Mechanical Performance of Lightweight Alkali Activated Cement-less Concrete Blocks by using Natural Rock Dust

Author
SOHAIL AHMAD
(Reg # 3-FET/MS CE/F22**)**

Supervised by
Dr. Muhammad Noman
Assistant Professor

Department of Civil Engineering
Faculty of Engineering & Technology
International Islamic University Islamabad
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بسم الله الرحمن الرحيم

FINAL APPROVAL

It is certificate that we have read the thesis submitted by Ms. Sohail Ahmad and it is our judgment that this thesis is of sufficient standard to warrant its acceptance by the International Islamic University, Islamabad for the MS Degree in Civil Engineering

COMMITTEE

External Examiner ______________________________

Internal Examiner ______________________________

Supervisor ______________________________

Chairman ______________________________

A thesis submitted to Department of Civil Engineering, International Islamic University, Islamabad as a partial fulfillment of requirement for the award of the Degree MS in Civil Engineering

DEDICATION

First and foremost, I thank Almighty Allah, the Most Merciful and the Most Compassionate, for His countless blessings, guidance, and strength throughout this journey. Without His grace, this achievement would not have been possible.

I dedicate this work to my beloved mother, whose unwavering love, sacrifices, and constant prayers have shaped me into the person I am today. It is her heartfelt supplications that have guided me through the toughest of times, and her encouragement has been a source of immense strength and motivation.

To my dear wife, whose love, encouragement, and understanding have been my anchor. Her patience and constant support have helped me overcome challenges and stay focused on my goals.

I am deeply grateful to Dr. Muhammad Noman, my supervisor, for his invaluable guidance, expertise, and continuous support throughout this research. His insightful feedback, encouragement, and patience were instrumental in the completion of this thesis.

This thesis is a reflection of the values of love, hard work, and dedication that each of you has instilled in me. May Allah bless you all.

DECLARATION

I hereby declare that the work present in the following thesis is my own effort, except where otherwise acknowledged and that the thesis is my own composition. No part of the thesis has been previously presented for any other degree.

Sohail Ahmad

3-FET/MS CE/F22

Date: ____________

CONTENTS

ACKNOWLEDGEMENTS

I am particularly thankful to Almighty Allah in the completion of my MS Research work and I acknowledge the support of Dr. Muhammad Noman in completion of this work on Mechanical Performance of Light-weight Alkali-activated cement-less concrete block using Natural Rock Dust. Deeply grateful to my Mother, who has been my greatest mentor, always supporting and encouraging me during my research and studies at IIUI.

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Full Form
AA	Alkali Activator
AAC	Alkali-Activated Concrete
AA-LWAC	Alkali-activated lightweight aggregate concrete
FA	Fly Ash
GBFS	Granulated Blast Furnace Slag
GWP	Granite Waste Powder
LWAC	Light Weight Aggregate Concrete
MWP	Marble Waste Powder
PWP	Pumice Waste Powder

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Abstract

This experimental study investigates the mechanical performance of Alkali-Activated Lightweight Aggregate Concrete blocks (AA-LWAC) incorporating industrial waste powders, specifically Granite Waste Powder (GWP), Marble Waste Powder (MWP), and Pumice Waste Powder (PWP), as partial substitutes for Fly Ash (FA). The objective was to evaluate how these waste powders influence compressive strength, stress-strain behavior, and secant modulus of lightweight concrete. Locally available lightweight pumice stones were used to replace the normal coarse aggregates, and X-ray diffraction analysis was conducted to investigate the characterization and reactivity of the waste powders. The FA precursor was replaced at ratios ranging from 25% to 100% with the waste powders. The results revealed that at lower replacement levels (25-50%), both GWP and PWP demonstrated superior mechanical performance compared to MWP, with PWP at 50% replacement achieving the highest compressive strength, nearly matching the control sample. However, at higher replacement levels (75-100%), all powders showed a notable decrease in strength, with GWP and MWP experiencing more significant reductions than PWP. Stress-strain analysis revealed that PWP exhibited superior ductility, higher ultimate strain, and more stable behavior than the other powders. Despite the reduction in stiffness at higher replacement levels, PWP retained better stiffness, making it suitable for lightweight, non-load-bearing applications. Overall, PWP emerged as the most balanced material, providing a favorable combination of strength, ductility, and stiffness, offering a sustainable and eco-friendly alternative for moderate-strength concrete applications. This research highlights the potential of using waste powders in AA-LWAC blocks to promote sustainable construction practices, reduce cement usage, and address the challenges of CO_2 emissions in the cement industry.

1 Introduction

1.1 Background

Climate change is one of the most pressing global challenges face today, largely due to increasing CO_2 emissions from human activities like burning fossil fuels and deforestation. Over the last two centuries, atmospheric CO_2 levels have surged from pre-industrial figures of 280 ppm to 422 ppm in 2024, leading to global warming, ocean acidification, and more frequent extreme weather events. The cement industry contributes significantly to this issue, accounting for 7-8% of global CO_2 emissions (Kate, 2024), primarily because of the energy-intensive nature of cement production. Although international agreements such as the Paris Agreement aim for ambitious emissions reductions, current methods like clinker substitution and carbon capture face limitations in terms of scalability and cost. In this scenario, Alkali-Activated Concrete (AAC), especially when combined with lightweight aggregate concrete (LAC), presents a promising low-carbon alternative. By incorporating industrial by-products like fly ash, slag, and various stone dusts (including marble, granite, and pumice), AAC can reduce CO_2 emissions by as much as 80% (Coppola et al., 2020). This method is additionally useful in addressing the problems connected with the management of waste in places where stone industry by-products exist. On the other hand, there is so much literature on AAC that is hardly available on lightweight aggregate concrete. The same concerns the use of natural stone dust as a composite binder although those of AAC technology seem to have great potential for reducing the release of airborne emissions with potential improvement in construction methods. Although it is well established the effectiveness of AAC in reducing emissions, in this particular case, the potential of stone dust as a binder is not clear. This is important because it is expected to improve the effectiveness of AAC in lightweight aggregate concrete as a way of curbing the emission of CO_2 and other related practices.

1.2 Problem Statement

The construction industry faces significant challenges due to the declining availability and inconsistent properties of traditional precursors like fly ash and granulated blast furnace slag (GBFS), compounded by supply disruptions and the global shift towards cleaner energy. Simultaneously, the stone processing industry generates billions of tons of waste in the form of marble, granite, and pumice powders, creating an environmental burden. Despite their potential, there is a lack of comprehensive understanding regarding the mechanical performance and suitability of these waste powders as sustainable precursors for alkali-activated lightweight aggregate concrete (AAC-LWAC). Additionally, in high-rise buildings, high strength is not always desirable for partition walls, highlighting the need for lightweight concrete blocks solutions to reduce structural load. This study aims to bridge these gaps by exploring the use of stone powders as precursors in AAC-LWAC, with the goal of developing a low-carbon, resource-efficient material that can meet the growing demand for lightweight concrete blocks in high-rise construction, offering a sustainable solution for both waste management and structural efficiency.

1.3 Objectives

- To **investigate the mechanical properties** of Alkali-activated lightweight aggregate (AA-LWAC) concrete blocks produced with varying replacement levels (25%, 50%, 75%, and 100%) of three industrial waste powders: Granite Waste Powder (GWP), Marble Waste Powder (MWP), and Pumice Waste Powder (PWP).
- To explore the **potential use of GWP, MWP, and PWP in low-strength, lightweight concrete blocks** applications where structural strength is not the primary requirement, thus promoting the sustainable utilization of industrial waste materials.
- To demonstrate the **viability of using industrial waste powders in concrete** as an eco-friendly alternative, reducing reliance on natural resources and minimizing the environmental impact of waste disposal.

1.4 Scope and Limitations

The study faces limitations due to the high expense of alkaline activators, the absence of standardization in AAC production, and its limited practical adoption. Furthermore, although AAC presents considerable environmental advantages, scaling current CO_2 reduction technologies in the cement industry poses challenges. Continued research is essential to address these issues and enhance AAC for wider application.

This research explores the replacement of fly ash with three natural rock dusts marble dust, granite dust, and pumice stone dust—as precursors in alkali-activated lightweight aggregate concrete (AALAC). The study investigates the effect of varying substitution percentages (25%, 50%, 75%, and 100%) on the performance of the concrete. The research also evaluates the environmental benefits of using these natural rock dusts as sustainable alternatives. Additionally, pumice stone crushed aggregate is used as a lightweight aggregate. This study specifically focuses on applications where high strength is not essential, such as the use of lightweight concrete blocks in partition walls of high-rise buildings, aiming to reduce the structural load on the building.

