical composition of the reclaimed glass plays a significant role in designing a successful stabilisation process. Different types of glass commonly found in the consumer market have varying chemical compositions. Reclaimed glass may be sourced from crystal and lead crystal, electric, soda-lime, and borosilicate glass, all of which have different processing requirements for recycling (Mohajerani et al., 2017). Glass waste may also be derived from construction and demolition activities. Types of glass originating from that stream include float glass, shatterproof glass, laminated glass, extra clean glass, chromatic glass, tinted glass, glass blocks, glass wool, insulated glazed glass, and toughened glass (Ulugöl et al., 2021). These types have different characteristics that may complicate their application in the stabilisation process. It is also essential to be mindful of the contamination level of recycled glass if it is used in a chemical process (Robayo-Salazar, Rivera, & de Gutiérrez, 2017). Therefore, finding a reliable source of reclaimed glass to ensure consistency of the chemical composition is a vital part of this research.

Following a local search for a supplier of reclaimed glass for this project, Commodities NZ Ltd was selected due to their reliability in providing crushed glass media. The reclaimed glass is available in different particle sizes, with the powder form (<0.2mm) as its finest. This material is classified as non-hazardous under ordinary conditions. It doesn't need respiratory protection, but hand protection, such as canvas or rubber gloves, needs to be used. Safety glasses with a side shield are also required as personal protective equipment when working with this material.

1.3.3 Potassium Hydroxide

Potassium hydroxide (KOH) is a strong alkaline compound commonly known as caustic potash. Its chemical formula is KOH, which indicates one potassium ion (K⁺) and one hydroxide ion (OH⁻) held together by an ionic bond. KOH is a white crystalline solid at room temperature and highly soluble in water, making it a potent base. It is commonly used to produce soaps, detergents, and fertilisers. It can also be used as a catalyst in organic synthesis and as an electrolyte in alkaline batteries. Due to its corrosive nature, KOH should be handled with caution and appropriate protective equipment. LabServ Pronalys™ Potassium Hydroxide Pellets were selected for this project. The required concentration of the KOH solution to be used in alkali-activation process samples was selected based on the findings of previous studies (Bondar, Lynsdale, Milestone, Hassani, & Ramezaniapour, 2011; Cristelo, Glendinning, Miranda, Oliveira, & Silva, 2012; Cristelo, Glendinning, & Teixeira Pinto, 2011; Fasihnikoutalab, Pourakbar, Ball, & Huat, 2017).

1.3.4 Test Plan and Analysis

The proposed soil stabilisation process underwent a comprehensive testing plan to evaluate its performance and determine its advantages and limitations. The test plan was designed based on the recommendation made in NZTA Report 622 (Gray, 2017). It included material characterisation through soil classification tests, soil index tests, chemical characterisation tests, and microstructural characterisation tests. It also involves the Unconfined Compressive Strength (UCS) and the California Bearing Ration (CBR) tests to determine the strength characteristics of the binder and stabilised soil. Table 1 lists the standard test methods to complete the discussed plan.

Table 1. Standard test methods for completion of the test plan.

Test Name	Standard Test Method
Particle Size Distribution	NZS4402 Test 2.8.1
Hydrometer Analysis	NZS4402 Test 2.8.4
Atterberg Limits	NZS4402 Test 2.2, 2.3, 2.4
Specific Gravity (Solid Density)	NZS4402 Test 2.7.2
Moisture Content	NZS4402 Test 2.1
Standard Compaction	NZS4402 Test 4.1.1
Heavy Compaction	NZS4402 Test 4.1.2
Unconfined Compressive Strength	NZS4402 Test 6.3.1
California Bearing Ratio	NZS4402 Test 6.1.1

The NZTA recommended life cycle assessment of pavements (LCAP) tool was selected to help analyse the whole-of-life carbon impacts of the proposed subgrade stabilisation design, including reclaimed glass. LCAP is a tool that provides a detailed analysis of the environmental impacts of a pavement system, including its carbon footprint (Vickers, Riordan, & Kershaw, 2022). By utilising this tool, an informed decision can be made about the capability of the proposed method in minimising the environmental impact of road construction.

The following sections include the results of the tests and the analysis of the environmental impact of the proposed soil stabilisation process.

1.4 Physical, Chemical, and Microstructural Analysis of the Materials

1.4.1 Particle Size Distribution and Soil Classification

The pumice soils used in this project were of-the-shelf 15L-bag products sourced from Daltons®. Two

types of pumice sands were initially selected and analysed in this project based on their particle sizes. The coarse pumice sand has a maximum particle size of 7mm, and the fine pumice sand particle size is limited to 3mm. The natural moisture contents (NZS4402 Test 2.1) of both types of sand have been determined in a range between 40% and 45%. Soil characteristic tests on both types of sand were conducted by the mechanical analysis of soil, including the sieve analysis (NZS4402 Test 2.8.1) and the hydrometer analysis (NZS4402 Test 2.8.4) tests.

The sieve analysis test results for the coarse and fine pumice sands are shown as particle size distribution curves in Figures 2 and 3, respectively. These results confirm the supplier’s claimed particle sizes in both types of sand and the consistency of the particle size distributions of these products. The consistency of particle size distribution is important because any sample size (500g and above) taken from any bag could confidently be used in the tests as a true representative of the soil. Figures 2 and 2 show the particle size distribution curves of the coarse and fine pumice sands, respectively.

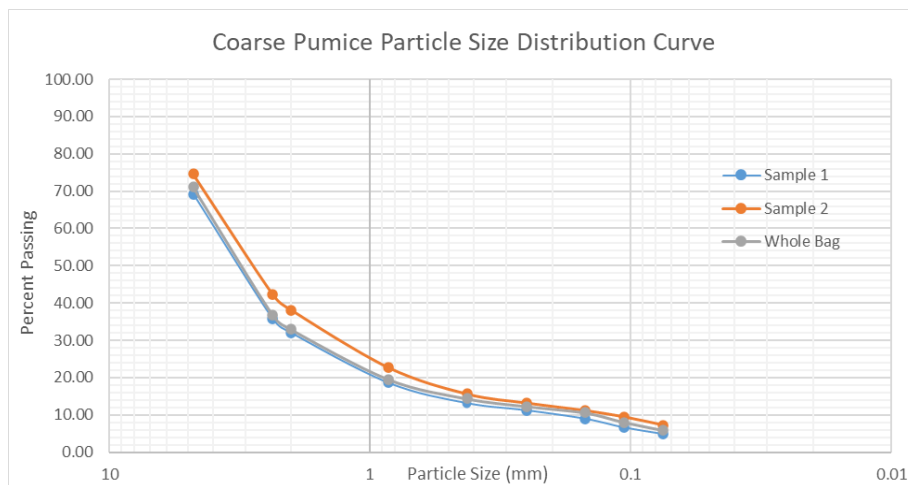


Figure 2. Particle size distribution curve of the coarse pumice sand.

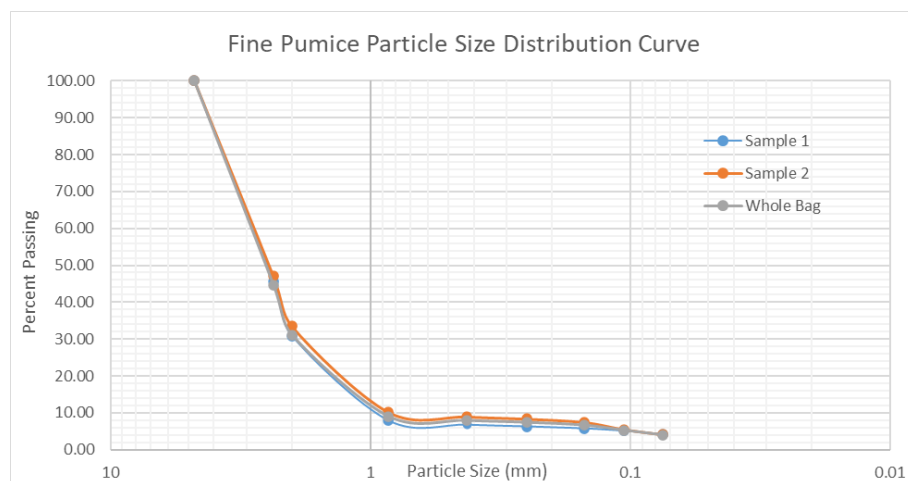


Figure 3. Particle size distribution curve of the fine pumice sand.

Since further analysis of soil particle sizes smaller than sieve no. 200 (with an opening of 0.075mm) is not practical through the sieve analysis, the hydrometer analysis was used to identify the separation between the fine particles of the sands. Figure 4 shows the results of hydrometer tests conducted on coarse and fine pumice sand passing through sieve no.200. As evident in these figures, the fine portion of both sands is almost identical in particle size distribution. The results for both soils indicate that most of the fine particles are in the range of silt, with approximately only 10% of the fines identified as clay size. Note that the separation of the soil particles in the range of silt and clay has been done based

on the Unified Soil Classification System (USCS) definitions. Based on this classification, both types of sand are classified as SP (poorly graded sand).

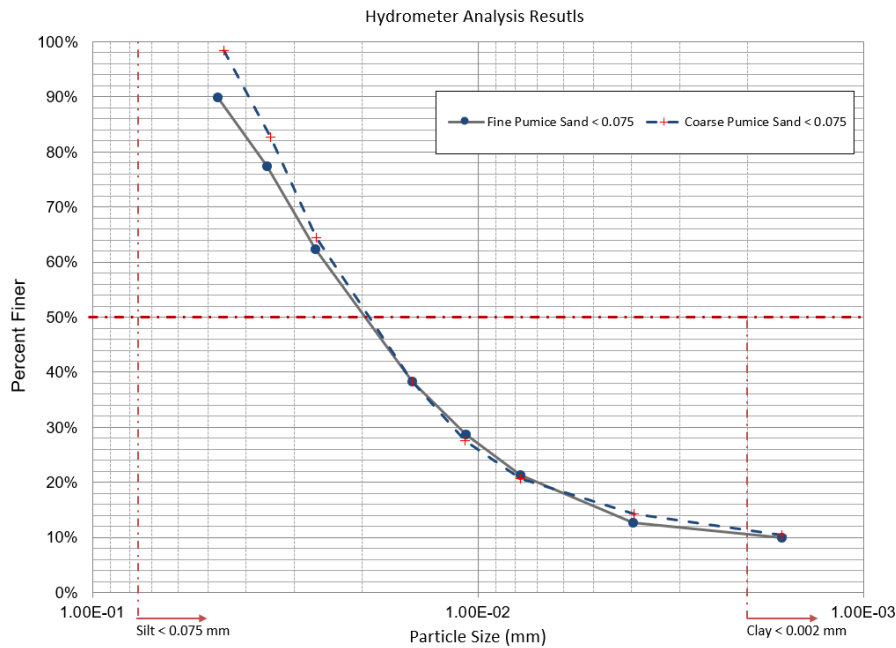


Figure 4. Hydrometer analysis results for the fine portion of the coarse and fine pumice sands.

Reclaimed crushed glass powder was sourced from Commodities NZ Limited in 25 kg bags. Table 2 shows the available sizing of the crushed glass produced by this supplier. The obtained reclaimed crushed glass for this research is a powder product with particles under 0.2mm, in the fine sand range.

Table 2. Particle size distribution of crushed glass.

Crushed Glass type	Particle Size
Powder	Under 0.2mm
Polish	0.2mm -0.4mm
Light	0.4mm -1.1mm
Medium	0.5mm - 1.5mm
Medium Plus	1.1mm - 1.8mm

Hydrometer analysis was employed to verify the particle size distribution of the crushed glass powder and further analyse the distribution of clay-size particles; the results of the test are shown in Figure 5 and confirm the claimed particle sizes to be mainly in the range of fine sand with around 15-20% silt content in the tested samples. Crushed glass powder exhibits very low plasticity and is classified as SP (poorly graded sand) based on the USCS.

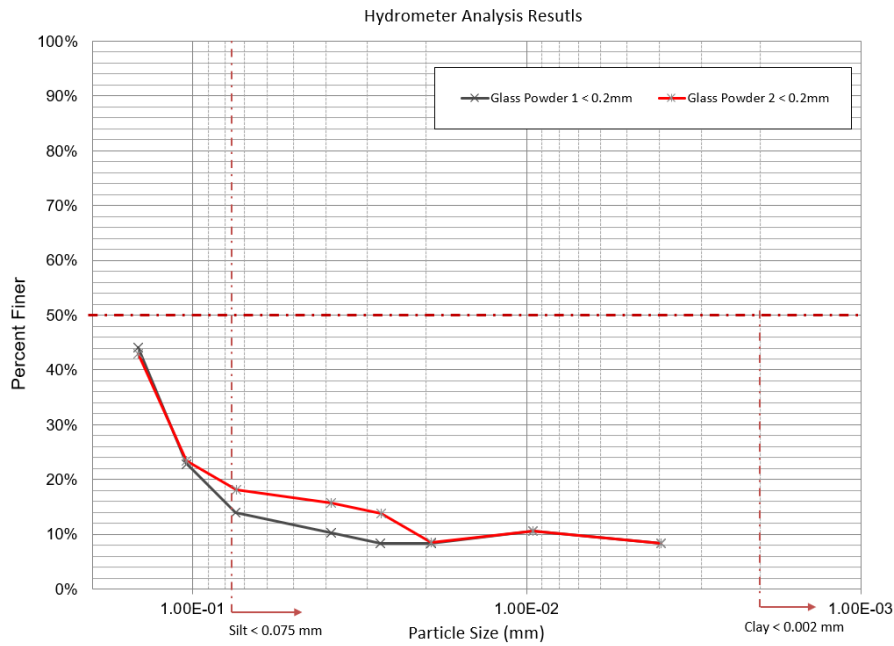


Figure 5. Hydrometer analysis results for the crushed glass powder.

1.4.2 Specific Surface Area and Volumetric Particle Size Analysis

The Brunauer, Emmett, and Teller (BET) analysis was conducted to determine the surface area of the pumice sand particles that passed through sieve no. 200. The results indicate a surface area of 8.93 m²/g, which provides valuable information about particle characteristics. The BET surface area graph, shown in Figure 6, visually represents the surface area measurement obtained from the analysis.

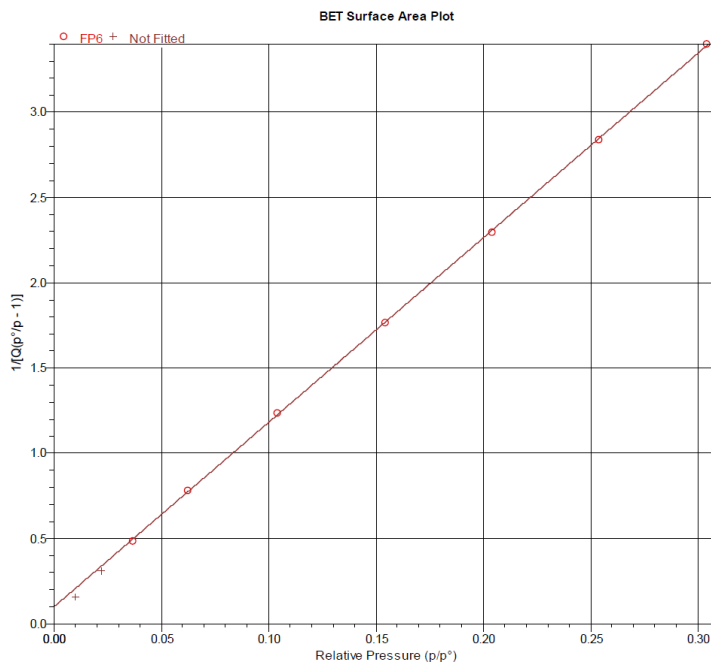


Figure 6. BET surface area graph for the pumice particles passing sieve no. 200.

The Particle Size Analyser (PSA) test was performed to assess the particle size distribution of the pumice sand particles that passed through sieve no. 200. The average D_{v50} value obtained from the PSA test was 33.99. This value represents the median particle diameter, indicating the size at which half of the particles are larger and the other half are smaller. Figure 7 presents the volumetric particle

size distribution graph, illustrating the distribution of particle sizes based on the PSA test results.

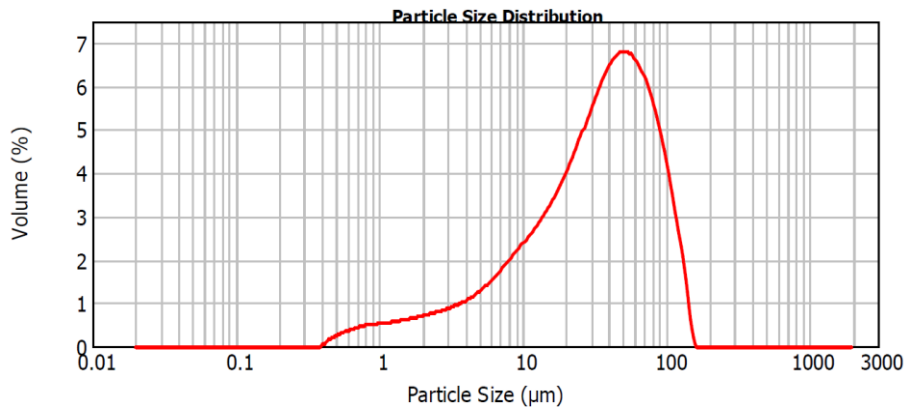


Figure 7. Volumetric particle size distribution graph for the pumice particles passing sieve no. 200.

The BET analysis was also conducted on reclaimed crushed glass powder to determine its surface area. The results indicate a surface area of 0.495 m²/g, providing valuable information about the specific characteristics of the glass powder particles. The surface area graph, depicted in Figure 8, visually represents the surface area measurement obtained from the BET analysis.

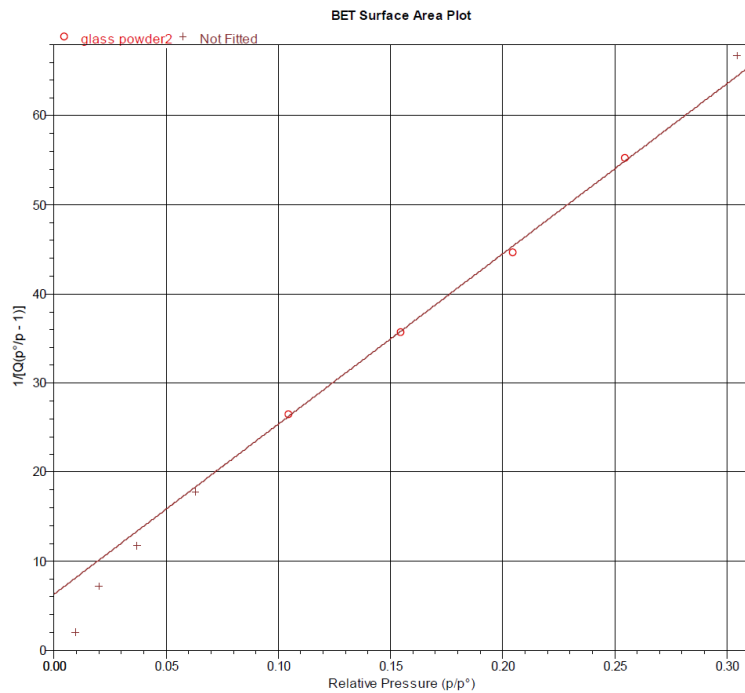


Figure 8. BET surface area graph for the reclaimed crushed glass powder.