1.5 Overview of the Thesis

The thesis comprises of six chapters with the first chapter being the introduction of the thesis. This chapter mentions the background of the study, the research gap, the objectives of the study and the limitations of the work.

The second 2nd chapter examines the existing literature on Alkali-Activated Concrete, concentrating on its materials, production methods, environmental advantages, and performance attributes. It underscores significant studies related to AAC and its components, such as fly ash and various natural stone dusts, while pinpointing research gaps that this thesis seeks to fill.

The third 3rd experimental methodology chapter outlines the materials utilized in this research, including different types of natural stone dusts like marble dust, granite dust, and pumice stone dust. It also details the experimental setup, the tests performed (including compressive strength, slump tests, and shrinkage tests), and the protocols followed to ensure the accuracy and reliability of the results.

The fourth 4th chapter Results and Discussion the conclude findings from the study are presented and analyzed. The results concerning the performance of Alkali-Activated Concrete, particularly with the incorporation of natural stone dusts, are compared to traditional concrete. Additionally, the chapter discusses the environmental and economic implications of adopting AAC as a sustainable alternative.

The fifth 5th chapter Conclusion and Future work provides a summary of the key findings from the research, affirming the hypothesis that AAC can significantly lower CO_2 emissions while maintaining strong performance. It also offers suggestions for future research, such as potential enhancements to the mix design and further investigation into AAC's applications within the construction industry.

The sixth 6th chapter References compiles all the sources cited throughout the thesis, including journal articles, books, and other academic materials that played a role in shaping the research.

The appendix contains additional information, including detailed calculations for the AAC mix proportions, raw experimental data, and supplementary materials that bolster the main content of the thesis.

2 Literature Review

2.1 Background

Climate change stands as one of the most urgent global issues, primarily fueled by increasing CO_2 levels from human activities like burning fossil fuels and deforestation. In the last two hundred years, atmospheric CO_2 concentrations have jumped from pre-industrial levels of 280 ppm to 422 ppm, with global CO_2 emissions hitting 41.6 billion metric tons in 2024 (Poorveekan et al., 2021). The consequences, including global warming, ocean acidification, and severe weather events, have created an immediate need for innovative solutions in emission-heavy industries such as cement and concrete production.

The cement sector alone accounts for about 7-8% of global CO_2 emissions, mainly due to the calcination process and the burning of fossil fuels (Kate, 2024). International agreements, like the Paris Agreement, aim for substantial emission reductions, targeting a 24% decrease by 2030 and carbon neutrality by 2050 (Yilmaz, 2024). Countries such as the United States, European Union, China, India, and Pakistan have set specific goals to cut emissions from their cement industries. However, traditional strategies like clinker substitution, enhancing energy efficiency, and implementing carbon capture technologies, while effective, encounter challenges related to scalability, cost, and resource availability (Qudrat-Ullah, 2022).

In this context, Alkali-Activated Concrete (AAC) has emerged as a promising low-carbon alternative. Unlike conventional Ordinary Portland Cement (OPC), AAC avoids the energy-intensive calcination process by utilizing industrial by-products such as fly ash, slag, marble dust, granite dust, and pumice stone dust as binders. This material not only cuts CO_2 emissions by up to 80% but also supports global sustainability objectives by embracing circular economy principles (Kate, 2024). In regions like Pakistan, India, and Turkey, where the stone industry generates large amounts of marble, granite, and pumice dust, AAC offers a practical solution to waste management issues while promoting environmentally friendly construction practices (Qudrat-Ullah, 2022).

AAC's compatibility with lightweight structures—boosted by the use of pumice lightweight aggregates—enhances its effectiveness for thermally efficient, fire-resistant, and structurally robust construction (Bayer et al., 2024). However, AAC does encounter challenges such as the expense of alkaline activators, a lack of standardization, and limited practical adoption. Nevertheless, ongoing research into the use of natural and industrial waste materials as binders shows promise in overcoming these obstacles, highlighting AAC's potential as a key player in sustainable construction technologies (Gernot, 1990).

This literature review will examine the development of CO_2 reduction strategies within the cement and concrete industry, emphasizing AAC as a superior alternative due to its environmental, economic, and performance benefits. The following sections will critically assess the global challenges posed by CO_2 emissions, the role of cement production in these emissions, and how AAC can effectively tackle these issues. By utilizing abundant natural and industrial by-products, AAC not only offers a means to reduce emissions but also highlights the significance of integrating waste management solutions with sustainable construction practices.

2.2 Global Climate Change & CO_2

Global climate change is mainly caused by the increase in atmospheric carbon dioxide (CO_2) levels, which result from human activities like burning fossil fuels and deforestation. Before the industrial era, CO_2 concentrations in the atmosphere were around 280 parts per million (ppm) (Qudrat-Ullah, 2022). However, by 2023, these levels have risen to approximately 422 ppm, indicating a significant increase over the last two centuries. This rise in CO_2 has led to global annual emissions reaching 41.6 billion metric tons in 2024. The aviation sector and coal usage are key contributors to these emissions. Among the largest emitters, China was responsible for 28% of global emissions, followed by the United States at 15%, the European Union at 10%, and India at 7%. Although Pakistan contributes only 0.5% of global CO_2 emissions, it remains extremely vulnerable to climate change, facing severe impacts from extreme weather events like floods, droughts, and heatwaves (Lin & Raza, 2019).

The rising CO_2 levels are closely associated with increases in global temperatures. Since the onset of the Industrial Revolution in 1750, both atmospheric carbon dioxide levels (represented by the raspberry line) and human emissions (depicted by the blue line) have shown a steady increase. The increasing global temperature trend has been shown in Figure 2-1 (Kate, 2024). Since the late 19th century, the Earth's average temperature has risen by 1.3°C, with the risk of surpassing the critical 1.5°C threshold if emissions are not curtailed immediately (M. K. Khan et al., 2019). Despite its minimal contribution to global emissions, Pakistan ranks among the top 10 countries most susceptible to climate change. The nation faces numerous challenges, including frequent floods, such as those in 2022, which displaced millions and caused damages exceeding $15 billion (Abukersh & Fairfield, 2011). Additionally, Pakistan is experiencing unprecedented heat waves that severely impact agriculture and water resources. The country also has one of the highest deforestation rates in the world, which significantly undermines its capacity to function as a carbon sink.

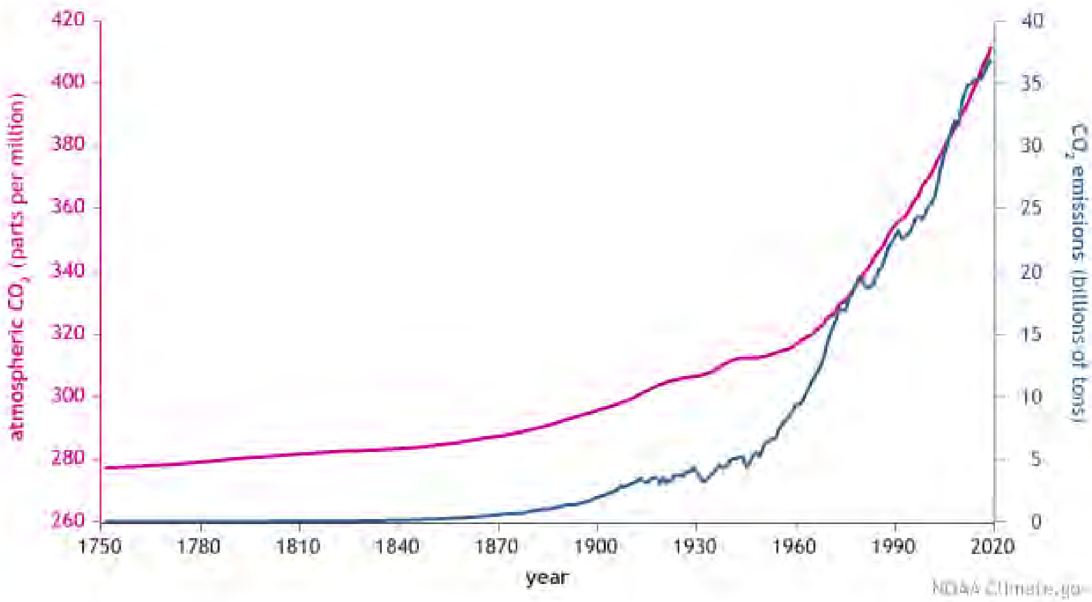

Figure 2-1: Global Temperature variation 1750-2020. (Kate, 2024)

Natural carbon sinks, like forests and oceans, absorb nearly half of global CO_2 emissions. However, deforestation in Pakistan, along with extreme climate events, has reduced the effectiveness of these sinks. While international agreements like the Paris Agreement have been established to tackle climate change, current policies fall short of what is needed to keep global warming below the 1.5°C target (Qudrat-Ullah, 2022). Pakistan, though a minor contributor to emissions, is advocating for increased climate financing to enhance resilience against climate impacts and a transition to renewable energy, promoting solar and wind energy projects. If global emissions are not curtailed, forecasts predict a potential temperature rise of up to 3.1°C by the end of the century, exacerbating climate-related challenges worldwide, particularly in vulnerable regions like Pakistan. This analysis underscores the urgent need to address CO_2 emissions on a global scale, while acknowledging the disproportionate effects on countries such as Pakistan.