Additionally, the PSA test was performed to assess the particle size distribution of the reclaimed crushed glass powder. The average Dv_{50} value obtained from the PSA test was 133.04, indicating the median particle diameter. Figure 9 illustrates the volumetric particle size distribution graph, showcasing the distribution of particle sizes based on the results obtained from the PSA test.

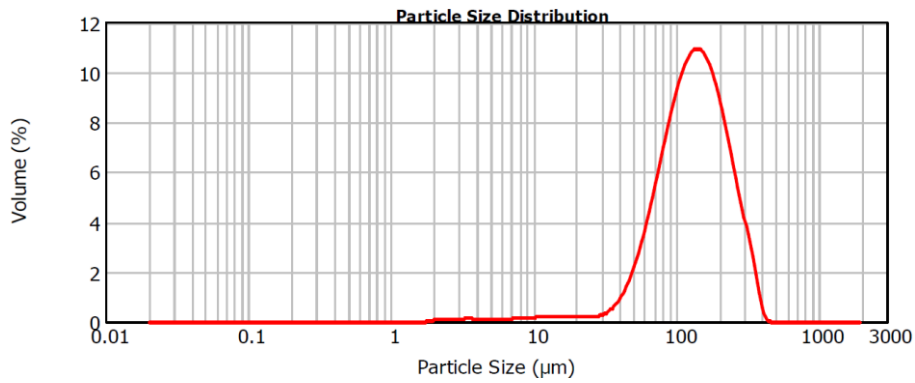


Figure 9. Volumetric particle size distribution graph for the reclaimed crushed glass powder.

1.4.3 Physical and Chemical Analysis

X-ray diffraction (XRD) testing was conducted on the pumice sand and reclaimed crushed glass powder, which indicates a combination of glassy and crystalline structures in the pumice sand while determining the glass powder as amorphous. This test used a non-destructive analytical method to examine the physical characteristics of substances, including the composition of phases, crystal structure, and orientation, in powdered, solid, and liquid samples. The results of XRD analysis for pumice and glass are shown in Figures 10 and 11, respectively.

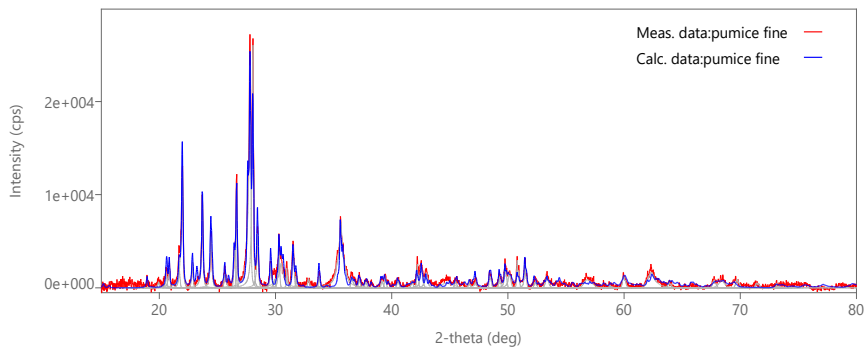


Figure 10. XRD analysis results for the pumice sand.

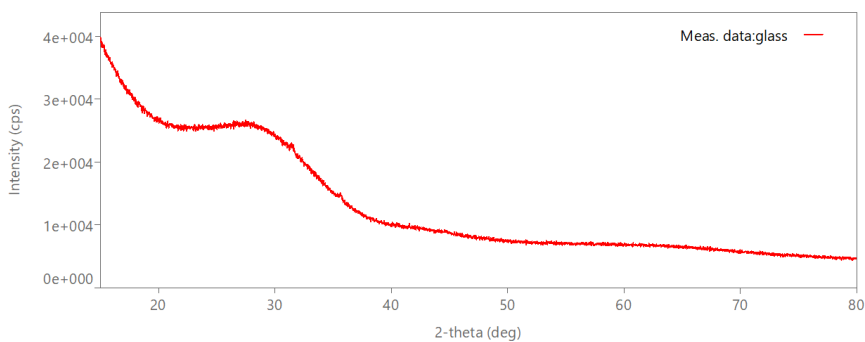


Figure 11. XRD analysis results for the reclaimed crushed glass powder.

Table 3 includes the mineral composition of the pumice obtained from XRD analysis. Four minerals were originally detected in pumice through XRD analysis, including Albite, Quartz, Jadeite, and Tridymite, further discussed below. Albite is a mineral commonly found in pumice. It is a type of feldspar and belongs to the plagioclase group. This mineral is typically present in pumice as white or colourless crystals. Quartz is a mineral that can be found in small amounts in pumice. It is a common mineral and one of the main components of many rocks. Quartz may appear as small, transparent, or translucent grains in pumice. Jadeite, on the other hand, is not typically found in pumice. It is a mineral

belonging to the pyroxene group, and it is commonly associated with metamorphic rocks, forming through the metamorphism of precursor rocks such as basalt or serpentinite. Pumice is formed from frothy lava when super-heated, highly pressurised lava is violently ejected from a volcano. Therefore, while pumice can contain various minerals depending on its source, jadeite is not a typical component of pumice, and its presence in the results is considered an overlapping peak error. Tridymite is a mineral that can occur in pumice. It is a high-temperature silica polymorph, forming under specific temperature and pressure conditions. Tridymite typically crystallises in volcanic rocks with high-temperature processes, such as those associated with rhyolitic magma. Tridymite can be detected as small, colourless, to white crystals in pumice.

Table 3. Mineral composition of the pumice obtained from XRD analysis.

Mineral	Peak (Percentage)
Albite	90.8(11)
Quartz	3.0(2)
Tridymite	4.3(3)

Chemical analysis of pumice was done by the mean of X-ray fluorescence (XRF) analysis. Figure 12 shows the results of the XRF analysis for pumice soil. XRF analysis is a non-destructive analytical technique used to determine the elemental composition of a sample. It involves the measurement of the characteristic X-rays emitted by the sample when exposed to high-energy X-rays or gamma rays. These emitted X-rays correspond to specific elements present in the sample, allowing for identifying and quantifying elements ranging from light to heavy elements. This analysis is widely used in various fields such as geology, environmental science, materials science, archaeology, and industry for elemental analysis of solids, liquids, and powders. It provides rapid and accurate results, making it a valuable tool for research, quality control, and process monitoring.

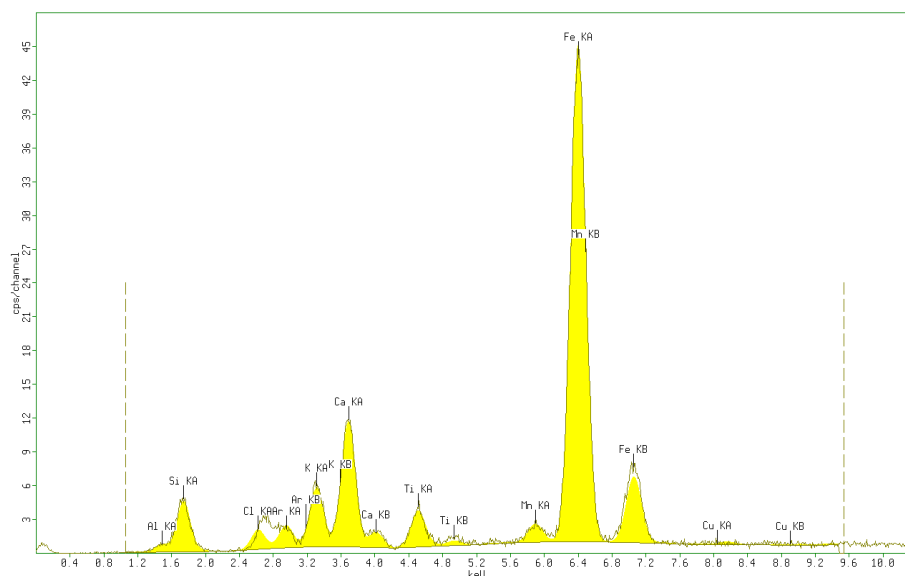


Figure 12. XRF analysis results for the pumice soil.

The elemental composition (in counts per second, cps) of the pumice soil obtained from the XRF test is shown in Table 4. Based on these results, the pumice soil sample contains various elements commonly found in volcanic rocks. Silicon (Si) and aluminium (Al) are present at moderate levels, indicating an abundance of silicate minerals. The high cps value of Si and the presence of Al in the XRF data is consistent with the pumice being dominantly composed of Albite, Quartz, and Tridymite. Potassium (K) and calcium (Ca) are also present, suggesting the presence of potassium-rich minerals and possible contributions from calcium-rich minerals such as feldspar. While no K-feldspar (like orthoclase) or calcium-bearing mineral is explicitly mentioned in the XRD data, the detected potassium and calcium

in the XRF might suggest trace amounts of relevant minerals or inclusions in the sample below the XRD analysis's detection limits. Iron (Fe) is detected at a relatively high level, indicating the presence of iron-bearing minerals in the pumice soil. Even though no Iron-bearing mineral is mentioned in the XRD data, it is possible that trace amounts of these minerals are present in the pumice or that Iron is present as a minor substituent in some of the identified minerals. Notably, argon (Ar) is a noble gas not typically found as a compound in soils. Its detection could be due to the atmospheric argon interacting with the instrument. Also, the negative value for copper (Cu) suggests that the concentration of copper in the sample is below the instrument's detection limit, as negative values are not meaningful in XRF readings. The other elements detected, like titanium (Ti), manganese (Mn), and chlorine (Cl), could be present as trace elements or be a part of minerals that were not detected in XRD due to their low abundance in the pumice sample.

Table 4. Elemental composition of the pumice soil obtained from the XRF test.

Element	Counts per Second (cps)
Aluminium (Al)	14.025
Silicon (Si)	95.586
Chlorine (Cl)	38.050
Argon (Ar)	43.476
Potassium (K)	117.585
Calcium (Ca)	249.863
Titanium (Ti)	74.638
Manganese (Mn)	38.985
Iron (Fe)	1086.062
Copper (Cu)	-1.702

The supplier provided the chemical composition of the recycled crushed glass powder. Table 5 includes the chemical composition of the crushed glass powder obtained from the supplier's datasheet. The major component of the glass powder is silicon dioxide (SiO₂), which accounts for approximately 72% of the compound. Silicon dioxide is the primary ingredient in glass and provides its structural integrity. The powder also contains trace amounts of iron (Ferric) oxide (Fe₂O₃) and aluminium oxide (Al₂O₃), with percentages less than 0.05 and 0.08, respectively. These oxides likely exist as impurities or contaminants in recycled glass. Sodium oxide (Na₂O) is present in small quantities, with a percentage of less than 15.0%, and potassium oxide (K₂O) is detected in very low amounts, less than 0.03%. These oxides may originate from the original glass composition but are in minimal concentrations. Calcium oxide (CaO) is found in minor quantities, less than 9.5%, and magnesium oxide (MgO) is detected in small amounts, less than 6.0%. Both calcium oxide and magnesium oxide may be residual components from the original glass material. This composition is characteristic of soda-lime glass, which is widely used for containers, windows, and many other common glass products.

Table 5. chemical composition of reclaimed crushed glass powder.

Compound	Percentage
Silicon Dioxide (SiO ₂)	72
Iron (Ferric) Oxide (Fe ₂ O ₃)	< 0.05
Aluminium Oxide (Al ₂ O ₃)	< 0.08
Sodium Oxide (Na ₂ O)	< 15.00
Potassium Oxide (K ₂ O)	< 0.03
Calcium Oxide (CaO)	<9.50
Magnesium Oxide (MgO)	< 6.00

The reclaimed glass powder is predominantly composed of silicon dioxide, as expected in glass

compositions, with the other elements and compounds present in relatively low percentages or trace amounts, indicating minor impurities or remnants from the original glass production process. This chemical composition suggests its potential in the alkali-activation process, particularly when considering key elements required for activation using potassium hydroxide (KOH). The powder's significant silicon dioxide (SiO₂) content, comprising approximately 72%, makes it a suitable candidate for alkali activation. SiO₂ is a crucial component that reacts with alkalis to form a gel-like structure, contributing to the development of strength and durability in the activated material.

The small quantities of sodium oxide (Na₂O) suggest that the glass powder may contain alkali elements, which can participate in the alkali-activation reaction. While the percentage of sodium oxide is below 15.0%, it can still contribute to the alkali-activation process, although its reactivity may be lower compared to higher concentrations. The potassium oxide (K₂O) detected in the glass powder is in very low amounts, less than 0.03%. This insignificant amount indicates that the powder may have limited inherent potassium content, suggesting the need for supplemental potassium sources, such as KOH, to optimise the activation process.

In the alkali-activation process of the glass powder described above, aluminium oxide (Al₂O₃) can play a significant role. While the glass powder's aluminium oxide content is detected in very low amounts, less than 0.08%, it still has the potential to contribute to the activation process. Aluminium oxide can act as a network modifier in alkali-activated materials. When alkali activators, such as potassium hydroxide (KOH), are added to the glass powder, they interact with the aluminium oxide in the powder. This interaction leads to the dissolution of aluminium oxide, releasing aluminium ions (Al³⁺) into the alkaline solution. These released aluminium ions can then participate in the formation of gel-like products during the alkali-activation reaction. They can also contribute to developing a three-dimensional network structure, enhancing the strength and durability of the activated material. Aluminium ions can also aid in binding other components, such as silicon dioxide (SiO₂), forming stable and rigid products.

The glass powder's calcium oxide (CaO) can also somewhat influence the alkali-activation process. Although the percentage of calcium oxide is detected in minor quantities, less than 9.50%, it still holds potential for participation in the activation reaction. Calcium oxide can react with alkalis, such as potassium hydroxide (KOH), forming calcium silicate hydrate (C-S-H) gel. This gel is crucial in providing strength and stability to the resulting alkali-activated material. The reaction between calcium oxide and alkalis contributes to the development of the binding matrix and can enhance the mechanical properties of the activated material.

Based on the conducted analysis, the chemical composition of reclaimed glass powder exhibits favourable potential for alkali-activation reaction. However, the physical characteristics of the glass powder may require further alteration to allow successful interaction between glass powder and alkalis within an optimised setting to form binding gels in the proposed alkali-activation process.

1.4.4 Microstructural and Elemental Analysis

Further analysis was conducted using Scanning Electron Microscope (SEM) and Energy Dispersive X-ray analysis (EDX) tests to study the microstructure and identify the elemental composition of pumice soil and reclaimed crushed glass powder. SEM is a versatile imaging technique to study samples' surface morphology and topography at high magnification. It utilises a focused electron beam to scan the sample, generating detailed images that reveal the microstructure and texture of the material. SEM provides valuable information about the sample's surface features, such as particle size, shape, and surface roughness, allowing for visual examination and analysis of the sample at a microscopic level. EDX, on the other hand, is an analytical technique often coupled with SEM to provide elemental composition information.

EDX measures the characteristic X-rays the sample emits when bombarded with the electron beam. These X-rays correspond to the material's elemental composition, enabling qualitative and quantitative analysis of the elements present. By collecting and analysing the X-ray signals, EDX can identify the elemental constituents and determine their relative abundances within the sample. This data allows for investigating elemental distribution and mapping and identifying impurities or chemical variations in the material being analysed.

In Figure 13, the SEM image at a magnification of 2500X shows a single grain of pumice sand. The image reveals the distinctive porous structure inherent to pumice, one of its fundamental characteristics. Numerous interconnected voids or pores within the pumice grain indicate its porous nature. This porous structure is responsible for the low bearing capacity of pumice. Additionally, the high crushability of pumice, or its propensity to easily break or crumble under applied pressure, can be attributed to the porous structure. The interconnected pores within the grain render it susceptible to compression or fragmentation when subjected to external forces.

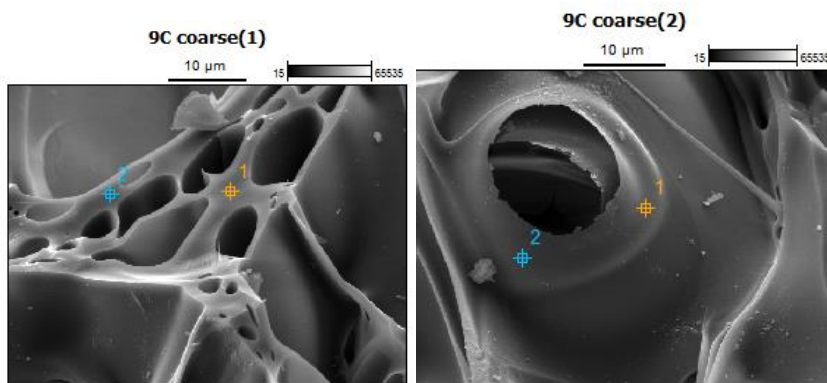


Figure 13. SEM results for 2500X magnification of a pumice sand grain.

EDX results were obtained at selected points indicated in Figure 13 for pumice sand grains, namely coarse (1) and coarse (2), indicating their elemental compositions. Figure 14 illustrates the EDX results for pumice sand grains, where peaks in the graphs suggest the presence of different elements.

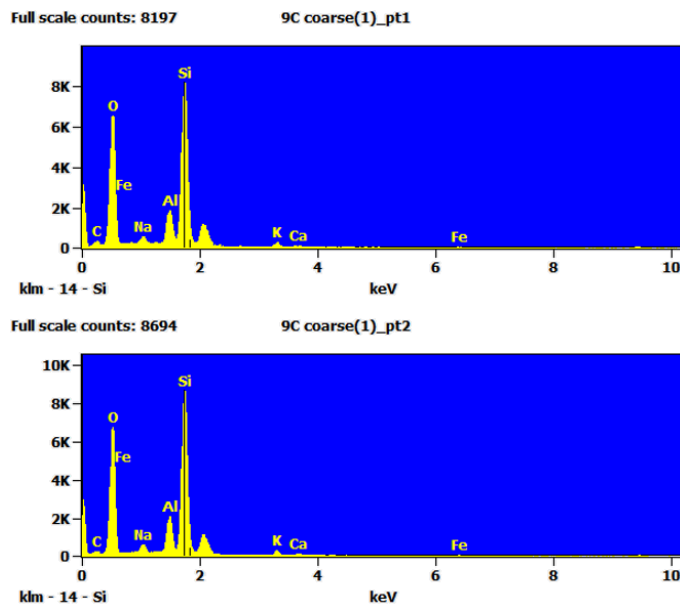


Figure 14. EDX results for pumice sand grains.

The obtained EDX results from four points of the pumice sand grain are as follows. These results provide information on the elemental composition at each analysed point of the pumice sand grain.

The net counts indicate the detected counts of each element, while the weight (%) and atom (%) represent each element's weight and atomic percentages, respectively.

- Point 1 of coarse (1) pumice:

Net Counts: C (1316), O (57707), Na (3667), Al (16929), Si (95679), K (2438), Ca (1248), Fe (639)

Weight %: C (4.77), O (58.91), Na (1.93), Al (4.96), Si (26.95), K (1.03), Ca (0.58), Fe (0.88)

Atom %: C (7.40), O (68.66), Na (1.57), Al (3.42), Si (17.89), K (0.49), Ca (0.27), Fe (0.29)

- Point 2 of coarse (1) pumice:

Net Counts: C (1036), O (56670), Na (4299), Al (18056), Si (98394), K (2848), Ca (1232), Fe (655)

Weight %: C (3.87), O (58.09), Na (2.25), Al (5.28), Si (27.83), K (1.20), Ca (0.57), Fe (0.90)

Atom %: C (6.08), O (68.53), Na (1.85), Al (3.70), Si (18.70), K (0.58), Ca (0.27), Fe (0.30)

- Point 1 of coarse (2) pumice:

Net Counts: C (639), O (27798), Na (1501), Al (11569), Si (68577), K (2557), Ca (965), Fe (549)

Weight %: C (4.31), O (52.93), Na (1.28), Al (5.53), Si (32.09), K (1.83), Ca (0.76), Fe (1.27)

Atom %: C (6.95), O (64.13), Na (1.08), Al (3.98), Si (22.15), K (0.91), Ca (0.37), Fe (0.44)

- Point 2 of coarse (2) pumice:

Net Counts: C (369), O (8844), Na (667), Al (6622), Si (42512), K (2115), Ca (859), Fe (573)

Weight %: C (5.64), O (40.96), Na (1.08), Al (6.12), Si (39.12), K (3.06), Ca (1.37), Fe (2.64)

Atom %: C (9.68), O (52.72), Na (0.96), Al (4.67), Si (28.68), K (1.61), Ca (0.71), Fe (0.97)

The results show variations in the elemental composition across the different points analysed. The major elements present are silicon (Si) and oxygen (O), consistent throughout the points. Other elements such as carbon (C), sodium (Na), aluminium (Al), potassium (K), calcium (Ca), and iron (Fe) are also detected but at lower percentages. These findings suggest that the pumice sand grain consists mainly of silica (SiO₂), which is expected given the composition of pumice. Other elements indicate possible impurities or trace elements within the pumice. The specific distribution and concentration of these elements can provide insights into the origin and formation of the pumice.

Figure 15 represents crushed glass powder grains under 700X and 400X magnifications using the SEM. The presence of different particle sizes is evident in these images. In contrast with pumice, the glass particles are solid and show no inner particle voids. EDX results at selected points indicated in Figure 15 for glass samples, namely glass (1) and glass (2), reveal their elemental compositions. Figures 16 (a) and (b) illustrate the EDX results for glass samples (1) and (2), where peaks in the graphs imply the presence of different elements in the samples.

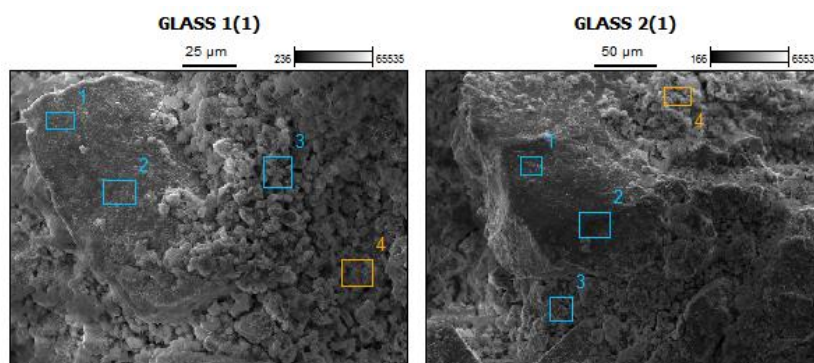
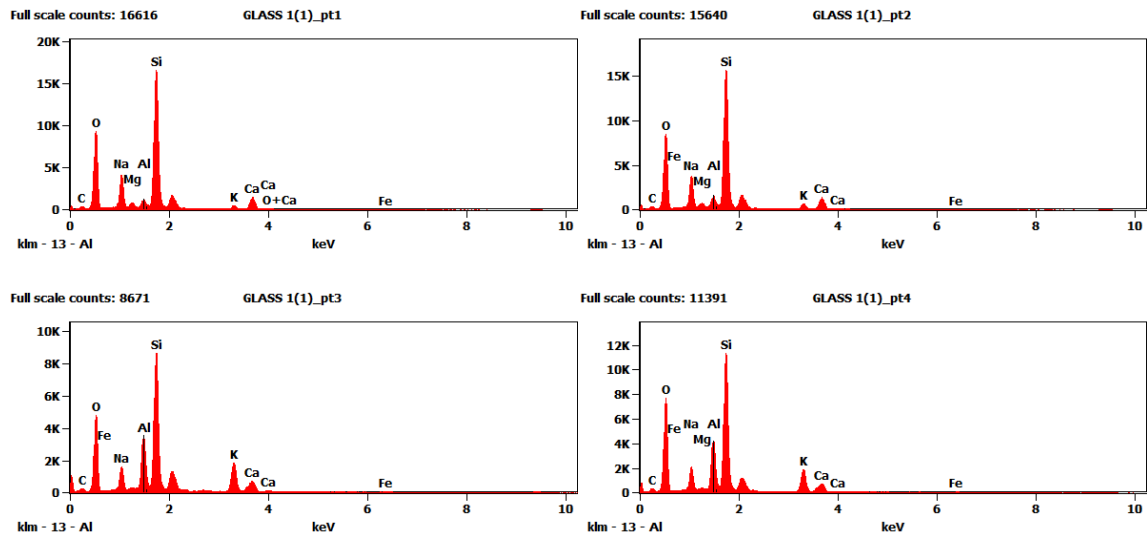
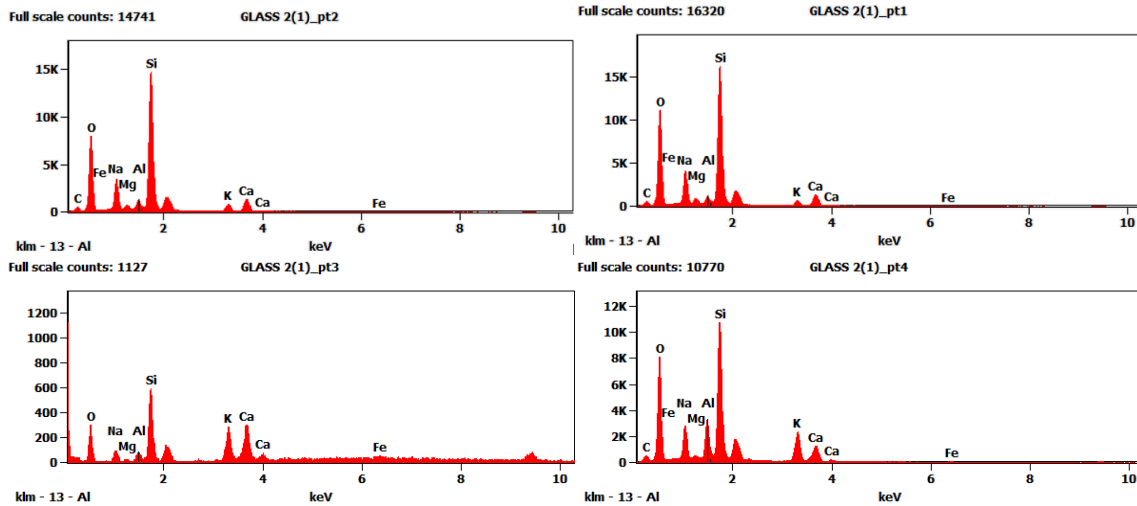


Figure 15. SEM results for (left) 700X and (right) 400X magnification of crushed glass powder.



(a) Sample 1



(b) Sample 2

Figure 16. EDX results for reclaimed crushed glass powder (a) sample 1 and (b) sample 2.

The EDX results from all points shown on the glass samples are as follows, providing information on the elemental composition at each analysed point. The net counts indicate the detected counts of each element, while the “Weight %” and “Atom %” represent each element’s weight and atomic percentages, respectively.

- Data Point 1 of GLASS 1:

Net Counts: C (1600), O (70153), Na (33592), Mg (4482), Al (6981), Si (169193), K (5111), Ca (17336), Fe (306)

Weight %: C (3.50), O (49.72), Na (9.71), Mg (1.04), Al (1.28), Si (28.38), K (1.28), Ca (4.83), Fe (0.25)

Atom %: C (5.74), O (61.17), Na (8.32), Mg (0.84), Al (0.94), Si (19.89), K (0.64), Ca (2.37), Fe (0.09)

- Data Point 2 of GLASS 1:

Net Counts: C (1516), O (63579), Na (30420), Mg (3760), Al (9786), Si (161449), K (6583), Ca (16872), Fe (350)

Weight %: C (3.52), O (48.83), Na (9.26), Mg (0.91), Al (1.88), Si (28.58), K (1.74), Ca (4.96), Fe (0.30)

Atom %: C (5.81), O (60.47), Na (7.98), Mg (0.74), Al (1.38), Si (20.17), K (0.88), Ca (2.45), Fe (0.11)

- **Data Point 3 of GLASS 1:**

Net Counts: C (1810), O (36073), Na (12146), Mg (30250), Al (90387), Si (22077), K (8027), Ca (519)

Weight %: C (5.53), O (45.77), Na (5.31), Mg (7.88), Al (23.30), Si (8.19), K (3.39), Ca (0.64)

Atom %: C (9.25), O (57.45), Na (4.64), Mg (5.86), Al (16.66), Si (4.21), K (1.70), Ca (0.23)

- **Data Point 4 of GLASS 1:**

Net Counts: C (639), O (56436), Na (15952), Mg (877), Al (37238), Si (115534), K (21689), Ca (7782), Fe (745)

Weight %: C (1.65), O (50.25), Na (5.69), Mg (0.23), Al (7.94), Si (24.31), K (6.54), Ca (2.65), Fe (0.74)

Atom %: C (2.78), O (63.55), Na (5.01), Mg (0.20), Al (5.96), Si (17.51), K (3.38), Ca (1.34), Fe (0.27)

- **Data Point 1 of GLASS 2:**

Net Counts: C (2691), O (83003), Na (33114), Mg (4929), Al (6420), Si (167260), K (7234), Ca (17667), Fe (341)

Weight %: C (4.96), O (52.48), Na (8.91), Mg (1.04), Al (1.07), Si (25.27), K (1.61), Ca (4.39), Fe (0.25)

Atom %: C (7.92), O (62.85), Na (7.43), Mg (0.82), Al (0.76), Si (17.24), K (0.79), Ca (2.10), Fe (0.09)

- **Data Point 2 of GLASS 2:**

Net Counts: C (2454), O (59285), Na (27267), Mg (3966), Al (8049), Si (150035), K (9234), Ca (17693), Fe (362)

Weight %: C (5.52), O (48.72), Na (8.54), Mg (0.97), Al (1.57), Si (26.70), K (2.44), Ca (5.22), Fe (0.32)

Atom %: C (8.97), O (59.44), Na (7.25), Mg (0.78), Al (1.13), Si (18.55), K (1.22), Ca (2.54), Fe (0.11)

- **Data Point 3 of GLASS 2:**

Net Counts: C (2077), O (760), Na (106), Mg (691), Al (6128), Si (2881), K (3637), Ca (334)

Weight %: C (41.53), O (4.41), Na (0.44), Mg (2.22), Al (17.81), Si (11.65), K (17.30), Ca (4.64)

Atom %: C (59.88), O (4.43), Na (0.42), Mg (1.90), Al (14.63), Si (6.87), K (9.96), Ca (1.92)

- **Data Point 4 of GLASS 2:**

Net Counts: C (2467), O (58213), Na (22174), Mg (1957), Al (26420), Si (112939), K (27236), Ca (15541), Fe (486)

Weight %: C (4.94), O (49.91), Na (7.09), Mg (0.47), Al (5.06), Si (20.50), K (7.03), Ca (4.57), Fe (0.42)

Atom %: C (8.10), O (61.44), Na (6.07), Mg (0.38), Al (3.70), Si (14.38), K (3.54), Ca (2.25), Fe (0.15)

The relative concentrations of different elements in the glass samples are evident in the data. For example, in GLASS 1, the main elements present are oxygen (O), silicon (Si), and sodium (Na), with varying amounts of carbon (C), aluminium (Al), potassium (K), calcium (Ca), and iron (Fe). GLASS 2 also exhibits similar patterns, with oxygen (O), silicon (Si), and sodium (Na) being the predominant elements. The consistency of the results is evidence of the homogeneity of the reclaimed crushed glass powder, which increases the reliability and repeatability of the results. The EDX results for the glass samples can also be interpreted regarding their potential for the alkali-activation process. The presence of sodium (Na), potassium (K), and calcium (Ca) in the glass powder is key to the alkali-activation process. Sodium and potassium are alkali elements that can act as activators, while calcium can contribute to the overall reactivity of the glass.

The weight percentages and atom percentages of Na, K, and Ca can help assess their potential for alkali activation. These results are aligned with previous findings, strengthening the potential of reclaimed glass being a suitable candidate for the alkali-activation process. Further analysis and experimentation determine the suitability and performance of glass powder in the proposed alkali-activation applications.

1.5 Strength Characteristics and Performance of the Proposed Alkali-activated Binder in Stabilising Pumice Soil

1.5.1 Compaction Properties and Crushability of Pumice Sand

Compaction tests using a standard proctor test device were conducted separately on the coarse and fine pumice sands to determine their maximum dry unit weight, optimum moisture content, and crushability. The standard Proctor test is a compaction test commonly used in geotechnical engineering to determine a soil or aggregate material's maximum dry unit weight and optimum moisture content. It involves compacting a soil sample at various moisture contents and measuring its compacted density to establish the relationship between moisture content and dry unit weight. In the case of the pumice sands, compaction tests using a standard Proctor test device were performed separately on the coarse and fine pumice sands.

The results of the tests, as shown in Figure 17, indicate a compaction curve with double peaks for both soils. The maximum dry unit weight for the fine and coarse pumice sands on the dry side is approximately 8.3 kN/m³ and 6.7 kN/m³, respectively. These results are obtained at an optimum moisture content of approximately 10% for both soils. On the wet side of the compaction curves, the second peaks indicate a maximum dry unit weight of approximately 8.3 kN/m³ for fine pumice sand and 7.2 kN/m³ for coarse pumice sand. Both soils again depict an optimum moisture content above 40% on the wet side of the compaction curve. Considering the range of natural moisture content for both pumice sands in between 40% to 45% and the moisture-dependent alkali-activation process, the values associated with the wet side of the compaction curve were selected in this project to achieve the highest density that can be achieved for pumice sand samples.

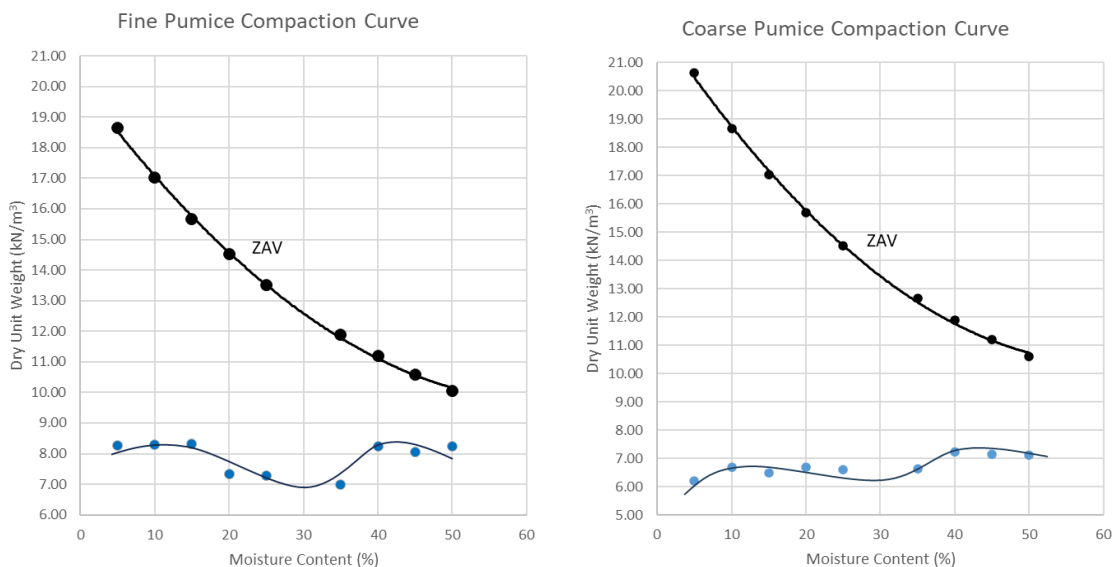


Figure 17. Results of standard proctor tests conducted on (left) fine and (right) coarse pumice sands.

Furthermore, the sieve analysis results after compaction for the fine and coarse pumice sands are presented in Figures 18 (a) and (b), respectively. These figures illustrate the changes in the particle size distribution of the pumice sands resulting from the applied compaction energy. It is observed that the compaction process causes the pumice grains to crush, leading to alterations in the particle size distribution. Particularly, the crushing effect on the pumice grains is more pronounced in the case of the fine pumice sand, as evident in Figure 18 (a). This result suggests that fine pumice sand is more susceptible to crushing and particle size redistribution than coarse pumice sand when subjected to compaction energy.

The other observation is the lack of a clear relationship between the crushability rate and the compaction moisture content. Finally, a more consistent behaviour was observed in coarse pumice sand, which has less sensitivity to the crushing effect. These findings provide important information about the compaction characteristics and crushability of the pumice sands, which are also relevant for their application in pavement design and soil stabilisation. Due to the more consistent particle size distribution of coarse pumice after compaction, this soil was selected for use in the following processes.

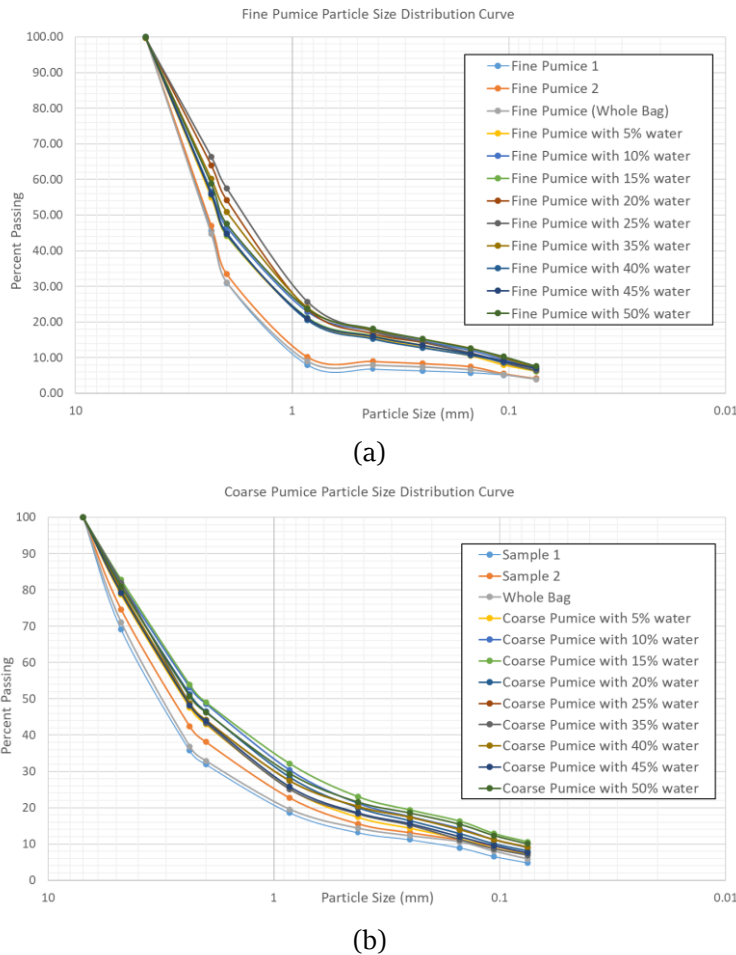


Figure 18. Results of sieve analysis on the compacted (a) fine and (b) coarse pumice sands.