2.3 Current Global Challenges

A growing concern that demands attention is the rise in carbon dioxide (CO_2) emissions and the environmental and societal challenges that come with it, all backed by solid research. One of the most significant consequences of increasing CO_2 levels is global warming. Since the late 1800s, the Earth's average temperature has increased by about 1.3°C, a trend closely tied to the rising concentration of CO_2 in the atmosphere (M. K. Khan et al., 2019).

Another major issue stemming from CO_2 emissions is ocean acidification. While many people may not fully understand the long-term effects, the slow acidification of oceans—which make up about 70% of the Earth's surface—is a direct result of higher CO_2 levels. Over the last two centuries, the oceans have seen a decrease of 0.1 pH units , a shift that disrupts marine ecosystems by impacting the habitats of marine life, including coral reefs and other organisms that depend on stable pH conditions (Suess, 2006).

Beyond these environmental issues, weather-related hazards have become more severe due to human activities, especially the excess CO_2 and other greenhouse gases in the atmosphere. These changes have resulted in a 20% increase in the intensity of heatwaves and a 12% rise in heavy rainfall over the past fifty years, further complicating the challenges posed by climate change (Siddiqua et al., 2022).

Another significant effect is the rise in sea levels. Since 1993, the average sea level has been increasing by about 3.3 mm per year due to the melting of ice caps and glaciers at the poles (Suess, 2006). This rise poses serious economic and social challenges for coastal communities, particularly in low-lying areas that are at greater risk of flooding. Additionally, vector-borne diseases are on the rise as a result of climate change. Diseases such as malaria and dengue fever have seen a 7% increase globally in recent years, as shifting climates have expanded the habitats of the vectors responsible for their transmission (Rios, 2022).

The economic impacts of climate change are becoming more apparent. Over the past five years, global economic losses due to climate-related disasters have averaged about $200 billion annually. If current emission trends persist, projections suggest that the global GDP could drop by as much as 10% by 2050. These insights highlight the urgent necessity for prompt and effective measures to cut CO_2 emissions to lessen the extensive repercussions of global warming, ocean acidification, extreme weather events, and other associated issues (Tol, 2013).

2.4 Cement industry & CO_2 International & National Goals

Around 7% of global CO_2 emissions can be attributed to the production of cement alone which is a high percentage in itself (Rashad, 2021). This is mostly a result of the calcination process and the burning of fossil fuels. Acknowledging this impact makes international and national organizations set targets within this sector to reduce the emissions produced.

Figure 2-2 shows the Cement production is a significant source of CO_2 emissions, primarily resulting from two key processes: kiln calcination ($CaCO_3$ + heat → CaO + CO_2) and the combustion of fossil fuels to provide the necessary heat. On average, the production of one ton of cement generates approximately one ton of CO_2. According to the U.S. Geological Survey, global cement production amounts to 4.2 gaga tons annually. Cement-related CO_2 emissions now account for nearly 10% of total global CO_2 emissions, a substantial increase from 4% in 1970 (Chang et al., 2019).

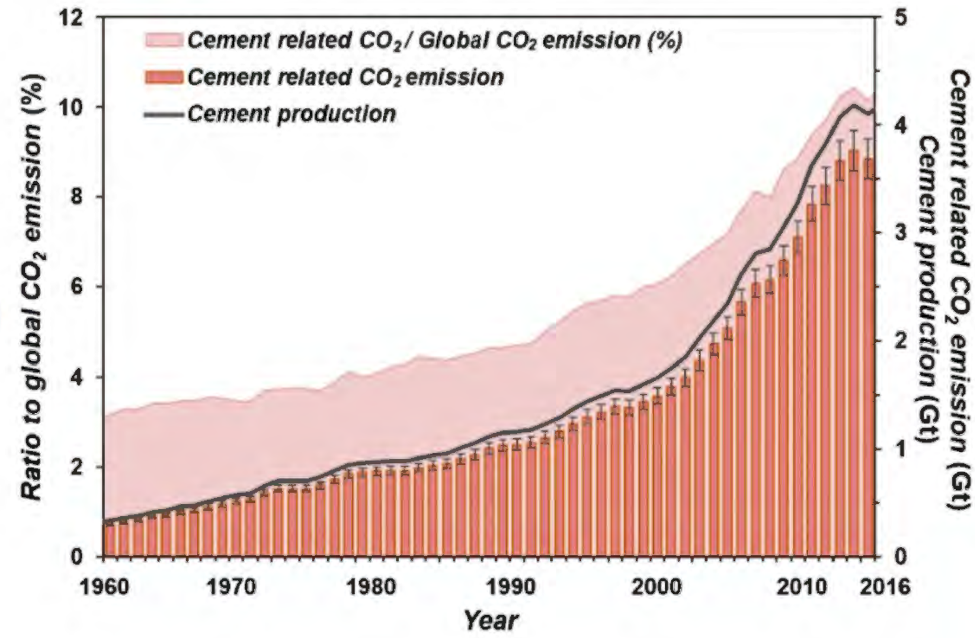

Figure 2-2: CO2 emissions related to the production of cement and its ratio to total CO2 emissions (Chang et al., 2019).

Figure 2-3 illustrates the contribution of various materials to the overall composition or usage in a construction context, expressed as percentages. Cement represents the largest proportion, contributing 30.3%, emphasizing its critical role in construction. Ceramic follows with 20.3%, likely reflecting its use in tiles, finishes, and fixtures. Steel, a vital material for structural reinforcement, accounts for 18.7%. Other notable contributions include lime (7.9%), used for mortar and finishes, and mortar (6.9%), an essential binding material.

Smaller contributions come from gravel (2.9%), pre-fabricated concrete (2%), and aluminum (2.3%), which are used in structural and decorative elements. Wood (1.1%) and PVC (1.0%) are included for specific applications, such as formwork and piping. Additives (1.5%) reflect the use of admixtures to enhance material properties. The category others (5.0%) likely includes miscellaneous materials not listed individually.

This breakdown highlights the dominance of cement and ceramic in construction materials, emphasizing the significant environmental impact of these materials due to their high production and energy demands. Sustainable alternatives and material efficiency strategies could help mitigate these impacts (Zabalza Bribián et al., 2011).

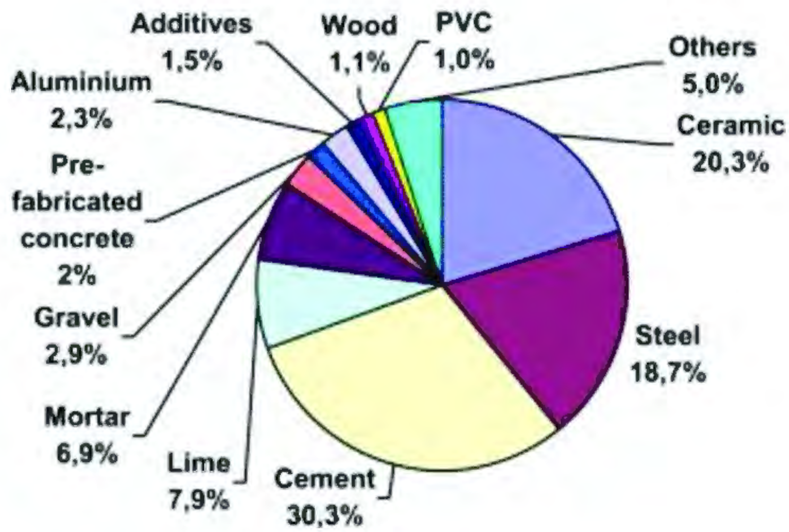

Figure 2-3: CO_2 contribution from various construction materials (Zabalza Bribián et al., 2011).