1.5.2 Design and Characterisation of Materials for Alkaline Activation Process

Adjusting the particle size distribution and specific surface area of the reclaimed crushed glass powder is critical in preparing this material to be a precursor in the alkali-activation process. A series of grinding experiments were carried out, employing various grinding ball sets and durations to identify the optimal grinding specifications. The Retsh PM-100 planetary ball mill was used with a revolution of 600 rpm for all the tests. These tests aimed to reduce the particle size of a portion of the glass powder to a similar size as clay particles ($<0.002\text{mm}$) while simultaneously increasing its specific surface area. Based on the literature, a precursor in this particle size range can exhibit desirable reactivity and provide the necessary properties for successful implementation in the alkali-activation process.

Figure 19 illustrates the outcomes of the hydrometer analysis on the reclaimed crushed glass powder obtained from the supplier and several iterations of ground glass powder prepared using different grinding specifications. By comparing the results, valuable insights can be gained regarding the effect of grinding on the particle size distribution and specific surface area of the glass powder. These experiments are critical in preparing crushed glass powder as a precursor for the alkali-activation

process. By fine-tuning the grinding parameters, achieving the desired particle size distribution and specific surface area with the lowest possible time and energy consumption is possible.

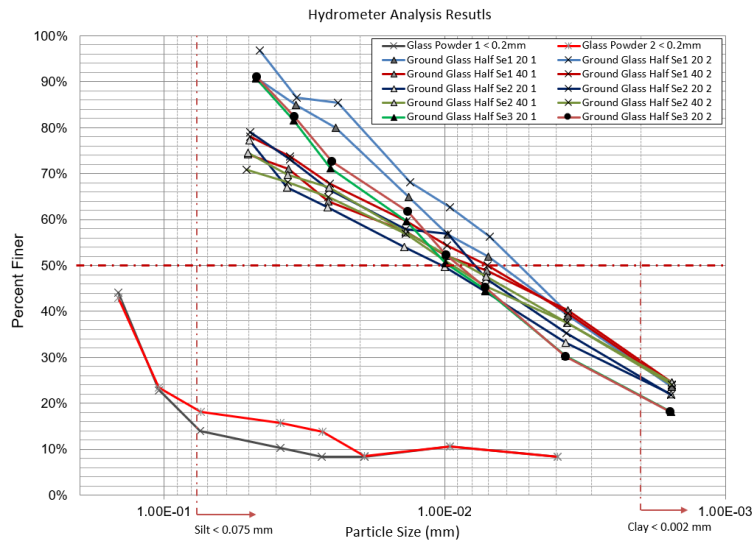


Figure 19. Hydrometer analysis results for the crushed glass powder versus ground glass powder.

The trials on grinding specification yielded notable findings, indicating a considerable increase in the ground glass's D50 value (median particle size) compared to the original crushed glass powder. The results also revealed that approximately 20% to 30% of the ground glass particles fell within the range of clay-size particles, depending on the specific grinding specification. This information is crucial as it demonstrates the effectiveness of the chosen grinding parameters in producing the desired particle size distribution, particularly in generating finer particles that closely resemble clay in size.

The results of the hydrometer analysis determined the optimal grinding specification for achieving the desired particle size distribution and specific surface area as a half-loaded grinding jar and a set of 16 steel grinding balls with 15mm diameter for 20 minutes at 600 rpm.

Figure 20 presents the outcomes of Particle Size Analyser (PSA) tests performed on both the crushed glass powder (referred to as Glass-0) and the optimised ground glass (referred to as Glass-20). The results from the PSA tests align with the findings of the hydrometer analysis, showcasing a shift in the particle size distribution towards smaller particles. This data confirms the efficacy of the chosen grinding specification in producing finer particles.

The PSA reports provide additional valuable information, presenting the values of D10, D50, and D90 (particle sizes at which 10%, 50%, and 90% of particles are smaller than the respective values) for both Glass-0 and Glass-20. For Glass-0, the values were reported as 61.847 μm (D10), 133.315 μm (D50), and 255.572 μm (D90). In contrast, the optimised ground glass (Glass-20) exhibited significantly finer particles, with values of 3.495 μm (D10), 17.978 μm (D50), and 72.722 μm (D90).

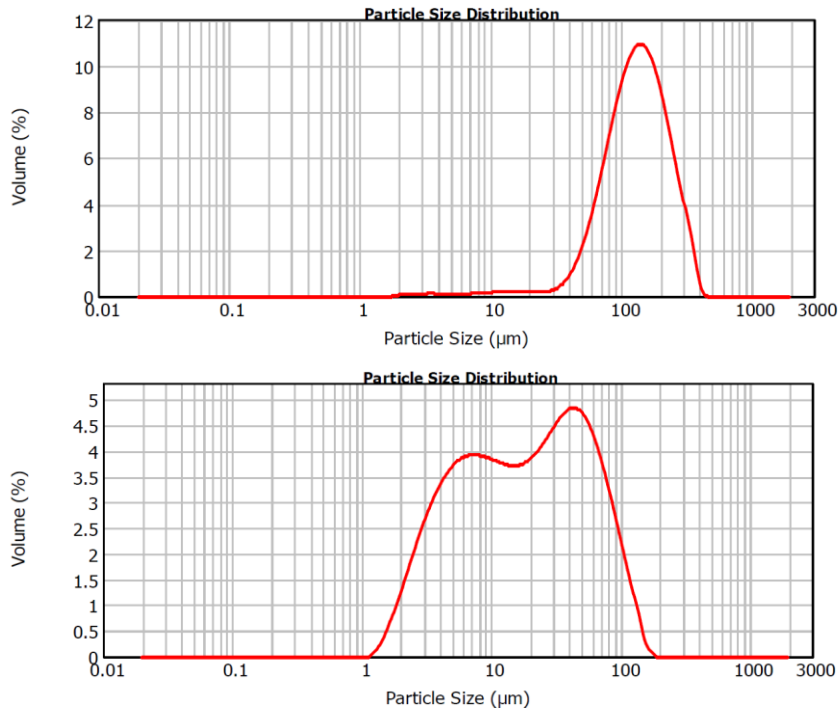


Figure 20. Particle Size Analyser results of (top) crushed glass powder and (b) optimised ground glass.

1.5.3 Design and Performance Analysis of the Alkali Activated Mortar

An alkaline agent, the activator, produces an alkali environment, which can effectively activate the glass components for the desired reactions. Through a thorough review of existing literature, Potassium Hydroxide (KOH) with a molarity of 10 was selected as the activator for the mortar mix design. The mortar mix was formulated as a two-component system consisting of solid ground glass powder (precursor) and a 10M KOH solution (activator). Five activator/precursor ratios were employed, ranging from 0.1 to 0.5, with an incremental increase of 0.1. These ratios were denoted as GG-K-0.1 to GG-K-0.5. Table 6 provides detailed information regarding the mix designs, including the activator/precursor ratios and other specifications. It is important to note that the specifications listed in the table are based on the mortar mix prepared for three individual samples for each mix design. This approach ensures consistency and allows for an accurate assessment of the mortar's properties and performance.

Table 6. Mix design details for alkali-activated mortar.

Mix ID	Precursor (g)	Activator/Precursor	Activator (g)
GG-K-0.1	585.00	0.10	58.50
GG-K-0.2	585.00	0.20	117.00
GG-K-0.3	585.00	0.30	175.50
GG-K-0.4	585.00	0.40	234.00
GG-K-0.5	585.00	0.50	292.50

Standard cubical steel moulds with dimensions of 50mm × 50mm × 50mm were utilised for sample preparation and curing based on ASTM C 109/C 109M-02 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). Three identical samples were constructed, cured, and tested for each mix design under identical conditions. Before pouring the mortar into the moulds, the samples were mixed thoroughly for a minimum of five minutes using a benchtop mixture.

A vibrating table was employed in the sample preparation process to ensure the removal of any trapped air bubbles. The moulds were securely fixed to the vibrating table, and the mortar was poured into the moulds in three steps of equal volume while the table was in operation. A specific curing regime consisting of 48 hours of curing at 65 degrees Celsius followed by 24 hours at room temperature was adopted based on the literature to speed up the strength gain of the mortar.

Three samples were carefully prepared for each mix design, subjected to the appropriate curing process, and subsequently tested using the MTS Universal Testing Machine. Figure 21 visually presents alkali-activated mortar samples obtained from different mix designs after experiencing failure during testing. Examining the failure behaviour of the samples reveals notable differences among them. In the case of samples GG-K-0.1 and GG-K-0.2, failure occurred at a relatively early stage of the testing process, characterised by a small stress level and axial deformation of approximately 1.2mm.

However, the remaining samples demonstrated a distinct behaviour, reaching failure at larger axial deformations ranging between 2mm and 3mm. Additionally, these samples recorded higher failure loads than the GG-K-0.1 and GG-K-0.2 samples. The failure mode and status of the mortar samples further support these observations, highlighting the variations in the response of different mix designs to the applied stress during testing. This difference in failure behaviour helps us understand the performance and strength characteristics of the alkali-activated mortars derived from various mix designs.

Figure 22 illustrates the stress-related behaviour of the mortars under UCS tests in terms of load versus deformation. It is evident from the graphs that all the mortar mixes show relatively similar behaviour under load, where an elastoplastic behaviour continues to the peak strength of the materials and is followed by excessive deformation after failure load. Mortar mixes with a lower ratio of activator/precursor tend to exhibit more plastic behaviour both before and after their peak strength. In contrast, mortars with a higher ratio of activator/precursor show a clear peak followed by a declining strength during excessive deformation. The strength gain of the cured mortars is early evidence of the successful activation of reclaimed crushed glass powder, confirming the hypothesis on the suitability of this waste material as a binder for soil stabilisation.

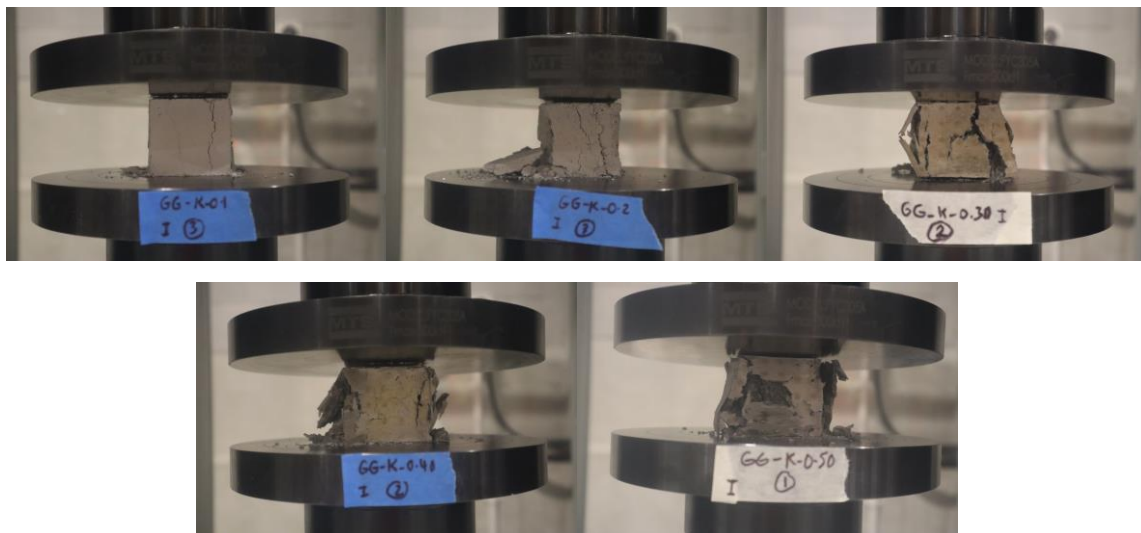


Figure 21. Samples of the alkali-activated mortars after failure.

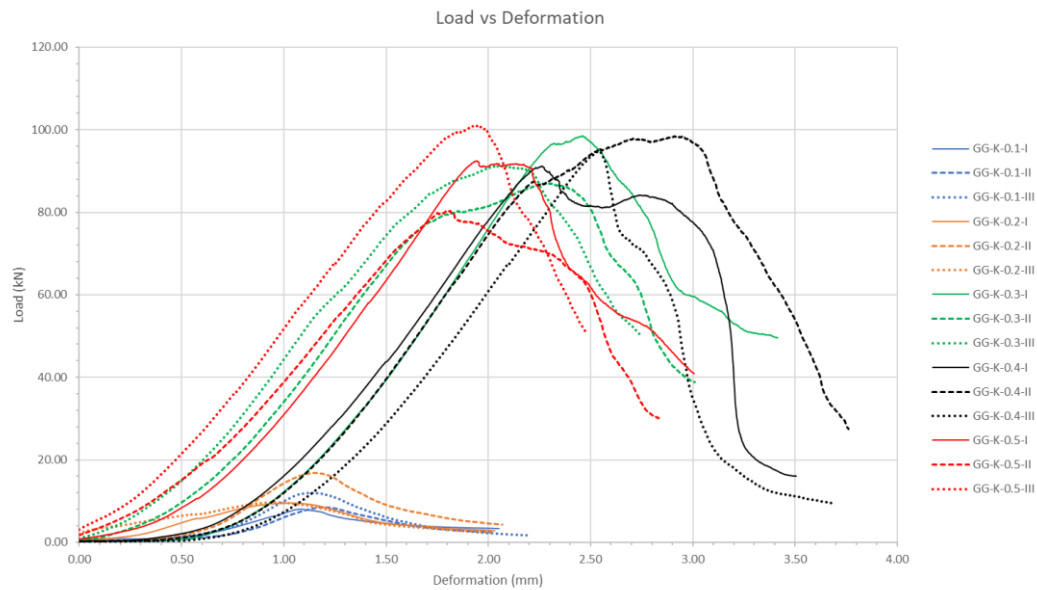


Figure 22. Load versus deformation graph for the alkali-activated mortars.

Figure 23 and Table 7 show the unconfined compressive strength of the alkali-activated mortars. As the ratio of activator/precursor increased from 0.2 to 0.3, the average compressive strength of the mortar mix exhibited a surge corresponding to an increase from 4.8 to 36.9 MPa. However, among the mix designs with activator/precursor ratios of 0.3 to 0.5, the average peak strength of the mortar does not show any significant changes.

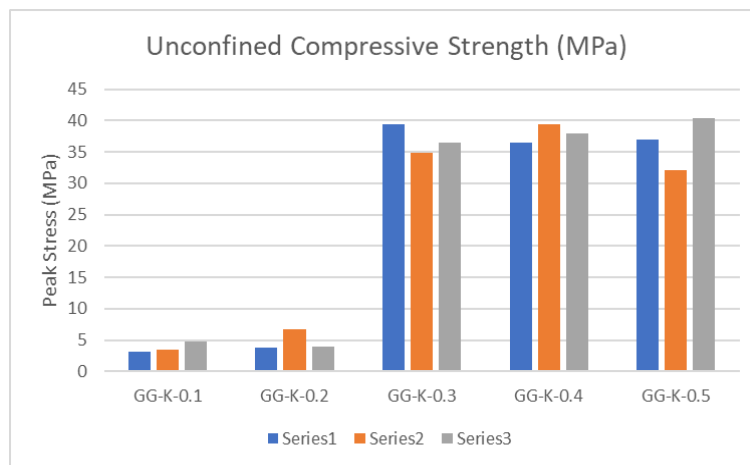


Figure 23. Unconfined compressive strength of the alkali-activated mortars.

Table 7. Peak unconfined compressive strength of the alkali-activated mortars.

Sample ID	Peak Strength (MPa)			Average
	Sample 1	Sample 2	Sample 3	
GG-K-0.1	3.2	3.4	4.8	3.8
GG-K-0.2	3.8	6.7	3.9	4.8
GG-K-0.3	39.4	34.8	36.5	36.9
GG-K-0.4	36.5	39.4	37.9	37.9
GG-K-0.5	37	32.1	40.4	36.5

Amongst all mix designs, GG-K-0.4 demonstrated the optimal balance between average strength and consistency in performance. This mix design, characterised by an activator/precursor ratio of 0.4, also provided great workability compared to other mixes, nominating it as the most suitable. Therefore, this

mix design is selected as the optimum mortar.

The microstructural and elemental analysis on the mortars was performed on samples of different mix designs to investigate the alkali-activation process using reclaimed crushed glass powder. Figure 24 presents the scanning electron microscope (SEM) results of samples GG-K-0.1 to GG-K-0.5 at a magnification of 500X. Careful examination of the SEM images reveals that the samples with activator/precursor ratios of 0.3, 0.4, and 0.5 (GG-K-0.3, GG-K-0.4, and GG-K-0.5) exhibited the presence of glass binder gels, forming a uniform matrix where individual glass particles are unrecognisable. This information suggests that the alkali-activation process was completed in these samples, creating a geopolymer matrix with a coherent microstructure.

In contrast, the samples with lower activator/precursor ratios (GG-K-0.1 and GG-K-0.2) showed a conglomeration of glass particles, indicating that the alkali-activation process was not completed adequately due to insufficient activator. The binder gels in these samples encapsulated some of the glass particles and held the rest together, resulting in a conglomerated microstructure. This conglomeration of glass particles is an evident sign of the lack of sufficient potassium hydroxide (KOH) to trigger the full alkali-activation reaction and the creation of a geopolymer. In other words, the lower activator/precursor ratios did not provide enough alkali activator to fully activate the glass particles, resulting in a weaker and less coherent microstructure.

These findings are in line with the strength analysis of the mortar samples. The UCS of the mortars showed a significant increase when the activator/precursor ratio was increased from 0.2 to 0.3, indicating an improvement in the mechanical properties of the alkali-activated glass. However, as the activator/precursor ratio was further increased beyond 0.3, the strength of the samples remained relatively similar. This data suggests that a critical activator/precursor ratio (around 0.3) is required for the successful alkali-activation process, beyond which increasing the activator/precursor ratio does not significantly improve the strength of the resulting material.