Figure 2-4 compares the carbon dioxide (CO_2) emissions of Alkali Activated concrete and traditional Ordinary Portland Cement (OPC) concrete, highlighting their environmental impacts. Alkali Activated concrete exhibits significantly lower total emissions at 0.107 t-CO_2/m^3 compared to 0.395 t-CO_2/m^3 for OPC concrete, showcasing its potential as a sustainable alternative. In Alkali Activated concrete, the largest contributor to emissions is fly ash (54.3%), followed by sodium silicate (33.1%) and sodium hydroxide (8.4%), both of which are used as activators. Aggregates and GGBFS (Ground Granulated Blast Furnace Slag) contribute minimally, at 2.9% and 1.3%, respectively. In contrast, OPC concrete emissions are dominated by the cement itself, accounting for 97.9% of total emissions, with aggregates contributing only 2.1%. This stark difference highlights the environmental advantage of Alkali Activated concrete, which utilizes industrial by-products like fly ash and GGBFS, drastically reducing emissions compared to the energy-intensive production of OPC. The findings emphasize the importance of adopting Alkali Activated technology to lower the carbon footprint in construction materials (Alsalman et al., 2021).

Figure 2-5 compares the total energy consumption of Alkali Activated concrete and traditional Ordinary Portland Cement (OPC) concrete. Alkali Activated concrete exhibits a lower total energy demand of 1.209 GJ/m^3 compared to 2.227 GJ/m^3 for OPC concrete, underscoring its energy efficiency. In Alkali Activated concrete, the highest energy contribution comes from sodium silicate, accounting for 50.8% of the total, followed by sodium hydroxide at 31.3%. Fly ash (FA) contributes 12.8%, aggregates account for 4.3%, and GGBFS (Ground Granulated Blast Furnace

Slag) contributes a negligible 0.9%. In contrast, OPC concrete's energy consumption is dominated by the production of cement, which accounts for 93.6% of the total, while aggregates contribute only 6.4%. This comparison highlights the significant energy savings of Alkali Activated concrete, largely due to the replacement of OPC with industrial by-products such as fly ash and GGBFS, despite the high energy demand of the alkaline activators (sodium silicate and sodium hydroxide). The results emphasize the potential of Alkali Activated concrete as a more energy-efficient alternative for sustainable construction (Alsalman et al., 2021).

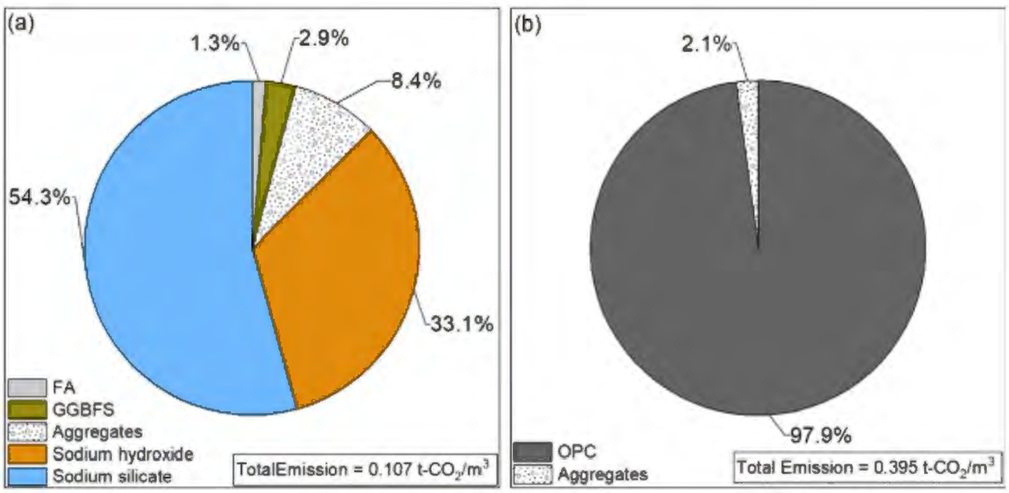

Figure 2-4: Emission of 40 MPa concrete mixtures (Alsalman et al., 2021).

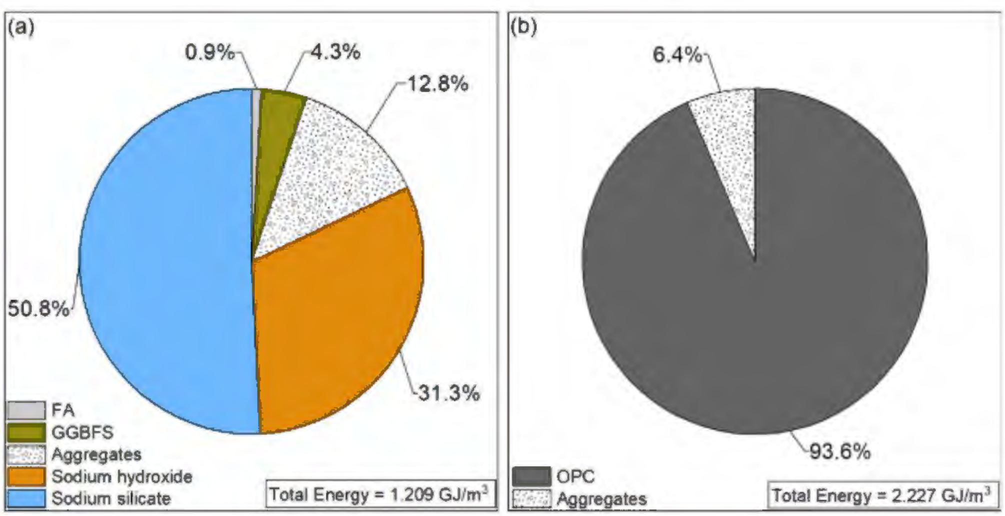

Figure 2-5: Energy of 40 MPa concrete mixtures (Alsalman et al., 2021).

2.5 International Goals

One of the targets of the Paris Agreement is to prevent global temperature from reaching more than two degrees and the preferred range being one point five degrees Celsius (Qudrat-Ullah, 2022). In order to meet this target, the cement industry must cut coal and gas emissions by 24% by 2030, and the aim should be to achieve zero emissions by 2050. By setting, the Global Cement and Concrete Association (GCCA) goals by 2050 to produce zero emittance concrete in the future. The emissions during the production of such concrete will be decreased by 25% by the year 2030 accounting to 5 gaga tones of CO_2 emissions per year (Traut et al., 2018).

Based on global CO2 emission data, cement plants have dramatically increased their carbon footprint, with emissions rising from 0.57 billion tons in 1990 to 2.9 billion tons in 2021 a nearly fivefold increase. Between 2006 and 2021, the leading contributors to CO2 emissions were China, India, Europe, and the United States. Notably, the Indian cement industry saw a significant surge, emitting approximately 149 million tons of CO_2 in 2021, up from just 22.35 million tons in 1990 (Figure 2-6). Scientific reports highlight the critical need to achieve net-zero emissions by the end of this century to meet the Paris Agreement goals. In response, comprehensive strategies are being developed across multiple sectors, including cement and concrete production, to enhance the efficiency and sustainability of cement-based materials (Barbhuiya et al., 2024).

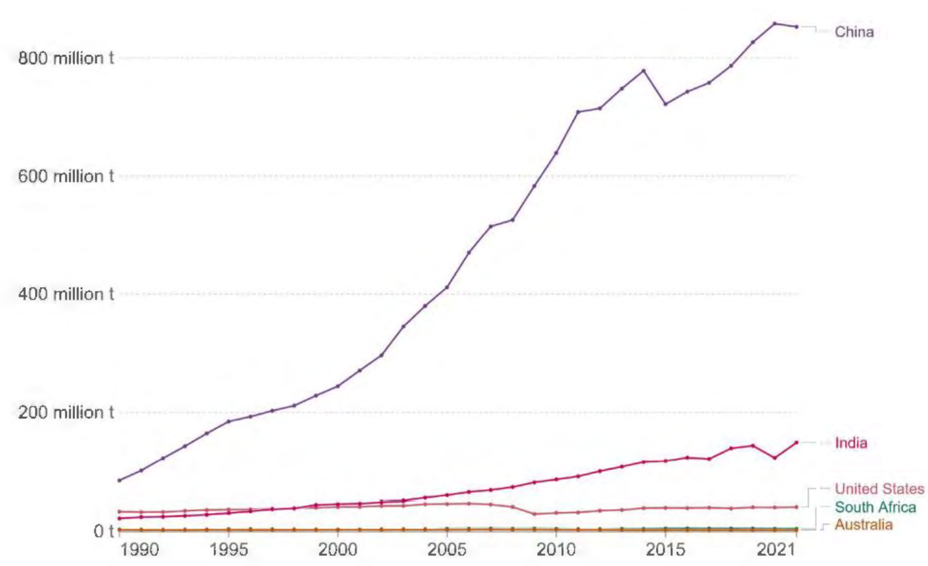

Figure 2-6: Global CO_2 emission from cement production (Global Carbon Project, 2022).