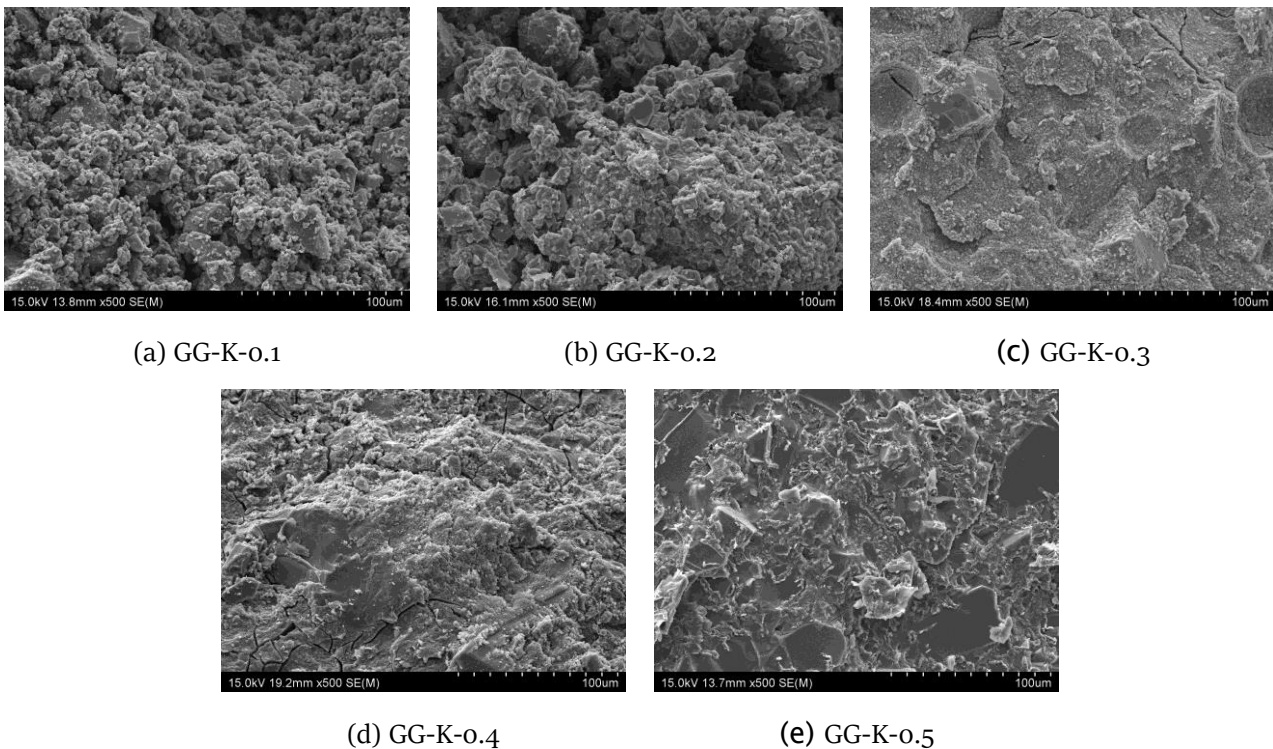


Figure 24. SEM results for (a) GG-K-0.1, (b) GG-K-0.2, (c) GG-K-0.3, (d) GG-K-0.4 and (e) GG-K-0.5.

Figure 25 displays the results of SEM/EDX analysis conducted on representative samples, GG-K-0.1 and GG-K-0.5, which were chosen to represent significant changes in the strength of the alkali-activated

mortars. The EDX examination was performed using a 4-point method, and the identified points on the SEM image were analysed. The analysis results, including net counts, weight percentages, and atom percentages of various elements in the samples, are presented in Tables 8 and 9.

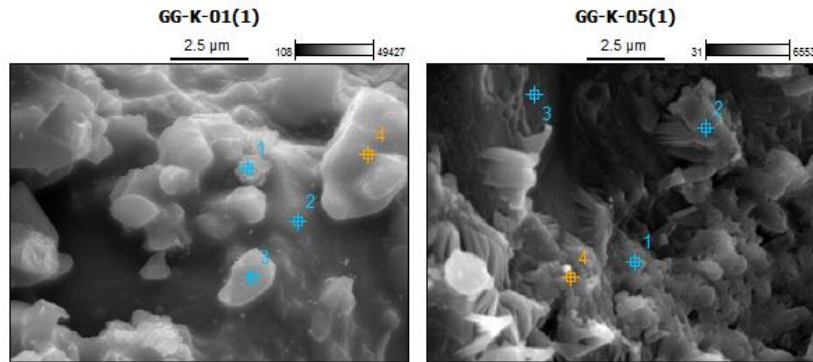


Figure 25. SEM/EDX results for (left) GG-K-o.1 and (right) GG-K-o.5.

Table 8. EDX results for GG-K-o.1 sample.

GG-K-01 Net Counts	C	O	Na	Mg	Al	Si	K	Ca
GG-K-01(1)_pt1	2770	61417	41240	8195		135534	7953	11858
GG-K-01(1)_pt2	2397	60712	22363	10105		167648	2425	13910
GG-K-01(1)_pt3	2701	63317	20170	8914		154714	7401	13823
GG-K-01(1)_pt4	2596	68133	26165	9327		162010	3797	14869
GG-K-01 Weight %	C	O	Na	Mg	Al	Si	K	Ca
GG-K-01(1)_pt1	6.33	48.13	12.79	2.13		24.93	2.14	3.55
GG-K-01(1)_pt2	5.96	49.28	7.14	2.48		30.25	0.67	4.23
GG-K-01(1)_pt3	6.21	51.25	6.54	2.19		27.66	2	4.16
GG-K-01(1)_pt4	5.8	50.94	7.99	2.21		27.82	0.98	4.25
GG-K-01 Atom %	C	O	Na	Mg	Al	Si	K	Ca
GG-K-01(1)_pt1	10.11	57.74	10.68	1.69		17.04	1.05	1.7
GG-K-01(1)_pt2	9.56	59.37	5.99	1.97		20.76	0.33	2.03
GG-K-01(1)_pt3	9.88	61.2	5.43	1.72		18.81	0.98	1.98
GG-K-01(1)_pt4	9.24	60.91	6.65	1.74		18.95	0.48	2.03

Table 9. EDX results for GG-K-o.5 sample.

GG-K-05 Net Counts	C	O	Na	Mg	Al	Si	K	Ca
GG-K-05(1)_pt1	2753	77341	40870	6895		139478	24312	12348
GG-K-05(1)_pt2	2783	53977	36944	5654		115284	21908	11249
GG-K-05(1)_pt3	697	41853	7472	5513		117700	18430	13350
GG-K-05(1)_pt4	1962	84409	33937	7594	1473	151665	22733	13934
GG-K-05 Weight %	C	O	Na	Mg	Al	Si	K	Ca
GG-K-05(1)_pt1	4.83	51.99	11.28	1.54		21.72	5.48	3.15
GG-K-05(1)_pt2	6.13	48.14	12.29	1.55		22.11	6.09	3.54
GG-K-05(1)_pt3	2.15	51.92	3.44	1.82		28.33	6.77	5.57
GG-K-05(1)_pt4	3.42	54.04	9.28	1.63	0.25	22.91	5.01	3.46
GG-K-05 Atom %	C	O	Na	Mg	Al	Si	K	Ca
GG-K-05(1)_pt1	7.74	62.51	9.44	1.22		14.88	2.69	1.51
GG-K-05(1)_pt2	9.91	58.39	10.37	1.24		15.27	3.02	1.72
GG-K-05(1)_pt3	3.6	65.3	3.01	1.51		20.3	3.48	2.8
GG-K-05(1)_pt4	5.51	65.29	7.81	1.29	0.18	15.77	2.48	1.67

Table 8 shows the EDX results for the GG-K-0.1 sample. The "Net Counts" columns provide the number of counts recorded for each element, and the "Weight %" and "Atom %" columns represent the weight percentages and atom percentages of the respective elements in the sample. The elements analysed include carbon (C), oxygen (O), sodium (Na), magnesium (Mg), aluminium (Al), silicon (Si), potassium (K), and calcium (Ca). The measurements were taken at multiple points labelled as GG-K-01(1)_pt1, GG-K-01(1)_pt2, GG-K-01(1)_pt3, and GG-K-01(1)_pt4.

Table 9 presents the EDX results for the GG-K-0.5 sample, following the same format as Table 8. Similarly, the measurements were taken at multiple points labelled as GG-K-05(1)_pt1, GG-K-05(1)_pt2, GG-K-05(1)_pt3, and GG-K-05(1)_pt4. Comparison and analysis of the results for the two samples provide valuable information regarding the indicators for a successful alkali-activation process at the microstructural level.

The net counts represent the number of X-ray counts recorded for each element. These values indicate the abundance of elements present in the samples. In both GG-K-0.1 and GG-K-0.5 samples, silicon (Si) consistently exhibits the highest net counts, indicating its prevalence. The weight percentages provide information about the relative mass fraction of each element in the samples. In GG-K-0.1, silicon (Si) and aluminium (Al) weight percentages are relatively higher than other elements. In GG-K-0.5, the weight percentages of silicon (Si) and aluminium (Al) are also significant, but potassium (K) and calcium (Ca) show relatively higher weight percentages compared to GG-K-0.1.

The atom percentages represent the relative atomic fraction of each element in the samples. In GG-K-0.1 and GG-K-0.5, oxygen (O) exhibits the highest atom percentages, indicating its strong presence in the samples. Silicon (Si) and aluminium (Al) also show relatively high atom percentages in both samples. Comparing GG-K-0.1 and GG-K-0.5, in terms of elemental composition, GG-K-0.1 and GG-K-0.5 show similarities, with silicon (Si) and aluminium (Al) being prominent elements. However, there are notable differences in other elements' weight and atom percentages. The GG-K-0.5 sample shows relatively higher weight percentages of potassium (K) and calcium (Ca) than GG-K-0.1. This fact suggests that the alkali-activation process with GG-K-0.5 resulted in a higher incorporation of potassium and calcium in the activated glass structure. The difference in elemental content between GG-K-0.1 and GG-K-0.5 samples might contribute to the variations in their mechanical properties and strength, as discussed earlier.

In the subsequent stage of mortar design, an investigation was undertaken to examine the impact of the particle size distribution of precursor glass on the unconfined compressive strength of the mortar. The objective of this test was twofold: first, to reduce the time and energy required for grinding the crushed glass, and second, to ensure a reasonable level of reactivity and strength development during the alkali-activation process. Three new mortar specifications were designed by altering the GG-K-0.4 mix by incorporating the original reclaimed crushed glass powder (Glass-0). The ratios of Glass-0 to ground glass powder (Glass-20) were set at 1, 1.5, and 2.33, resulting in GPG-K-1-0.4, GPG-K-1.5-0.4, and GPG-K-2.33-0.4, respectively. Table 10 provides detailed information regarding the redesigned mix mortars. It is important to note that the specifications listed in the table are based on the mortar mix prepared for three individual samples per redesign mix to ensure the consistency and accuracy of the results. For each mix design, three samples were carefully prepared in the same cubic moulds, subjected to identical curing conditions as previous samples, and tested using the same procedures.

Table 10. Redesigned mix details of alkali-activated mortars.

Mix ID	Glass-0 (g)	Glass-20 (g)	Activator/ Precursor	Activator (g)
GPG-K-1-0.4	292.50	292.50	0.40	234.00
GPG-K-1.5-0.4	351.00	234.00	0.40	234.00
GPG-K-2.33-0.4	409.32	175.68	0.40	234.00

Figure 26 visually represents the redesigned samples after failure. Visual examination of failure types in the redesigned samples reveals their tendency to fail at lower axial deformation (1mm and 2mm) compared to the original GG-K-0.4 samples (2mm and 3mm).

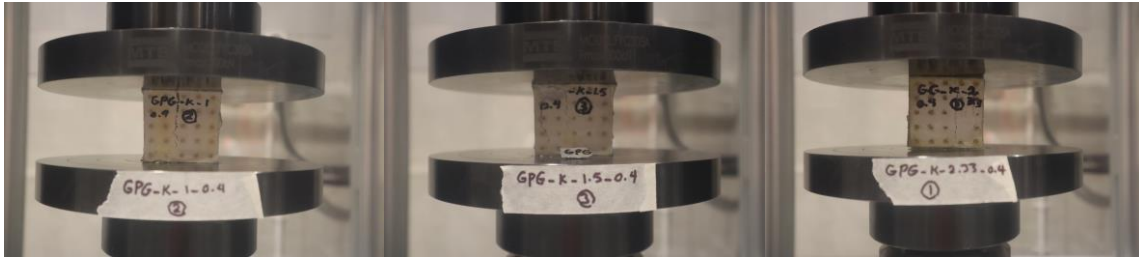


Figure 26. Samples of the redesigned alkali-activated mortars after failure.

Figure 27 shows the stress-related behaviour of the redesigned mortars during unconfined compressive strength tests, illustrating the load versus deformation relationship. The results obtained from these tests indicate that the activity of the mortar diminishes as the particle size increases, which aligns with the expected behaviour. This reduction in activity influences the peak strength and overall behaviour of the cured alkali-activated material.

Notably, there is a gradual decline in the strength of the cured mortar with an increase in the Glass-0 to Glass-20 ratio, signifying the effect of particle size on the mortar’s strength characteristics. These findings provide crucial insights into the relationship between particle size distribution and the unconfined compressive strength of the mortar and highlight the importance of optimising particle size distribution to achieve the desired strength and reactivity in the alkali-activation process at the same time as reducing the embedded time and energy of the alkali-activated material.

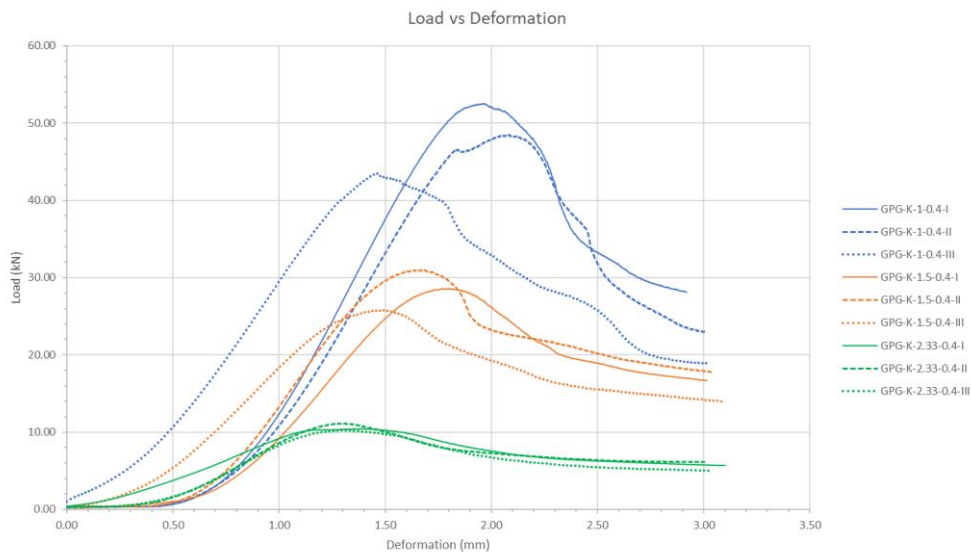


Figure 27. Load versus deformation graph for the redesigned alkali-activated mortars.

Figure 28 and Table 11 show the unconfined compressive strength of the three samples of the redesigned mortar mixes. The compressive strength of all the redesigned mortars decreased compared with the original mix, GG-K-0.4. By increasing the ratio of Glass-0/Glass-20 in the redesigned samples, the average compressive strength of the cured material decreases from 19.3 to 4.3 MPa. The highest average strength belongs to GG-K-1-0.4 at 19.3 MPa, which has a precursor of a one-to-one mix of Glass-0 to Glass-20. This value of 19.3 MPa falls within the range of moderate strength and is generally considered suitable for applications requiring moderate strength. Therefore, it is selected as the optimised mortar for the subsequent project stage when glass mortar is used as a binder for stabilising pumice sand.

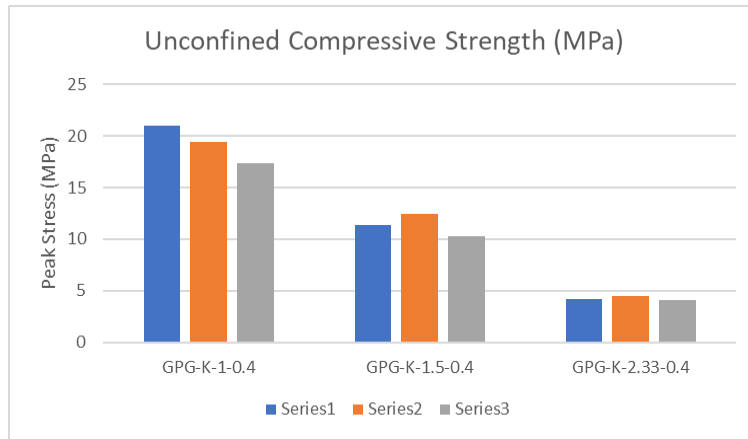


Figure 28. Unconfined compressive strength of the three series of redesigned alkali-activated mortars.

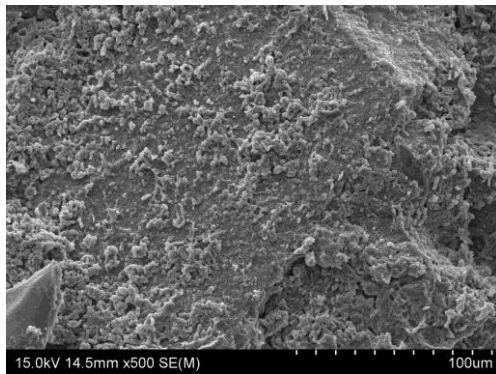
Table 11. Peak unconfined compressive strength of the redesigned alkali-activated mortar.

Sample ID	Peak Strength (MPa)			
	Sample 1	Sample 2	Sample 3	Average
GPG-K-1-0.4	21	19.4	17.4	19.3
GPG-K-1.5-0.4	11.4	12.4	10.3	11.4
GPG-K-2.33-0.4	4.2	4.5	4.1	4.3

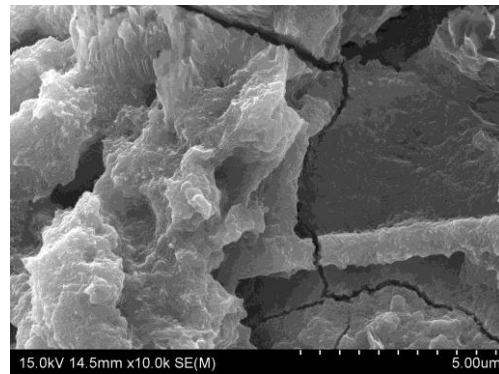
The microstructure of the three samples, GPG-K-1-0.4, GPG-K-2-0.4, and GPG-K-2.33-0.4, were examined through SEM analysis, and the results are presented in Figure 29. Visual examination of the samples allows for observations of their microstructural characteristics. It is evident that GPG-K-1-0.4, as shown in Figure 29 (1-b), exhibits a more coherent microstructure than the other two samples.