2.5.1 National Goals

To effectively address the global challenge of reducing CO_2 emissions, several countries have committed to ambitious targets for emissions reduction, particularly within the cement industry. These targets reflect a collective effort to mitigate the environmental impact of cement production, one of the largest sources of industrial CO_2 emissions worldwide. Below are the key targets set by various nations to reduce emissions and promote sustainable practices within the sector (Höhne et al., 2017):

- United States: Targets of 20% reduction of CO2 emissions per ton cementitious product by the year 2030 that comes up to 100 million in metric tons per year of reduction in emissions.
- European Union: The EU under the Emissions Trading System (ETS) aims for an overall emission reduction of 43% by the year 2030 compared with the 2005 levels.
- China: Commits to achieving a peak in emissions by 2030 and fully achieving carbon neutrality by 2060. The goal also underlines the intention of China's cement industry to lower its output by 16 percent of its current level by 2025, which would be 400 million metric tons per year.
- India: Within the framework of this commitment, it is expected that CO_2 emissions will be reduced from the 2010 levels by 45% by 2030. This relates to 375 million metric tons of emissions cut per annum.
- Pakistan: Relying mainly on its cement industry, Pakistan pays special emphasis on energy conservation and utilization of substitute fuels in CO_2 emission reduction efforts. Under its Nationally Determined Contributions (NDCs), Pakistan has expressed its commitment to a 20% reduction in total greenhouse gas emissions by 2030, international funding assisting, and cement industry as a key area of focus.

2.5.2 Emission cut measures

To significantly reduce CO_2 emissions from the cement industry, various strategies are being explored and put into practice to decrease the carbon footprint of cement production. These approaches emphasize the use of alternative materials, improving energy efficiency, and adopting advanced technologies to lessen the environmental impact (Liu et al., 2023):

- Utilization of alternative fuels: Diminishing the fuel component with biomass as well as combustion derived substitutes allows for a 40% reduction in CO_2 emissions
- Clinker substitution: The total emissions per ton cement produced can be lowered by 30% through the use of other cement types such as fly ash and slag, natural stone dusts like marble dust, granite dust and pumice stone dust.
- Energy Efficiency: Emissions can decrease by a factor of around 10% due to the application of technological improvements.
- Carbon Capture and Storage (CCS): The use of CCS can lower CO_2 emissions by a staggering 90%.

To achieve these goals, representatives from industry, policymakers and researchers have to work together to design and implement CO_2 emission control strategies for this sector. Due to the upgrading of industries and the support of the international community, Pakistan's vow of sustainable development illustrates that it is contributing to

2.6 Solutions towards CO_2 reduction

The cement and concrete industry is responsible for about 7-8% of global CO_2 emissions, primarily due to the energy-intensive production of ordinary Portland cement (OPC) (Kothari, 2017). Various strategies have been investigated to mitigate these emissions, including the use of alternative binders, enhancements in production processes, and carbon capture technologies. A brief comparison is shown in Table 2-1. Among these, Alkali-Activated Concrete (AAC) stands out as a particularly promising option due to its sustainability and effectiveness. However, its potential, especially when incorporating natural stone dust, has not been fully explored (Samadhiya et al., 2024).

A common method for reducing emissions in cement production is to replace OPC clinker with supplementary cementitious materials (SCMs) like fly ash, slag, or limestone. This substitution can lead to a reduction in CO_2 emissions of 10-30%, depending on how much is replaced. However, the availability of SCMs can be limited in certain areas, and too much substitution may compromise the durability of the concrete. Another approach is to enhance energy efficiency through advanced kiln technologies and the use of alternative fuels such as biomass or waste-derived materials, which can reduce energy-related emissions by 20-40% in some facilities. Unfortunately, these advancements do not tackle the calcination process, which is responsible for 60% of cement-related CO_2 emissions, and they often require substantial capital investment.

Carbon capture and storage (CCS) technology has been suggested as a method to capture up to 90% of CO_2 emissions from cement production. However, its broader adoption is limited by high operational costs and substantial energy demands. Alternative cement types, such as low-clinker, magnesium-based, or sulfoaluminate cements, can reduce emissions by 30-50%, but they encounter issues related to cost, scalability, and performance when compared to ordinary Portland cement (OPC).

On the other hand, Alkali-Activated Concrete (AAC) presents notable benefits over these alternatives. Unlike OPC, the production of AAC does not involve calcination, which is the primary source of CO_2 emissions. Consequently, AAC can achieve an impressive 80% reduction in emissions, significantly exceeding other options. Furthermore, AAC incorporates industrial by-products like fly ash, slag, and natural stone dust, including marble, granite, and pumice stone dust, as binders. This positions it as a zero-clinker solution that promotes a circular economy by minimizing landfill waste and converting by-products into high-performance concrete.

AAC is also more energy-efficient, using 50-60% less energy than OPC since it eliminates the need for high-temperature kiln processes. Additionally, the inclusion of lightweight aggregates such as pumice can further decrease energy use during transportation in construction projects. In terms of performance, AAC provides comparable or even superior compressive strength (30-60 MPa) and exhibits excellent durability, including resistance to chemical attacks, thermal stability, and reduced permeability. These characteristics ensure long-term performance while lowering emissions associated with maintenance and repairs.

Additionally, AAC is in line with global sustainability initiatives, such as the Paris Agreement, and supports national objectives, including Pakistan's goal to cut CO_2 emissions by 20% by 2030. However, the potential of AAC, especially when using natural stone dust as a binder, has not been fully explored. Most current research tends to focus on materials like fly ash and slag, neglecting the plentiful availability and waste-reducing advantages of natural stone dust. This study seeks to address this gap by examining the feasibility and performance of AAC made with marble dust, granite dust, and pumice stone dust, providing a sustainable and scalable solution for the construction sector to lower CO_2 emissions.

Table 2-1: Comparison of Different CO_2

Solution	CO_2 Reduction	Cost	Scalability	Performance	Waste Utilization
Clinker Substitution	10-30%	Moderate	High	Moderate (at high SCM %)	Low
Energy Efficiency	20-40%	High	Moderate	High	None
Carbon Capture (CCS)	Up to 90%	Very High	Low (limited by cost)	Moderate	None
Alkali-Activated Concrete	Up to 80%	Moderate	High (with standards)	High	High

2.7 Alkali Activated Concrete as a viable solution

Alkali-activated concrete (AAC), often referred to as geopolymer concrete, is a cutting-edge building material that serves as a sustainable alternative to traditional Portland cement concrete (Liu et al., 2023). This innovative material significantly lowers emissions linked to cement production while meeting or surpassing performance standards. By utilizing industrial and natural by-products like marble dust, granite dust, pumice stone dust, and lightweight pumice aggregates, AAC shows great promise as a low-carbon option for construction (Rashad, 2021).

AAC is characterized by the replacement of conventional cement with industrial waste and by-products. Commonly used materials include fly ash (fine particles resulting from burned coal), ground granulated blast furnace slag (a by-product from iron and steel manufacturing), and natural stone by-products such as marble dust, granite dust, and pumice stone dust (Freidin, 2007). These components not only enhance strength and durability but also help to reduce environmental impact. The inclusion of lightweight pumice stone aggregates further decreases the overall weight of AAC, making it ideal for lightweight and thermally efficient structures. Unlike Ordinary Portland Cement (OPC), AAC avoids the use of energy-intensive rotary kilns, relying instead on chemical reactions between precursors and alkaline activators like sodium hydroxide or sodium silicate.

From an environmental prospective, AAC presents significant advantages. It has the potential to cut CO_2 emissions by up to 80% thanks to the use of waste materials and the elimination of calcination. The incorporation of by-products such as marble dust, granite dust, and pumice stone aggregate aids in effectively managing industrial waste, thereby reducing landfill overflow. Furthermore, the production of AAC consumes 50-60% less energy compared to OPC, establishing it as an energy-efficient alternative (Samadhiya et al., 2024).

AAC provides compressive strength depending on the mix proportions and the use of fillers like marble, granite dust and pumice stone dust. These additives improve mechanical properties, while lightweight pumice aggregates help lower the density of AAC, making it a great choice for lightweight construction. Additionally, AAC is highly resistant to sulphate and acid attacks and maintains stability at high temperatures due to its dense microstructure, which further boosts its durability (Alqarni, 2022).

However, there are challenges in implementing AAC. Handling concentrated alkaline solutions necessitates strict safety protocols because of their corrosive nature. The cost of alkaline activators, such as sodium silicate, can be higher than that of ordinary Portland cement (OPC), although using low-cost by-products like marble dust can help mitigate this cost (Song et al., 2023). Furthermore, the absence of widely recognized international standards for AAC production and testing hampers its broader acceptance in the construction sector.

AAC is extremely versatile in its applications. It is especially well-suited for precast elements like beams, slabs, and lightweight panels that incorporate pumice aggregates. Its durability and resistance to weather make it an excellent choice for infrastructure projects, including bridges and road networks. Moreover, the incorporation of stone and industrial waste products aligns AAC with eco-friendly construction practices and green building certifications.

From a sustainability standpoint, AAC plays a significant role in reducing carbon emissions in the construction industry. By using marble and granite dust with alkali activation, it can lead to substantial decreases in CO_2 emissions. The material also supports waste management initiatives by promoting a circular economy through the reuse of industrial and natural by-products. Additionally, lightweight AAC with pumice aggregates enhances the thermal efficiency of buildings, aiding in energy conservation.

In conclusion, AAC that includes marble dust, granite dust, pumice stone dust, and lightweight pumice aggregates provides a low-carbon alternative to conventional concrete. This cutting-edge material merges environmental sustainability, economic advantages, and enhanced performance, offering a sustainable and effective solution for contemporary construction. As research and development in this area progress, AAC is set to lead a significant change towards greener and more sustainable building practices.

2.8 Dust and their associated Problems

Natural stone dusts, such as marble dust, granite dust, and pumice stone dust, are byproducts of stone cutting and grinding, presenting both opportunities and challenges. While these materials can be reused in construction, art, and landscaping (El-shafie & Wang, 2023), they pose significant health risks when inhaled due to crystalline silica, which can lead to respiratory diseases like silicosis and lung cancer (Sato et al., 2018). Environmental issues also arise from improper disposal, as the dust can contaminate waterways, soil, and air, negatively impacting ecosystems (Siddiqua et al., 2022). Managing with large amounts of dust poses a significant challenge for various industries, complicating both storage and disposal processes. In the construction sector, the fine particles in these dusts can impact how materials work together, potentially affecting the strength and performance of concrete or mortar. Additionally, overuse in surface applications can lead to abrasion or damage to materials. As a result, it is essential to implement proper handling, waste management, and safety measures to reduce the risks associated to natural stone dust.

Even with these challenges, natural stone dust can be effectively used in the production of alkali-activated concrete blocks. When added to the mixture, these dust can improve the mechanical properties and durability of the concrete, leveraging their mineral content to enhance strength and resistance to environmental factors. (Samadhiya et al., 2024). The cementitious properties of these dusts stem from their aluminosilicate composition, which reacts with alkaline solutions during activation, contributing to form the overall binding matrix. The studies have proven the capability of these waste dusts as cement replacement. By repurposing these dust in alkali-activated concrete, waste is minimized, and the overall sustainability of construction materials is improved, aligning with eco-friendly practices (Abukersh & Fairfield, 2011).

Natural stone dusts, such as marble dust, granite dust, and pumice stone dust, are plentiful by-products of the stone processing industry in countries like Pakistan, India, and Turkey, presenting significant opportunities for sustainable concrete production. In Pakistan, areas like Khyber Pakhtunkhwa and Balochistan produce millions of tons of granite and marble dust each year due to the expanding granite industry, yet a large portion of this waste remains underutilized (Malkani et al., 2018)(Z. Khan et al., 2021). Likewise, India, one of the leading marble producers globally, generates over 50 million tons of marble annually, with a significant amount resulting in marble dust (Shukla et al., 2020). In states such as Rajasthan and Tamil Nadu, the granite industry also produces millions of tons of granite dust annually, much of which is not fully utilized (Lohar et al., 2024). Furthermore, pumice stone dust, sourced from volcanic regions, is readily available in Turkey, Greece, and parts of Pakistan and Afghanistan. In Turkey, where pumice extraction is prominent, up to 3.5 million tons of pumice are produced each year, leading to substantial amounts of pumice dust (Bayer et al., 2024).

The extensive availability of these stone dusts in countries like Pakistan, India, Afghanistan and other countries represents an untapped resource for developing alkali-activated concrete, which could provide an eco-friendly alternative to traditional cement by utilizing these by-products as sustainable binders. This innovative use of stone dust not only tackles waste management issues but also creates opportunities for low-carbon, lightweight concrete solutions that can enhance sustainable construction practices in regions rich in stone industry by-products.

2.9 Requirement of Lightweight Structures

The existing literature has addressed the significance of lightweight concrete blocks including low thermal conductivity, thermal insulation, structural efficiency, and fire resistance (Song et al., 2023), However, there is still a gap exists using lightweight alkali-activated concrete blocks (AAC) using natural stone dust as a binder material, including marble, granite and pumice dust.

Incorporation of Industrial by-products through alkali activations This type of research is proving the more sustainable and durable options concrete can take. (Liu et al., 2023)(Rashad, 2021), yet the specific combination of these materials has not been thoroughly explored. Stone dust, an industrial waste from the marble, granite and pumice stone industry could be used as a low-cost and environmentally friendly alternative to improve the performance and sustainability of lightweight concrete. That strategy might help in cutting down industrial waste and enhancing the mechanical properties & durability of concrete but it remains a largely unexamined topic in the literature. Ignoring the promising aspect of stone and other waste materials for producing eco-friendly and high-performance concretes, the alkali-activated lightweight concrete must be further investigated since it combines a sustainable method of reducing waste along with green building technologies that can change the face of construction.

2.10 Conclusion from the state of the art

Alkali-Activated Lightweight Aggregate Concrete (AA-LWAC) is a groundbreaking option in the construction sector, tackling both environmental and structural issues. By utilizing industrial and natural by-products like marble dust, granite dust, pumice stone dust, and pumice lightweight aggregates, AALC provides a sustainable alternative to conventional cement-based concrete. It significantly cuts CO_2 emissions by up to 80% while offering excellent performance in thermal insulation, structural efficiency, and fire resistance. Additionally, its lightweight characteristics improve construction flexibility and lower energy use during transportation and installation. AALC marks a significant step forward in sustainable building materials, effectively combining high performance with eco-friendliness, making it a perfect fit for green construction and circular economy initiatives.

2.11 Research Gap from the literature

Despite its potential, research on Alkali-Activated Lightweight Concrete (AALC) is still in its early stages, especially in these key areas:

- The availability of traditional precursors like fly ash (FA) and granulated blast furnace slag (GBFS) is declining due to shifts towards cleaner energy and changes in industrial practices, posing a challenge to the production of alkali-activated concrete (AAC).

- Despite their potential, the use of natural stone by-products, such as marble, granite, and pumice powders, as sustainable precursors in alkali-activated concrete (AAC) is underexplored. These waste powders have cementitious properties but their performance in AAC is not well understood.
- In high-rise buildings, the demand for lightweight concrete solutions, particularly for partition walls, is increasing. However, the potential of alkali-activated lightweight concrete (AALC), especially incorporating stone waste powders, to reduce structural load while maintaining adequate performance is not fully studied.

3 Experimental Methodology

3.1 Materials

3.1.1 Volcanic Pumice Stone

The pumice stone used in this study was from volcanic mines in Chagai district of Baluchistan province. The stones are white in color and porous as shown in Figure 3-1. The density of the pumice stones is 1150 kg/m^3 which is very low. When placed in water some of the stones float on the surface which confirms their light weight.

Figure 3-1: Volcanic Pumice Stone

Pumice is a volcanic glass that forms when lava is cooled rapidly during volcanic eruptions. The porous structure of pumice is due to the expansion of gas bubbles during the cooling process which creates cavities in the material making it very light and abrasive. These properties make pumice a good material for many applications like construction (as a lightweight aggregate), cosmetic products and filtration media.

The main chemical composition of pumice includes silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), with silica being the predominant component. This high silica content is critical for its pozzolanic properties.