The microstructure of GPG-K-1-0.4 appears to be well-formed and cohesive, indicating the presence of a fine matrix of glass binder that effectively encapsulates the larger crushed glass particles. In contrast, the microstructure of GPG-K-2.33-0.4, as shown in Figure 29 (e-f), reveals a lack of binder. This absence of a sufficient amount of glass binder results in an insufficient formation of a fine matrix to encapsulate the larger crushed glass particles.

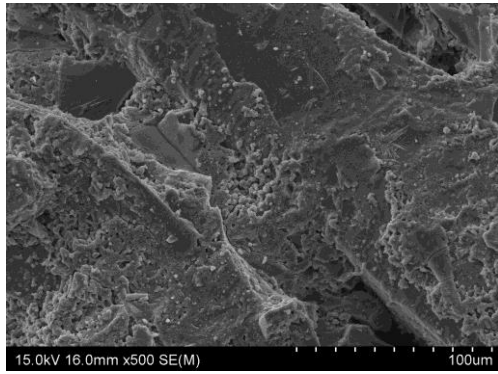
These observations align with the strength characteristics previously discussed, where the lack of binder in GPG-K-2.33-0.4 is expected to cause the weakened mortar. It should be noted that samples used for the SEM/EDX analysis were taken from the specimens after the completion of the strength tests. Therefore, the microcracks observed in the SEM results are likely a result of the propagation of tension cracks during the strength tests.



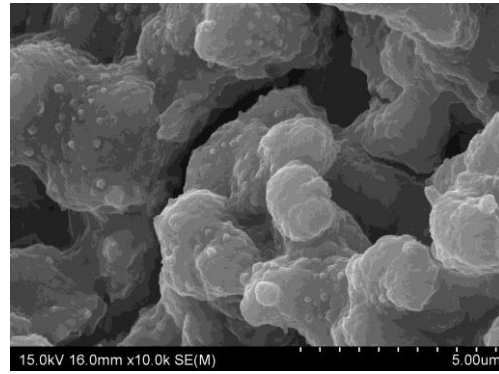
(a) GPG-K-1-0.4 (x500)



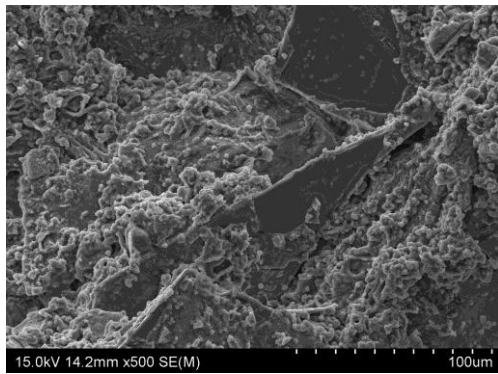
(b) GPG-K-1-0.4 (x10,000)



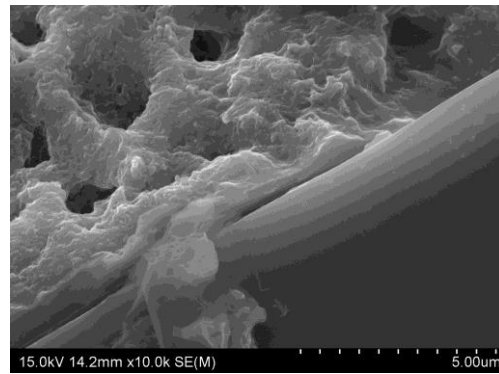
(c) GPG-K-1.5-0.4 (x500)



(d) GPG-K-1.5-0.4 (x10,000)



(e) GPG-K-2.33-0.4 (x500)



(f) GPG-K-2.33-0.4 (x10,000)

Figure 29. SEM results for (a-b) GPG-K-1-0.4, (c-d) GPG-K-1.5-0.4, and (e-f) GPG-K-2.33-0.4.

1.5.4 Strength Characteristics of the Stabilised Soil Using UCS Test

The subsequent phase of the research focuses on employing an optimised binder mix for stabilising pumice soil. A comprehensive test plan was developed involving cylindrical split moulds with a diameter of 70mm and a length of 140mm. These moulds were selected for the construction and curing of stabilised pumice soil specimens based on the dimensions of the largest pumice grain (<7mm) for UCS tests.

The optimised mortar mix, GPG-K-1-0.4, was chosen as the binder for this experiment. It was mixed with coarse pumice sand, which served as the aggregate component. Three different precursor to aggregate ratios were considered 0.3, 0.4, and 0.5. The materials were thoroughly mixed for five minutes using a desktop mixer, and the resulting mixture was poured into the moulds and placed on a vibrating table. This process ensured the elimination of any air voids within the mix.

A 40% by-weight water was premixed with the pumice sand 24 hours before being mixed with the mortar to enhance the workability of the mix and provide enough moisture for the alkali-activation process. Given the larger volume of the samples compared to the mortar samples, a modified curing regime was implemented. This regime involved subjecting the specimens to 72 hours of curing at 80 degrees Celsius, followed by an additional 24 hours at room temperature. This modified regime promotes optimal curing conditions and achieves reliable and consistent results. Three samples were constructed for each mix, ensuring consistency and accuracy checks throughout the experimentation process.

Table 12 provides detailed information regarding the mix compositions, offering insights into each sample's specific proportions of the binder mix, pumice sand, and moisture content. These details play a crucial role in evaluating the performance and characteristics of the stabilised pumice soil under

unconfined compressive strength testing.

Table 12. Mix details of stabilised pumice coarse.

Mix ID	Aggregate (g)	Aggregate Moisture (g)	Precursor/Aggregate	Glass-0 (g)	Glass-20 (g)	Activator/Precursor	Activator (g)
GPG-PC-K-0.30	2200	880	0.3	330	330	0.4	264
GPG-PC-K-0.40	2200	880	0.4	440	440	0.4	352
GPG-PC-K-0.50	2000	800	0.5	500	500	0.4	400

After the designated curing period, all the samples were removed from the moulds for further evaluation. However, it should be noted that the samples from the GPG-PC-K-0.30 series did not exhibit sufficient cohesion and strength to be extracted intact. As a result, these samples were excluded from the UCS test plan. This exclusion concluded that a minimum precursor to the aggregate ratio of 0.4 is necessary for proper cohesion and bonding between the uncompacted pumice sand particles.

Although the GPG-PC-K-0.30 series did not meet the requirements for the UCS testing, the potential of utilising this ratio was still investigated in terms of the strength characterisation of the stabilised soil using the California Bearing Ratio (CBR) testing. Subjecting the samples to CBR testing made it possible to assess the strength and load-bearing capacity of the stabilised soil under specific conditions. This additional testing allowed for a comprehensive understanding of the performance and suitability of the stabilised soil with a precursor to the aggregate ratio of 0.3, expanding the characterisation beyond just the unconfined compressive strength evaluation.

Cured samples of GPG-PC-K-0.40 and GPG-PC-K-0.50 underwent testing using the Universal Testing Machine to assess their UCS value. Figure 30 presents images of the stabilised pumice coarse samples for these specific mix designs, showcasing their appearance both before the test and after experiencing failure.

To better understand the mechanical behaviour of the stabilised coarse pumice samples, Figure 31 illustrates the stress-related response of these samples during the unconfined compressive strength tests. This graph shows the relationship between load and deformation, providing valuable insights into the performance of the samples. The results indicate an increase in the strength of the stabilised soil as the precursor/aggregate ratio increases, aligning with expectations. Within each group of samples, consistent outcomes are observed regarding stress-strain behaviour. Samples with a higher ratio of precursor to aggregate display more distinctive peak strength, followed by a sudden loss in strength after failure. On the other hand, samples with a lower ratio of precursor to aggregate exhibit lower strength and a more gradual deformation following failure.



Figure 30. Samples of stabilised pumice coarse before and after failure.

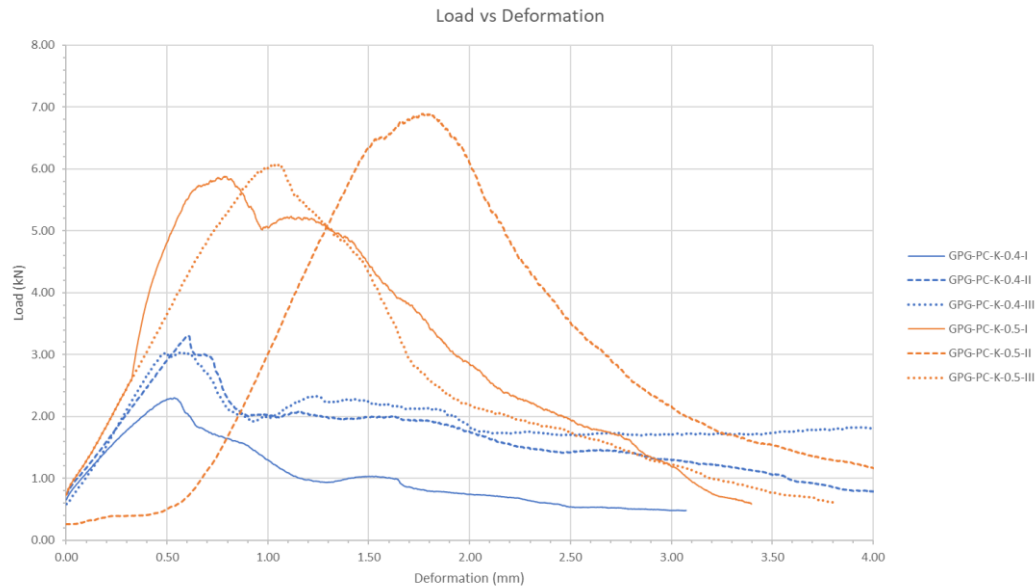


Figure 31. Load versus deformation graph for the UCS tests on stabilised coarse pumice samples.

Figure 32 and Table 13 present the unconfined compressive strength results obtained from the three samples of stabilised pumice soil for each mix design. The data reveals important insights into the performance of the stabilised soil samples. Specifically, the average compressive strength of the GPG-PC-K-0.5 samples exceeds more than double that of the GPG-PC-K-0.4 samples. Despite this difference, the peak strength values within each group of samples exhibit close agreement.

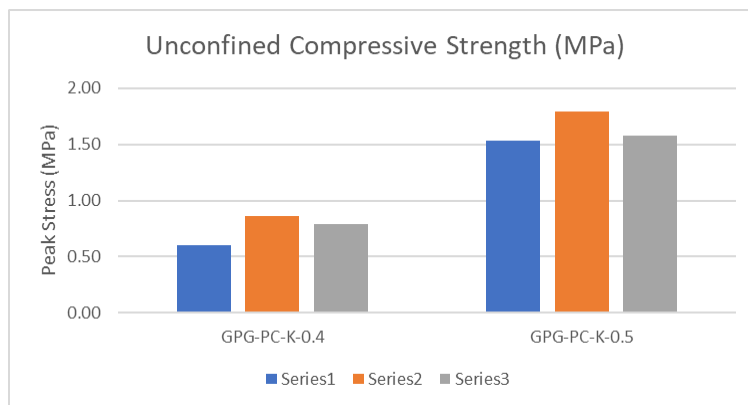


Figure 32. Unconfined compressive strength of the three series of stabilised pumice coarse samples.

Table 13. Peak unconfined compressive strength of the stabilised pumice coarse samples.

Sample ID	Peak Strength (MPa)			
	Sample 1	Sample 2	Sample 3	Average
GPG-PC-K-0.4	0.60	0.86	0.79	0.7
GPG-PC-K-0.5	1.53	1.79	1.58	1.6

The results of the UCD test of stabilised, unconfined coarse pumice soil provide strong evidence of the successful application of the proposed alkali-activation process in stabilising pumice soil. However, it is essential to conduct further investigation to determine the optimal values of pumice moisture content and precursor to aggregate ratio, considering different strengths and behavioural requirements. By refining these parameters, it will be possible to fine-tune the stabilisation process and optimise the performance of the stabilised pumice soil for specific applications. Further research would be required to enhance the effectiveness and reliability of the alkali-activation process, enabling the tailored

development of stabilised pumice soil with desired strength and characteristics.

1.5.5 Strength Characteristics of the Stabilised Soil Using CBR Test

The strength characteristics of stabilised pumice soil using the proposed alkali-activation binder were examined following the standardised California Bearing Ratio (CBR) test procedure. The CBR test is a laboratory test widely employed to assess soil's mechanical strength and load-bearing capacity. It is commonly conducted on soil samples to determine their suitability for pavement design and construction.

The test entails subjecting the soil to controlled conditions and measuring the resistance a plunger encounters as it penetrates the soil. The primary objective of this test is to evaluate the relative strength of a soil sample by comparing its resistance to penetration with that of standard material, typically crushed stone or well-graded aggregates. By doing so, engineers and geotechnical professionals can gather valuable information about the capacity of soil to withstand applied loads and its appropriateness for various construction applications.

Table 14 provides a comprehensive overview of the materials and methods for preparing each sample. The terms "Light" and "Heavy" in the table denote the sample preparation technique, with "Light" referring to the three-layer compaction method and "Heavy" indicating the use of the five-layer CBR compaction technique. The term "Cured" signifies that the samples underwent a curing regimen of 72 hours at 80 degrees Celsius, followed by 24 hours at room temperature before testing.

The preparation of the remolded "Rem" samples began with sieving the coarse pumice soil to eliminate finer particles, utilising only particles that passed through a 20mm sieve and were retained on a 4.75mm sieve. In the sample IDs, "PS" represents pumice sand, "0.4" corresponds to the moisture content of the pumice sand, "5C" indicates five-layer compaction, "GPG" signifies the inclusion of the reclaimed glass precursor in the sample, "0.3" denotes the ratio of precursor to pumice sand, "K" indicates the addition of KOH for alkali-activation process. Finally, "R" implies using remoulded pumice sand in the sample.

By conducting the CBR test and employing the abovementioned sample preparations, we aimed to assess the strength characteristics of the stabilised pumice soil. Incorporating alkali-activation binders and reclaimed glass in the samples adds a novel dimension to the investigation. These tests allow for a comprehensive understanding of the performance of the stabilised pumice soil under various conditions, aiding in the refinement of the stabilisation process and optimising the soil behaviour for specific applications.

Table 14. Peak unconfined compressive strength of the stabilised pumice coarse samples.

Sample ID	Coarse Pumice (g)	Moisture (%)	Glass-0 (g)	Glas-20 (g)	10M KOH (g)	Water (g)	Method
CBR-PS-0.4	1	0.4	0	0	0	0	Light
CBR-PS-0.4-5C	1	0.4	0	0	0	0	Heavy
CBR-PS-0.4-GPG-0.3-K	1	0.4	0.15	0.15	0.12	0	Light - Cured
CBR-PS-0.4-GPG-0.3-K-5C	1	0.4	0.15	0.15	0.12	0	Heavy - Cured
CBR-PS-0.4-5C-R	1	0.4	0	0	0	0	Heavy - Rem
CBR-PS-0.4-R	1	0.4	0	0	0	0	Light - Rem
CBR-PS-0.4-GPG-0.3-R-5C	1	0.4	0.15	0.15	0	0.12	Heavy - Rem
CBR-PS-0.4-GPG-0.3-R	1	0.4	0.15	0.15	0	0.12	Light - Rem

At the outset, two samples of each mix design were prepared and tested to gauge the accuracy of the results. Additional tests were conducted in some cases to ensure the required precision based on the

obtained accuracy. The results of these CBR tests for the two samples with acceptable accuracy are presented in Table 15. The CBR values presented in this table reflect the load-bearing capacity of the tested soil samples. Higher CBR values indicate greater strength and load-bearing capacity of the soil. Among the various mix designs tested, several samples demonstrate relatively high CBR values, such as CBR-PS-0.4-GPG-0.3-K-5C-II (CBR_{2.5}: 35.02, CBR_{5.0}: 67.63) and CBR-PS-0.4-GPG-0.3-K-I (CBR_{2.5}: 33.36, CBR_{5.0}: 44.80). These samples exhibit robust resistance to penetration and possess higher load-bearing capacities, signifying their ability to withstand applied loads effectively.

Table 15. CBR test results for stabilised pumice soils in different settings.

Mix ID	CBR _{2.5}	CBR _{5.0}
CBR-PS-0.4-I	19.37	21.05
CBR-PS-0.4-II	22.39	22.23
CBR-PS-0.4-5C-I	31.83	33.20
CBR-PS-0.4-5C-II	32.99	32.38
CBR-PS-0.4-GPG-0.3-K-I	33.36	44.80
CBR-PS-0.4-GPG-0.3-K-II	33.35	39.16
CBR-PS-0.4-GPG-0.3-K-5C-I	30.03	61.77
CBR-PS-0.4-GPG-0.3-K-5C-II	35.02	67.63
CBR-PS-0.4-5C-R-I	26.56	24.25
CBR-PS-0.4-5C-R-II	24.75	22.08
CBR-PS-0.4-R-I	12.55	12.34
CBR-PS-0.4-R-II	14.46	12.87
CBR-PS-0.4-GPG-0.3-R-5C-I	33.21	34.54
CBR-PS-0.4-GPG-0.3-R-5C-II	36.66	33.25
CBR-PS-0.4-GPG-0.3-R-I	24.04	23.83
CBR-PS-0.4-GPG-0.3-R-II	24.13	23.48

Table 16 includes the unit difference and percentage difference between CBR_{2.5} and CBR₅ for each pair of samples. This table provides valuable information regarding the variations between CBR values obtained from different tests and the corresponding percentage differences. This accuracy check assesses the consistency and reliability of the CBR test results, providing insight into the level of agreement among repeated tests and the precision of the measurements. Most mix designs exhibit small differences and percentages, indicating consistent and accurate test results. However, certain mix designs, such as CBR-PS-0.4-GPG-0.3-K-5C and CBR-PS-0.4-R, exhibit slightly larger differences and percentages, although they still fall within the acceptable range.

Table 16. CBR accuracy checks for the stabilised soil samples.

Mix ID	Unit Difference		Percentage Difference	
	CBR _{2.5}	CBR _{5.0}	CBR _{2.5}	CBR _{5.0}
CBR-PS-0.4	3.03	1.19	13.52%	5.35%
CBR-PS-0.4-5C	1.16	0.81	3.53%	2.45%
CBR-PS-0.4-GPG-0.3-K	0.02	5.64	0.06%	12.58%
CBR-PS-0.4-GPG-0.3-K-5C	4.99	5.86	14.25%	8.67%
CBR-PS-0.4-5C-R	1.81	2.18	6.82%	8.97%
CBR-PS-0.4-R	1.91	0.52	13.18%	4.07%
CBR-PS-0.4-GPG-0.3-R-5C	3.44	1.29	9.39%	3.74%
CBR-PS-0.4-GPG-0.3-R	0.09	0.35	0.38%	1.48%

Figure 33 shows the CBR graphs for all the samples, with the legend arranged in ascending order of ultimate performance at 12.5mm penetration. It is important to note that the raw results are presented in this graph without applying the zero correction. The graph illustrates that CBR-PS-0.4-GPG-0.3-K-

5C samples exhibit the highest ultimate strength, while CBR-PS-0.4 samples display the lowest. These results allow for interpretation regarding the impact of several parameters on the strength gain of the stabilised pumice sand, as follows.

The first parameter to consider is the effect of compaction on soil strength. Comparing identical mix designs, it becomes evident that samples subjected to higher compaction efforts using 5-layer compaction exhibit greater strength than those prepared using 3-layer compaction. This observation aligns with the initial expectations.