Pumice exhibits high pozzolanic activity due to its elevated silica content. Pozzolanic materials, when finely ground and mixed with water, react with calcium hydroxide ($Ca(OH)_2$) produced during the hydration of cement. The primary chemical reaction is as follows:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C.S.H \qquad \text{Eq. 3-1}$$

Calcium silicate hydrate (C-S-H) is the primary contributor to the strength and durability of concrete. The silica (SiO_2) content of pumice, ranging from 60% to 80% depending on the source, is highly reactive when combined with cement. The pozzolanic reaction between pumice and calcium hydroxide leads to the formation of additional hydrated compounds over time, enhancing the compressive strength, density, and structural integrity of concrete. This makes pumice a sustainable and effective alternative to conventional aggregates.

In addition to its silica content, pumice contains alumina (Al_2O_3), which reacts with calcium hydroxide to form calcium aluminate hydrate (C.A.H), as shown in the reaction:

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C.A.H \qquad \text{Eq. 3-2}$$

Calcium aluminate hydrate contributes to early strength development and improves resistance to sulfate attack, a common issue in cement-based materials exposed to aggressive environments.

Pumice also reduces the risk of alkali-silica reactivity (ASR), a phenomenon that can cause cracking and deterioration in concrete. By reacting with calcium hydroxide, pumice decreases the availability of alkali ions in the mix, thereby mitigating ASR and improving the long-term durability of concrete:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow Stable, non - expansive\ silica\ gel \qquad \text{Eq. 3-3}$$

These reactions highlight pumice's ability to enhance concrete's mechanical properties, chemical resistance, and sustainability (Barone et al., 2021).

3.1.2 Natural coarse aggregate

The crushed stone aggregates used in this study were obtained from quarries in the Margalla Hills region, located north of Islamabad, Pakistan. The quarries in Margalla Hills are recognized for producing high-quality crushed stone, commonly utilized in infrastructure construction and concrete manufacturing.

The processing of these crushed stone aggregates involves breaking down the raw material into smaller, uniform particles, usually between 10 mm and 20 mm in size. The angular and jagged texture of these aggregates enhances their interlocking capabilities within the concrete mix, thereby improving both compressive strength and durability. These attributes make the crushed stone aggregates from Margalla Hills a favored option for creating high-strength concrete and other robust construction materials.

3.1.2.1 Physical and Chemical Properties:

- Density: The bulk density of the crushed stone aggregates is 1650 kg/m^3 as per ASTM C 29/C 29M – 07 (ASTMC29, 2009).
- Absorption Capacity: The aggregates sourced from Margalla Hills exhibit low water absorption of 1.75%. This minimal absorption helps maintain the integrity and strength of the concrete, preventing problems such as water-related weakening or excessive shrinkage.
- Shape and Texture: The aggregates are crushed into an angular shape, which improves the bonding between the aggregates and the cement paste. This interlocking shape plays a significant role in the workability and compressive strength of the concrete mix.
- Grading: The crushed stone aggregates display a well-graded particle size distribution, typically conforming to the standards required for concrete production. The graded aggregates ensure optimal performance in construction applications

3.1.3 Fly Ash

Fly ash is a by-product created when pulverized coal is burned in power plants, consisting mainly of fine, powdery particles. It is commonly utilized in concrete production because of its cement-like properties, which enable it to react with calcium hydroxide ($Ca(OH)_2$) in the presence of water, resulting in the formation of additional calcium silicate hydrate (C-S-H) gels (Şenol & Karakurt, 2024), much like the reaction seen with Portland cement. This characteristic makes fly ash a valuable supplementary cementitious material (SCM) that improves the performance and durability of concrete (Freidin, 2007).

Typically, fly ash consists of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3), with silica being the most abundant, accounting for 40% to 60% of its total composition. The high silica and alumina content contribute to fly ash's pozzolanic nature, enabling it to chemically react with calcium hydroxide ($Ca(OH)_2$) produced during the hydration of cement.

The pozzolanic reaction of silica in fly ash with calcium hydroxide forms calcium silicate hydrate (C-S-H), which enhances the strength and durability of concrete. The primary reaction is as follows:

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow Stable, non - expansive\ silica\ gel \qquad \text{Eq. 3-4}$$

Similarly, alumina (Al_2O_3) in fly ash reacts with calcium hydroxide to produce calcium aluminate hydrate (C-A-H), which contributes to early strength development and enhances the resistance of concrete to chemical attacks:

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow C.A.H \qquad \text{Eq. 3-2}$$

These reactions generate additional hydrated compounds, filling the pores in the cement matrix and improving the compressive strength, density, and long-term durability of concrete (Kang et al., 2019).

3.1.4 Alkali Activators

The alkali activator (AA) is essential in the geopolymerization process and was created using a 12-molar sodium hydroxide (NaOH) solution combined with a sodium meta silicate (Na_2SiO_3) solution. To improve the silica-to-alumina ratio, sodium meta silicate was mixed with NaOH in a 2:1 mass ratio, which is crucial for optimizing the activation of the precursor materials. The high alkalinity of the NaOH solution, made at a 1:1 mass ratio of NaOH to water, helps to decompose the aluminosilicate structures of the raw materials, resulting in a highly reactive gel-like substance.

Likewise, the sodium metasilicate solution, prepared by mixing 1-part sodium metasilicate with 2 parts water by mass, provides the necessary silica for the geopolymerization reaction.

These two solutions were combined in the specified proportions to create an effective activator capable of breaking down the silicate structures in the aluminosilicate precursors, aiding their transformation into geopolymeric compounds. The inclusion of sodium metasilicate is particularly important, as it supplies both silica (SiO_2) and alkaline hydroxide (OH^-) ions, which are vital for maintaining the alkaline environment needed for the geopolymerization process. By adjusting the silica-to-alumina ratio, the activator mixture affects the final structure and strength of the geopolymer concrete, ensuring a dense and durable product.

The alkali activators were prepared 24 hours before casting the specimens. This time frame allows the solution components to activate, ensuring that the chemical reactions between NaOH and sodium metasilicate are fully realized. This maturation period also promotes optimal chemical bonding between the activators and the aluminosilicate materials in the concrete mix, leading to the formation of geopolymeric gel phases such as N-A-S-H (sodium alumino-silicate hydrate) gel. This gel effectively binds the aggregate particles together, resulting in a strong, cohesive material with enhanced mechanical properties compared to conventional concrete.

The precise control over the composition of the activator, along with the careful preparation of alkaline solutions, improves the workability and durability of geopolymer concrete, while also supporting its environmental sustainability. Geopolymer concrete, activated with sodium hydroxide and sodium metasilicate, is recognized for its lower carbon footprint, as it reduces the reliance on traditional Portland cement. Additionally, incorporating industrial by-products like fly ash or slag with the alkali activators results in a highly durable and chemically resistant material, making it suitable for use in harsh environmental conditions.

3.1.5 Waste powders

For this study, we selected three different types of waste powders: Granite Waste Powder (GWP) Figure 3-2, Marble Waste Powder (MWP) (Figure 3-3), and Pumice Waste Powder (PWP) Figure 3-4 . These powders were obtained from the local stone processing industry, which produces a considerable amount of by-products during the cutting and shaping of stones. To maintain consistency in the material properties, the waste powders were oven-dried at a constant temperature of 105°C for 24 hours to eliminate any moisture. After drying, the powders were sifted through a No. 200 sieve to ensure that the particle size did not exceed 75 µm.

The crystalline structure of the powders was examined using X-ray Diffraction (XRD), with the results displayed in Figure 4-1. This technique offered a thorough understanding of the morphological characteristics and physical properties of the waste powders, which are crucial for their effective integration into the geopolymer concrete mix.

Table 3-1 summarizes the physical and chemical properties of the waste powders, highlighting chemical composition. These assessments ensure that the waste powders fulfill the necessary criteria for use as supplementary cementitious materials (SCMs) in the production of alkali-activated lightweight concrete blocks. Incorporating these waste powders not only improves the mechanical properties and sustainability of the concrete but also helps reduce construction waste, fostering a more environmentally friendly approach in the building industry.