The presence of fine particles in the soil mix represents the next parameter and its influence on the strength of the stabilised soil. The CBR-PS-0.4 and CBR-PS-0.4-5C samples solely consist of remoulded pumice sand, lacking particles finer than 4.75mm, which explains their relatively weaker performance. Comparing each pair of identical mix designs, and differentiating them using remoulded pumice sand, further supports the hypothesis that the presence of fine particles contributes to the strength of the stabilised soil. The same conclusion is evident when comparing the CBR-PS-0.4 graph with the CBR-PS-0.4-R graph and the CBR-PS-0.4-5C graph with the CBR-PS-0.4-5C-R graph.

Another confirmation of this hypothesis is achieved by comparing two samples, one with the addition of a non-activated precursor, by comparing the CBR-PS-0.4-R graph with the CBR-PS-0.4-GPG-0.3-R graph and the CBR-PS-0.4-5C graph with the CBR-PS-0.4-GPG-0.3-R-5C graph. In both cases, the only distinction between the former and latter samples is the addition of the precursor (a mixture of Glass-0 and Glass-20) to the latter samples, with a precursor to pumice sand ratio of 0.3. Despite not being activated (due to the absence of KOH activator in these samples), the added glass mix is believed to compensate for the lack of fines in the remoulded samples. This observation further confirms that fines can aid in stabilising pumice sand. However, additional research is required to validate this finding and investigate the optimal percentage and particle size distribution of added fines based on specific project requirements.

Lastly, relevant graphs can be compared to examine the role of the proposed alkali-activation process utilising reclaimed crushed glass for stabilising pumice soil. Although the graph indicates that the best-performing pairs, CBR-PS-0.4-GPG-0.3-K and CBR-PS-0.4-GPG-0.3-K-5C, are those stabilised using the proposed process, further analysis can enhance our understanding of this aspect. CBR-PS-0.4-GPG-0.3-K is prepared by adding the proposed alkali-activated binder to the same mix as CBR-PS-0.4 and following the curing process. The same applies to CBR-PS-0.4-GPG-0.3-K-5C compared to CBR-PS-0.4-5C, where the former samples are prepared using the proposed alkali-activated binder and cured using the previously discussed process. In both cases, the CBR graphs demonstrate superior strength gain in samples stabilised using the proposed alkali-activation process, providing evidence of the effectiveness of this innovation for stabilising pumice sand in road subgrades. While these results confirm the project's objectives, they also open the door for further investigation, research, and potential application of the proposed process in road construction.

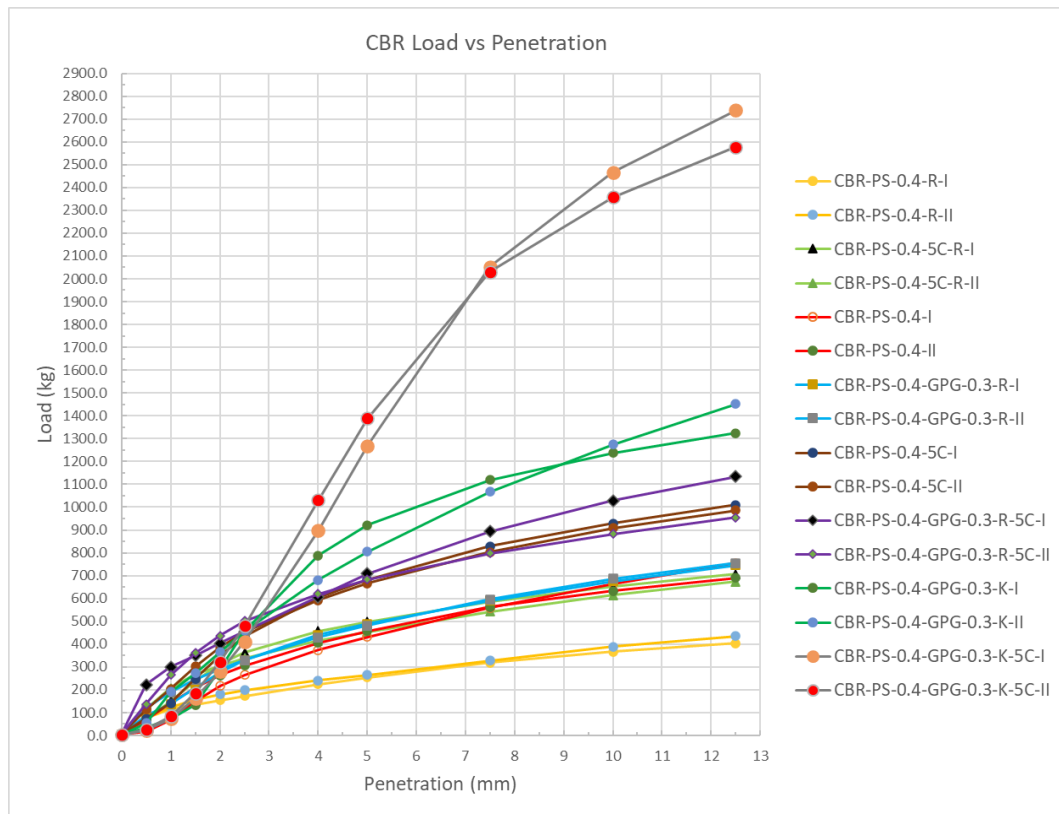


Figure 33. CBR graphs for stabilised pumice soils in different settings.

1.6 Life Cycle Assessment for Stabilisation of Pumice Soil Using the Proposed Alkali-Activated Binder Compared with Cement and Lime

The production of Ordinary Portland Cement (OPC) is well-known for its significant contribution to CO₂ emissions due to the calcination process of obtaining limestone (Pradhan, Kumar, & Barai, 2020). In response to this environmental concern, there has been a growing interest in alternative building materials that offer lower environmental impacts. Alkali-activated materials (AAMs) and geopolymers (GPs) have emerged as promising options, as they demonstrate the potential to reduce energy requirements and global warming potential while maintaining comparable compressive strength to OPC (Provis & Bernal, 2014).

AAMs and GPs are considered sustainable construction materials due to their ability to minimise the environmental impact associated with OPC production (Shoaei et al., 2022). Common precursors used in AAM production include ground granulated blast furnace slag (GGBFS), fly ash (FA), and metakaolin (MK) (Samson, Cyr, & Gao, 2017). However, the availability and sustainability of these materials raise concerns due to environmental regulations and economic considerations (Mohajerani et al., 2019). A potential alternative precursor for AAM production is reclaimed glass powder. This material exhibits alkaline characteristics due to soda (sodium oxide) and lime (calcium oxide) fluxing agents. By utilising reclaimed glass powder, the environmental impact of the production process can be reduced (Rodier & Savastano Jr, 2018).

When conducting a life cycle assessment (LCA) for AAMs, selecting an appropriate functional unit (FU) is crucial. While 1 m³ of mortar is commonly used as an FU in the literature, other FUs, such as 1 kg or 1 ton, can be employed for studies focusing on AAM binders or pastes. Comparability between alternatives is ensured using FUs that measure strength grades or the required mortar/concrete volume per unit of strength. Some studies adopt FUs that consider environmental emissions (mainly CO₂-eq) divided by mechanical properties, such as compressive strength.

Based on literature reviews, AAMs demonstrate lower environmental impacts than PC mortars, even when their mechanical strength is lower (Provis & Bernal, 2014). While recycled products are often assumed to be burden-free, it is essential to consider transportation, collection, and processing impacts. Although AAMs generally exhibit a lower carbon footprint than traditional concrete, assessing the precise environmental benefits of GP compared to OPC proves challenging due to variations in materials and methods across studies. However, utilising reclaimed glass powder as a precursor in AAM production holds promise for environmental advantages. This material can be employed as a cement substitute and soil stabiliser, particularly in road construction projects (Rodier & Savastano Jr, 2018).

This technology offers several advantages by reducing the consumption of raw materials for OPC and considering climate change regulations, waste glass reuse, and stabilisation of soil in road construction. This section of the report includes an LCA study to investigate the reuse of reclaimed glass in the alkali-activation process under local conditions compared to conventional stabilisers. The Waka Kotahi Life Cycle Assessment of Pavements (LCAP) tool is employed to investigate the global warming potential of soil stabilisation in three scenarios as follows:

- Scenario 1: Soil stabilisation using alkali-activation technology with reclaimed glass.
- Scenario 2: Soil stabilisation using cement.
- Scenario 3: Soil stabilisation using lime.

LCA studies comparing laboratory test results with industry practice by considering the scale effect can provide valuable insights into the environmental performance of different materials and technologies. However, there are potential limitations and essential considerations that should be taken into account for a comprehensive and fair comparison in such studies, as outlined below:

- **Laboratory vs. Real-world Conditions:** Laboratory tests often provide controlled environments that may not fully represent the real-world conditions of material production and application. Factors such as variations in raw material quality, production techniques, transportation distances, and local infrastructure can significantly impact the environmental performance of materials when scaled up to industrial levels. Acknowledging these limitations when comparing lab results with industry practice is essential.
- **Scale Effect:** The scale at which materials are produced and used can influence their environmental impacts. In many cases, the production processes for alternative materials such as AAMs may not be as mature or optimised as those for conventional materials like cement and lime. Large-scale production of AAMs might have different environmental implications compared to small-scale laboratory production. Therefore, it is important to consider the scale effect when extrapolating the results of lab-scale studies to real-world scenarios.
- **Boundaries and Systematic Effects:** LCA studies involve defining system boundaries and accounting for all relevant life cycle stages, including raw material extraction, manufacturing, transportation, use, and end-of-life disposal. However, capturing all interconnected effects and impacts throughout the life cycle can be challenging. For instance, the transportation and processing impacts of reclaimed glass or other precursors should be considered in addition to their recycled benefits. Ensuring comprehensive and accurate data collection is crucial to obtaining reliable results.
- **Variability in Study Parameters:** LCA studies rely on various assumptions and parameters, such as functional units, allocation methods, and impact assessment models. These choices can significantly influence the outcomes and comparability of different alternatives. Sensitivity analysis should be performed to assess the robustness of the results and understand the impacts of various parameters on the overall conclusions.

Since the scope of this project focuses on the feasibility study of utilising alkali-activated reclaimed glass for stabilising pumice sand in the subgrade of roads, it is important to acknowledge the limitations and assumptions made for a fair comparison among the outcome of different tools, such as LCAP, SimaPro, GaBi, openLCA software, etc. It is recognised that further research and studies would be necessary to scale up the current project to a comparable real-world practice, allowing for more realistic data measurements to inform the LCA.

At this stage, the processes and parameters involved in the mentioned scenarios are assumed to be similar, with the differentiating factors primarily related to the production of the stabiliser agents for subgrade improvement. Assumptions are made to maintain consistency in the analysis, and typical values for road construction are considered. However, it is essential to note that these assumptions may not fully capture all the complexities and variations in real-world applications.

The road dimensions considered are 7m × 1km, a 2-lane road with a 1.6% annual traffic volume growth rate, a 2.7% annual increase in driving (fuel) efficiency (Government, 2016), a 25-year life, and a 1% assumed environmental discount of impacts to account for annual technology efficiency improvements consistent in all scenarios. In addition, all the variables except the soil stabilisation method are assumed to be the same. The ratio of mortar to soil is considered 0.3 for the soil stabilisation process using reclaimed glass. The details of road layers are shown in Table 17. The energy consumption of the powdered glass waste grinding process is assumed to be 0.072 MJ (in the form of electricity) (Bianco, Tomos, & Vinai, 2021). Although the reclaimed glass used in this laboratory testing is a mixture of ground and powdered glass, such energy consumption is considered conservative in this research.

Table 17. Parameters used in life cycle assessment study.

Layer	Scenario 1 Reclaimed glass	Scenario 2 Cement	Scenario 3 Lime
Upper Subbase	Aggregate (Hard Rock)	Aggregate (Hard Rock)	Aggregate (Hard Rock)
Subgrade Improvement	Soil stabilisation using alkaline- activated reclaimed glass binder (Custom defined material)	Cement-modified subgrade	Lime-modified subgrade
Subgrade	Pumice Soil	Pumice Soil	Pumice Soil

The environmental impacts of raw materials for the three scenarios are presented in Figure 34. The carbon dioxide emissions of soil stabilisation using cement and lime are 21% and 15% higher than those of the proposed approach of soil stabilisation using reclaimed glass. McLellan et al. (2011) reported that the location, mix design, and application selected for the binders significantly impact the estimated CO₂ saving range from 9% to 97% compared with the Portland cement application.

Supplying the raw materials, especially the activator (e.g., potassium hydroxide or sodium silicates), is crucial in the environmental assessment of alkali activation technology due to energy consumption for high-temperature processing of these materials (Fawer, Concannon, & Rieber, 1999). For instance, previous research identified alkali silicates as the most effective activators in AABs (Fernández-Jiménez & Palomo, 2005; Wang, Scrivener, & Pratt, 1994); however, due to the melting of soda and silica sand in the process of manufacturing sodium silicate activator, such production is quite costly and energy-intensive (Turner & Collins, 2013).

It should be noted that although the activator commonly accounts for less than 10% of CO₂ emissions per ton of AABs, such quantity is still much lower in comparison to CO₂ emissions in Portland cement products (Fawer et al., 1999; Habert et al., 2011; McLellan et al., 2011). In addition, considerable differences are evident in emissions regarding the source of utilised alkali carbonate in terms of chemical and mining routes employed (Provis & Bernal, 2014). The global warming potential

breakdown of carbon dioxide emissions and the annual impacts across a 25-year design life are visible in Figures 35 and 36, respectively.

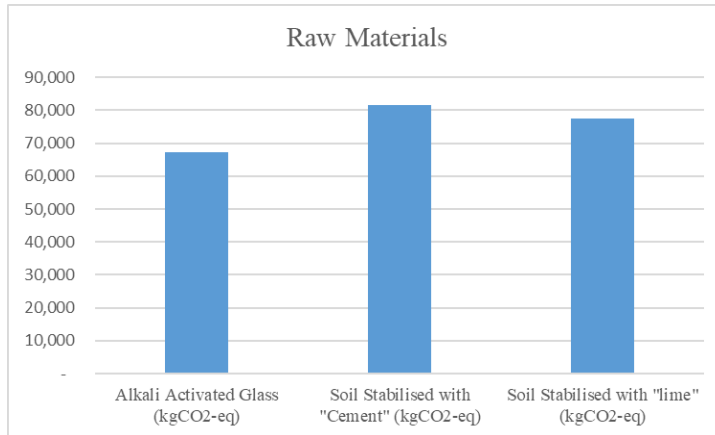


Figure 34. The environmental impacts of raw materials for three scenarios.

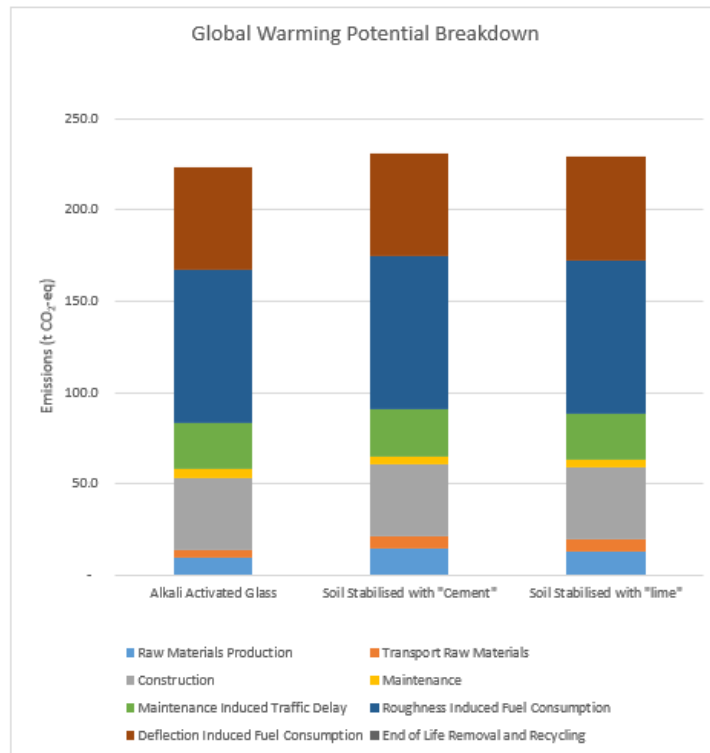


Figure 35. The global warming potential breakdown.

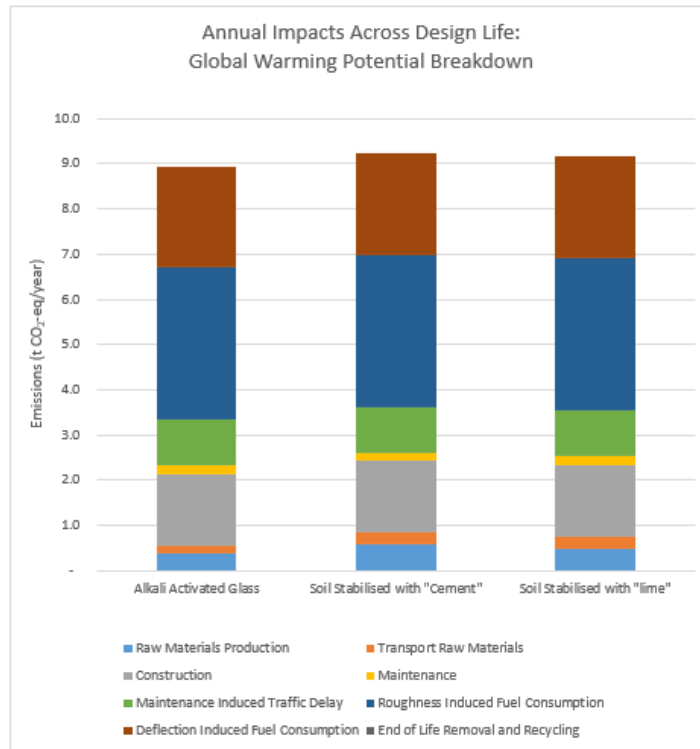


Figure 36. Annual impacts of global warming potential breakdown across 25-year design life.

While the LCA comparing laboratory test results with industry practice is insightful, potential limitations and important considerations should be considered and possibly eliminated for a fair comparison. The following recommendations can be considered for future studies to expand beyond the feasibility stage and encompass a broader range of factors and considerations in the LCS study:

- **Field Testing and Validation:** Conducting field tests and pilot projects to validate the laboratory findings and assess the performance of alkali-activated reclaimed glass compared to cement and lime in actual road construction scenarios. This approach would provide valuable data on the parameters, materials, and methods involved under real-world conditions and will provide sufficient data for a comprehensive LCA study.
- **Comprehensive LCA Analysis:** Expanding the scope of the LCA study to include a wider range of environmental impacts and indicators, such as water consumption, resource depletion, and impacts on the ecosystem. Additionally, considering other life cycle stages, including raw material extraction, waste management, and end-of-life scenarios, can provide a more holistic understanding of the environmental performance of different stabilisation methods.
- **Sensitivity Analysis:** Performing sensitivity analysis to identify the key parameters and assumptions influencing the results and their variability. This analysis would help us understand the uncertainties and robustness of the findings and guide future decision-making processes.
- **Technological Improvements:** Considering the potential for technological advancements and process optimisation in producing and applying alkali-activated materials. Research efforts should focus on developing more efficient and sustainable methods for producing activators and optimising the curing processes to reduce environmental impacts.

Addressing these recommendations and conducting further research and testing can provide a more comprehensive and reliable assessment of the environmental benefits of using alkali-activated reclaimed glass in soil stabilisation for road construction. This approach will enable better-informed decision-making processes and facilitate the adoption of sustainable and environmentally friendly practices in the construction industry.

2. What were some of the challenges you faced (e.g., regulatory barriers, access to data)?

During the research, we encountered several challenges that impacted our work:

- Limited availability of comprehensive data: Accessing relevant and up-to-date data regarding the environmental impact of different stabilisers was a challenge. The lack of standardised data and variations in reporting methodologies hindered our ability to conduct a robust analysis.
- Regulatory barriers: Some regulatory frameworks did not explicitly address using alkali-activated reclaimed glass as a soil stabiliser. For instance, stabilising agents in NZTA (2020b) are limited to chemical stabilising agents as either one or a combination of lime and cement. Binder types included in Gray (2017) are more inclusive but still limited to cement and cementitious blends, including fly ash, lime as hydrated or burnt lime (CaO), hot bitumen, bitumen emulsion, foamed bitumen, granular, and polymer including proprietary polymer materials used as dust suppression and finer soil particle modifier. These lists lack alkali-activated materials overall, specifically the use of reclaimed glass. Lack of specific guidelines and regulations created uncertainty and posed challenges in assessing the feasibility and acceptance of the innovative approach.
- Variability in materials and methods: There was a lack of standardisation in the production and testing methods for alkali-activated materials. This variability introduced uncertainties, making comparing results across different studies and establishing consistent benchmarks challenging.

3. What was the approach you took, and did you achieve your deliverables and milestones?

The research project followed a systematic approach to achieve its objectives and deliverables, as outlined in the project plan, by taking the following key steps:

- Literature review: We extensively reviewed existing studies and research papers to gather relevant information on alkali-activated materials, soil stabilisation, and environmental impacts.
- Laboratory experiments: We performed controlled laboratory experiments to compare the environmental performance of alkali-activated reclaimed glass with cement and lime. These experiments involved sample preparation, testing, and data collection.
- Life cycle assessment (LCA): Based on the laboratory results, we conducted a comprehensive LCA study to evaluate the three scenarios' carbon emissions and global warming potential. This analysis involved LCA data collection, analysis, and interpretation.
- Analysis and recommendations: We analysed the LCA results, considered the limitations and assumptions, and provided recommendations for future studies and actions to enhance the understanding and adoption of sustainable practices in the construction industry.

4. What worked well?

Several aspects of the project worked well, contributing to the successful execution of the research:

- Collaboration and expertise: The project benefited from a multidisciplinary team with diverse expertise in material science, environmental engineering, and construction. The collaborative approach allowed for comprehensive analysis and robust findings.
- Rigorous experimental setup: The laboratory experiments were meticulously designed and

executed, ensuring reliable and reproducible results. Standardised testing protocols were followed to minimise variability and enhance the accuracy of the findings.

- **Methodological soundness:** The LCA study employed recognised methodologies and considered a comprehensive range of environmental impacts. The inclusion of sensitivity analysis provided a deeper understanding of the factors influencing the results.
- **Stakeholder engagement:** Throughout the research, we actively engaged with industry stakeholders, regulatory bodies, and potential end-users. This approach facilitated knowledge sharing, feedback, and validation of our findings and increased the potential for future adoption of alkali-activated reclaimed glass.

5. What didn't work well?

Despite the overall success of the project, some challenges and areas for improvement were identified:

- **Limited sample size:** The laboratory experiments were conducted with a relatively small sample size due to resource constraints. Increasing the sample size could have provided a more statistically significant dataset and validated the findings.
- **External factors:** The research was conducted under controlled laboratory conditions, which may not fully represent real-world scenarios. The influence of external factors such as climate variations, soil composition, and construction practices could not be fully accounted for.
- **Data limitations:** As mentioned earlier, data availability and consistency were a challenge. Some data gaps and uncertainties influenced the accuracy and completeness of the analysis. Additional efforts to gather comprehensive and standardised data would have strengthened the study.

6. What would you do differently next time (e.g., how you allocated resources and funding)?

Based on our experience, there are several areas where we would consider making improvements in future research projects:

- **Resource allocation:** Next time, we will aim to allocate more resources to increase the sample size in laboratory experiments. This approach would enhance the statistical significance of the findings and provide a more robust basis for comparisons.
- **Field testing:** To address the limitations of controlled laboratory conditions, we would allocate resources for field testing and pilot projects. Field trials would allow us to evaluate the performance of alkali-activated reclaimed glass in real-world road construction scenarios, considering the influence of external factors.
- **Enhanced data collection:** We would proactively engage with industry partners and regulatory bodies to improve data availability and standardisation. Collaborating with stakeholders and establishing data-sharing agreements would ensure a more comprehensive and accurate analysis.

7. Has our support led to further opportunities (e.g., further funding, partnerships with other organisations)?

The support provided by the Hoe ki angitū - Innovation Fund has been instrumental in completing this research project. It has also opened further opportunities for collaboration and partnerships. As a result of the project's findings, we have received interest from other organisations, including industry

stakeholders and research institutions, for potential collaborations and partnerships. This initial interest encourages us to initiate further discussions with potential end-users regarding funding opportunities to conduct field trials and expand the scope of our research.

8. How will you accelerate your innovation from here (next steps)?

We would like to outline the need for a more extended research period, broader environmental testing, and the exploration of the practical challenges of implementing our findings in diverse ground conditions. Building on the outcomes of this research project, our next steps to accelerate the innovation and further advance the utilisation of alkali-activated reclaimed glass as a soil stabiliser are as follows:

- **Field testing and pilot projects:** We will pursue opportunities to secure funding and resources to conduct field trials and pilot projects to assess the performance of alkali-activated reclaimed glass under real-world conditions. This research will provide valuable insights into its practical applicability, durability, and effectiveness in road construction.
- **Collaborative initiatives:** We will actively seek collaborations with industry partners, regulatory bodies, and research institutions to share knowledge and exchange expertise. These partnerships will help accelerate the adoption of alkali-activated materials and foster innovation in the construction industry.
- **Continued research and development:** We will continue to invest in research and development to address the limitations and improve the understanding of alkali-activated materials. This approach includes exploring technological advancements, optimising production processes, and conducting further studies to evaluate a broader range of environmental impacts.

9. Highlights

The research project investigated the feasibility of utilising alkali-activated reclaimed glass as a soil stabiliser in road construction. The key highlights of the research include:

- **Demonstrated lower carbon dioxide emissions:** The life cycle assessment indicated a 21% and 15% reduction in carbon dioxide emissions of the proposed approach of soil stabilisation using reclaimed glass compared to soil stabilisation using cement and lime, respectively. The environmental benefits of this approach can contribute to reducing the construction industry's carbon footprint.
- **Feasibility of alkali-activated materials:** The research confirmed the feasibility of using reclaimed glass as a cement substitute and soil stabiliser. The laboratory experiments provided evidence of the potential of alkali-activated materials to improve soil stability and contribute to sustainable road construction practices. A critical activator/precursor ratio (around 0.3) was found to be required for the successful alkali-activation process, beyond which increasing the activator/precursor ratio does not significantly improve the strength of the resulting material. A one-to-one ratio of coarse glass/ground glass was proven effective in reducing the grinding effect while maintaining the activity of the binder. A minimum precursor/aggregate ratio of 0.4 was necessary for bonding between the uncompacted pumice sand particles. The CBR test results demonstrated superior strength gain in samples stabilised using the proposed alkali-activation process, providing evidence of the effectiveness of this innovation for stabilising pumice sand in road subgrades.
- **Recommendations for future actions:** The research report provided recommendations for future studies and actions, including conducting field tests, expanding the scope of the life cycle

assessment, performing sensitivity analysis, and exploring technological improvements. These recommendations aim to enhance the understanding and adoption of sustainable practices in the construction industry.

Overall, the research project has contributed valuable insights into the environmental benefits and potential applications of alkali-activated reclaimed glass, paving the way for further advancements in sustainable road construction.

10. Appendix

Due to the short project time and our focus on establishing a solid scientific foundation for our findings, we strategically decided not to publicly discuss the results or engage in media stories at this stage. We believe it is crucial to ensure the accuracy and integrity of our research before sharing it with a broader audience. This approach allows us to review and validate our findings thoroughly, consider potential implications, and engage in meaningful discussions within the scientific community and relevant stakeholders. While no media stories are currently associated with our research, we remain open to future opportunities to communicate our work and its impact on the public.

11. Reference List

- Aitcin, P.-C. (2000). Cements of yesterday and today: concrete of tomorrow. *Cement and Concrete Research*, 30(9), 1349-1359.
- Alqaisi, R., Le, T. M., & Khabbaz, H. (2020). *Applications of recycled sustainable materials and by-products in soil stabilization*. Paper presented at the Recent Thoughts in Geoenvironmental Engineering: Proceedings of the 3rd GeoMEast International Congress and Exhibition, Egypt 2019 on Sustainable Civil Infrastructures–The Official International Congress of the Soil-Structure Interaction Group in Egypt (SSIGE).
- Andrew, R. M. (2018). Global CO₂ emissions from cement production. *Earth System Science Data*, 10(1), 195-217.
- Attom, M. F., Taqieddin, S. A., & Mubeideen, T. (2000). Shear strength and swelling stabilization of unsaturated clayey soil using pozzolanic material. In *Advances in unsaturated geotechnics* (pp. 275-288).
- Aydilek, A. H., & Arora, S. (2004). Fly ash amended soils as highway base materials. In *Geotechnical Engineering for Transportation Projects* (pp. 1032-1041).
- Bianco, I., Tomos, B. A. D., & Vinai, R. (2021). Analysis of the environmental impacts of alkali-activated concrete produced with waste glass-derived silicate activator—a LCA study. *Journal of cleaner production*, 316, 128383.
- Bondar, D., Lynsdale, C., Milestone, N. B., Hassani, N., & Ramezani-pour, A. A. (2011). Effect of type, form, and dosage of activators on strength of alkali-activated natural pozzolans. *Cement and Concrete Composites*, 33(2), 251-260.
- Cristelo, N., Glendinning, S., Miranda, T., Oliveira, D., & Silva, R. (2012). Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction. *Construction and building materials*, 36, 727-735.
- Cristelo, N., Glendinning, S., & Teixeira Pinto, A. (2011). Deep soft soil improvement by alkaline activation. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, 164(2), 73-82.
- Environment, M. o. t. (2022). Estimates of waste generated in Aotearoa New Zealand. Retrieved from <https://environment.govt.nz/facts-and-science/waste/estimates-of-waste-generated/#types-of-waste-going-to-class-1-landfills>
- Fasihnikoutalab, M. H., Pourakbar, S., Ball, R. J., & Huat, B. K. (2017). The effect of olivine content and curing time on the strength of treated soil in presence of potassium hydroxide. *International Journal of Geosynthetics and Ground Engineering*, 3, 1-10.

- Fawer, M., Concannon, M., & Rieber, W. (1999). Life cycle inventories for the production of sodium silicates. *The International Journal of Life Cycle Assessment*, 4, 207-212.
- Fernández-Jiménez, A., & Palomo, A. (2005). Composition and microstructure of alkali activated fly ash binder: Effect of the activator. *Cement and concrete research*, 35(10), 1984-1992.
- Government, A. (2016). *Improving the efficiency of new light vehicles* Retrieved from https://www.infrastructure.gov.au/sites/default/files/migrated/vehicles/environment/forum/files/Vehicle_Fuel_Efficiency_RIS.pdf
- Gray, W. (2017). Best practice guide for pavement stabilisation August 2017.
- Habert, G., De Lacaillerie, J. D. E., & Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of cleaner production*, 19(11), 1229-1238.
- Hall, B., Grenfell, J., Pandelidi, C., Yaghoubi, J., Chaudry, U., Lyons, M., . . . Feigen, D. (2022). Best practice expert advice on the use of recycled materials in road and rail infrastructure: part A technical review and assessment.
- Hall, B., Grenfell, J., Pandelidi, C., Yaghoubi, J., Lyons, M., O'Connor, G., . . . Xue, S. (2022). Best practice expert advice on the use of recycled materials in road and rail infrastructure: part B sustainability impacts report.
- Hewitt, A. E., Balks, M. R., Lowe, D. J., Hewitt, A. E., Balks, M. R., & Lowe, D. J. (2021). Pumice Soils. *The Soils of Aotearoa New Zealand*, 179-198.
- Hills, T. P., Sceats, M., Rennie, D., & Fennell, P. (2017). LEILAC: Low cost CO₂ capture for the cement and lime industries. *Energy Procedia*, 114, 6166-6170.
- Liu, Y., Shi, C., Zhang, Z., & Li, N. (2019). An overview on the reuse of waste glasses in alkali-activated materials. *Resources, Conservation and Recycling*, 144, 297-309.
- McKinsey. (2022). Laying the foundation for zero-carbon cement. Retrieved from <https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement>
- McLellan, B. C., Williams, R. P., Lay, J., Van Riessen, A., & Corder, G. D. (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of cleaner production*, 19(9-10), 1080-1090.
- Mesfun, R. T., Quezon, E. T., & Geremew, A. (2019). Experimental study of stabilized expansive soil using pumice mixed with lime for subgrade road construction. *International Journal of Research-Granthaalayah*, 7(7), 118-124.
- Mohajerani, A., Suter, D., Jeffrey-Bailey, T., Song, T., Arulrajah, A., Horpibulsuk, S., & Law, D. (2019). Recycling waste materials in geopolymer concrete. *Clean Technologies and Environmental Policy*, 21, 493-515.
- Mohajerani, A., Vajna, J., Cheung, T. H. H., Kurmus, H., Arulrajah, A., & Horpibulsuk, S. (2017). Practical recycling applications of crushed waste glass in construction materials: A review. *Construction and building materials*, 156, 443-467.
- NZTA. (2020a). *PILOT NOTES TO SPECIFICATION FOR IN-SITU SUBGRADE STABILISATION*. Waka Kotahi NZ Transport Agency Retrieved from <https://nzta.govt.nz/assets/resources/pilot-specification-for-in-situ-subgrade-stabilisation/pilot-specification-for-in-situ-subgrade-stabilisation-notes-NZTA-B09-2020.pdf>
- NZTA. (2020b). *PILOT SPECIFICATION FOR IN-SITU SUBGRADE STABILISATION*. Waka Kotahi NZ Transport Agency Retrieved from <https://nzta.govt.nz/assets/resources/pilot-specification-for-in-situ-subgrade-stabilisation/pilot-specification-for-in-situ-subgrade-stabilisation-NZTA-B09-2020.pdf>
- Olivier, J. G., Peters, J. A., & Janssens-Maenhout, G. (2012). Trends in global CO₂ emissions. 2012 report.
- Orense, R. P., Pender, M. J., Hyodo, M., & Nakata, Y. (2013). Micro-mechanical properties of crushable pumice sands. *Géotechnique Letters*, 3(2), 67-71.
- Perera, S. T. A. M., Zhu, J., Saberian, M., Liu, M., Cameron, D., Maqsood, T., & Li, J. (2021). Application

- of glass in subsurface pavement layers: A comprehensive review. *Sustainability*, 13(21), 11825.
- Pourakbar, S., Asadi, A., Huat, B. B., & Fasihnikoutalab, M. H. (2015). Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement. *Transportation Geotechnics*, 3, 24-35.
- Pradhan, S., Kumar, S., & Barai, S. V. (2020). Multi-scale characterisation of recycled aggregate concrete and prediction of its performance. *Cement and Concrete Composites*, 106, 103480.
- Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related alkali-activated materials. *Annual Review of Materials Research*, 44, 299-327.
- Provis, J. L., Palomo, A., & Shi, C. (2015). Advances in understanding alkali-activated materials. *Cement and Concrete Research*, 78, 110-125.
- Provis, J. L., & Van Deventer, J. S. (2013). *Alkali activated materials: state-of-the-art report, RILEM TC 224-AAM* (Vol. 13): Springer Science & Business Media.
- Robayo-Salazar, R. A., Rivera, J. F., & de Gutiérrez, R. M. (2017). Alkali-activated building materials made with recycled construction and demolition wastes. *Construction and building materials*, 149, 130-138.
- Rodgers, L. (2018). Climate Change: The Massive CO₂ Emitter You May Not Know about. 2018. In.
- Rodier, L., & Savastano Jr, H. (2018). Use of glass powder residue for the elaboration of eco-efficient cementitious materials. *Journal of cleaner production*, 184, 333-341.
- Samson, G., Cyr, M., & Gao, X. X. (2017). Formulation and characterization of blended alkali-activated materials based on flash-calcined metakaolin, fly ash and GGBS. *Construction and building materials*, 144, 50-64.
- Scrivener, K. L., & Kirkpatrick, R. J. (2008). Innovation in use and research on cementitious material. *Cement and Concrete Research*, 38(2), 128-136.
- Selby, M., & Hosking, P. (1973). The erodibility of pumice soils of the North Island, New Zealand. *Journal of Hydrology (New Zealand)*, 32-56.
- Shi, C., Krivenko, P., & Roy, D. (2006). Alkali-Activated Cements and Concretes. Chapter 4. Hydration and microstructure of alkali-activated slag cements. In: London: Taylor & Francis ed.
- Shoaei, P., Ameri, F., Karimzadeh, M., Atabakhsh, E., Zareei, S. A., & Behforouz, B. (2022). Difference between geopolymers and alkali-activated materials. In *Handbook of Sustainable Concrete and Industrial Waste Management* (pp. 421-435): Elsevier.
- Teh, S. H., Wiedmann, T., Castel, A., & de Burgh, J. (2017). Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. *Journal of cleaner production*, 152, 312-320.
- Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO₂-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and building materials*, 43, 125-130.
- Ulugöl, H., Kul, A., Yıldırım, G., Şahmaran, M., Aldemir, A., Figueira, D., & Ashour, A. (2021). Mechanical and microstructural characterization of geopolymers from assorted construction and demolition waste-based masonry and glass. *Journal of cleaner production*, 280, 124358.
- Vickers, J., Riordan, B., & Kershaw, C. (2022). *Life cycle assessment of pavements: development of a calculator*.
- Vinai, R., & Soutsos, M. (2019). Production of sodium silicate powder from waste glass cullet for alkali activation of alternative binders. *Cement and Concrete Research*, 116, 45-56.
- Wang, S.-D., Scrivener, K. L., & Pratt, P. (1994). Factors affecting the strength of alkali-activated slag. *Cement and concrete research*, 24(6), 1033-1043.
- Wesley, L. (2003). Geotechnical properties of two volcanic soils. Geotechnics on the volcanic edge. Tauranga, March.
- Wilson, D. (1949). New Zealand pumice as a lightweight concrete aggregate.