Figure 3-2 Granite Waste powder

Figure 3-3 Marble waste powder

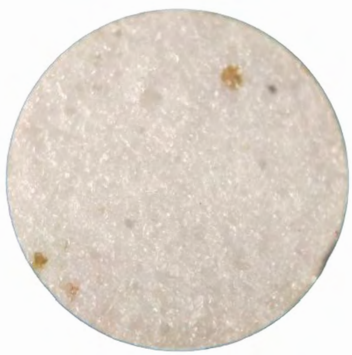

Figure 3-4 Pumice stone waste powder

Table 3-1: Physical and Chemical Properties of Waste Powders

Property	**MWP**	**GWP**	**PWP**
Physical Properties			
Color	White to light grey	Pink to grey	White
Texture	Smooth, fine	Coarse, granular	Porous, fine
Specific Gravity	2.64	2.72	0.8 – 1.0
Bulk Density (kg/m³)	1232	1418	600 – 900
Water Absorption (%)	0.15	0.16	30 – 60

Chemical Properties			
SiO_2 (%)	4	68	72.1
CaO (%)	53	3	1.7
Al_2O_3 (%)	< 1	13	12.8
Fe_2O_3 (%)	< 0.5	3.5	1.5
MgO (%)	0.78	0.72	0.6
K_2O (%)	< 0.2	4.3	3.1
Na_2O (%)	< 0.1	2.25	3.2
LOI (%)	41	0.75	6

3.2 Sample preparation

The mix design for the alkali-activated concrete (AAC) was created using methods outlined in recent studies (Şenol & Karakurt, 2024), with specific adjustments made to accommodate the unique characteristics of lightweight aggregate (LWA). Table 3-2 shows the detailed mix proportions utilized in this research. The ratio of precursor to coarse aggregate was set at 1:3, while the ratio of precursor to fine aggregate was established at 1:2. The ratio of alkali activator (AA) to precursor remained constant at 1:2.

To maintain consistency, the alkali activator, sand and coarse lightweight aggregate shown in Figure 3-6, Figure 3-7, and Figure 3-8 were combined in a volumetric ratio of 1:2:4. However, because pumice aggregates have a naturally high water absorption capacity, the initial workability of the trial mixtures was less than ideal. To remedy this, additional water and a superplasticizer shown in Figure 3-9 were added to the mix. The amount of extra water was adjusted to achieve a water-to-precursor ratio of 0.42, which included the water needed for preparing the alkali activator. As a result, the total density of the fresh concrete mixture was calculated to be 1521 kg/m³.

The AAC mix was freshly prepared and poured into cylindrical molds that were 100 mm in diameter and 200 mm in height shown in Figure 3-5. The samples remained in the molds for 48 hours at room temperature to allow for initial setting. After this period, the samples underwent heat curing in an electric oven at a steady temperature of 60°C for 72 hours to develop the necessary mechanical properties.

In this experimental program, 15 different mix proportions were designed listed in *Table 3-3* to assess how partial and complete replacement of fly ash with various types of waste stone dusts affects the mechanical properties of alkali-activated lightweight aggregate concrete (AA-LWAC).

The fly ash in the AAC mixtures was replaced at levels of 25%, 50%, 75%, and 100% using granite waste powder (GWP), limestone waste powder (LWP), and pumice waste powder (PWP). A reference mixture (CS) was also prepared without lightweight aggregates to provide a comparison benchmark. Detailed descriptions of all sample mixtures can be found in *Table 3-3*.

For each mix, three specimens were casted to ensure the results were reproducible and reliable. This method led to the creation of a total of 45 concrete specimens. The average values from the three specimens for each test were used to analyze and report the experimental results.

Figure 3-5: Fresh concrete poured into cylinders

Figure 3-6: Alakli Activator

Figure 3-7: Lightweight Aggregate

Figure 3-8: Sand

Figure 3-9 Super plasticizer

Table 3-2: Mix design of the AA-LWAC

Material	**Mass (kg)**
Marble/Granite/Pumice Dust	214.5
Fine Aggregate (Sand)	457.6
Coarse Aggregate (Pumice)	651
Sodium Hydroxide (NaOH) (12 M)	35.75
Sodium Metasilicate (Na_2SiO_3)	71.5
Water from NaOH Solution	32.18
Water from Na_2SiO_3 Solution	35.75
Additional Water for Workability	21.45 kg
Total Water Content	89.4 kg (89.4 litres)
Superplasticizer	2.15 kg

Table 3-3: Samples variation and nomenclature

Nomenclature	**LWA (%)**	**CA (%)**	**FA (%)**	**GWP (%)**	**MWP (%)**	**PWP (%)**
CS	0	100	100	0	0	0
LCS	100	0	100	0	0	0
LFA100	100	0	100	0	0	0
LGWP25	100	0	75	25	0	0
LGWP50	100	0	50	50	0	0
LGWP75	100	0	25	75	0	0
LGWP100	100	0	0	100	0	0
LMWP25	100	0	75	0	25	0
LMWP50	100	0	50	0	50	0
LMWP75	100	0	25	0	75	0
LMWP100	100	0	0	0	100	0
LPWP25	100	0	75	0	0	25
LPWP50	100	0	50	0	0	50
LPWP75	100	0	25	0	0	75
LPWP100	100	0	0	0	0	100

3.3 Testing

In this section, a series of tests were conducted to evaluate the key properties of the materials under investigation, following the relevant ASTM standards. The testing procedures are designed to assess specific characteristics critical to understanding the material's performance and suitability for this research study. These tests were carried out as per the guidelines set by ASTM to ensure consistency, accuracy, and reliability of the results. Detailed descriptions of each test, including methodologies and results, are presented in the subsequent sections.

3.3.1 Sieve Analysis of Aggregates

The sieve analysis of coarse aggregate was performed to obtain the particle size distribution and ensure compliance with the required gradation for construction. A dry representative sample of coarse aggregate was weighed accurately. The sample was passed through different sieves (25 mm to 4.75 mm) and was mechanically sieved for a particular time. The material on each of these sieves was collected separately, weighed and their percentage was calculated. The procedure followed ASTM C136 (AASTMC136, 2001).

3.3.2 Bulk density

The bulk density of aggregates was measured using ASTM C29 (ASTMC29, 2009). This standard outlines how to determine the bulk density (unit weight) of aggregates. The container was filled with a known volume of the aggregate. It is make sure to compact it to reduce air space. Then record the mass of the filled container. To calculate the bulk density, the mass of the aggregate is divided by the container's volume.

The ordinary crushed aggregate had a bulk density of 1650 kg/m^3. The lightweight aggregate's bulk density was 1150 kg/m^3. These findings aligned with ASTM C29 standards. This data plays a key role in concrete mix design and helps estimate materials for construction projects.

3.3.3 Workability of concrete

To check how easy the concrete was to work with using the slump cone test, following ASTM C143 (ASTMC143, n.d.). slump cone was filled with concrete in three layers pressing each layer 25 times with a tamping rod. The cone was lifted and the slump as the space between the top of the cone and the highest spot of the slumped concrete. This was done three times to get an average slump value, which showed how workable the mix was. The numbers fell within the range needed for what it wanted to use it for.

3.4 Ultrasonic pulse velocity test:

Ultrasonic Pulse Velocity (UPV) testing, as outlined in ASTM C597 (ASTM-C597-22, 2018), is a non-destructive technique widely used to evaluate the quality and integrity of concrete and other materials. This method measures the travel time of ultrasonic pulses through the material to assess its density, uniformity, and detect defects such as cracks, voids, or honeycombing. The test involves using a pulse generator, transducers (transmitter and receiver), and a digital display to record the pulse travel time. Proper preparation of the test surface, including cleaning and applying a coupling agent, ensures accurate measurements. The velocity of the ultrasonic pulse is calculated by dividing the travel path length by the pulse travel time. Higher UPV values, typically above 4000 m/s, indicate dense, well-compacted, and high-quality concrete, whereas moderate values (3000–4000 m/s) suggest minor imperfections. Values below 3000 m/s often reflect significant defects or poor-quality concrete. This technique is instrumental in evaluating concrete uniformity, identifying structural defects, estimating elastic modulus and compressive strength indirectly, and monitoring changes in concrete properties over time. Its effectiveness makes UPV testing a crucial tool for quality control in construction and the assessment of existing structures' health.

3.4.1 Compressive Strength Testing

The compressive strength of concrete was determined using a Universal Testing Machine (UTM) as per ASTM C39 (ASTMC39, 2021). Concrete cylinders with a height of 203.2 mm and a diameter of 101.6 mm were prepared and cured for 28 days. After curing, the specimens were placed in the UTM shown in Figure 3-10, and a compressive load was applied gradually until failure. The maximum load at failure shown in Figure 3-11 was recorded, and the compressive strength was calculated by dividing the failure load by the cross-sectional area of the specimen. This method provided crucial data on the concrete’s compressive strength, which is essential for evaluating its suitability for structural applications.

Figure 3-10: Concrete Cylinder before Rupture in UTM

Figure 3-11: Concrete Cylinder after Rupture in UTM

4 Results & Discussion

4.1 XRD of the Precursors

The results of X-ray diffraction (XRD) analysis in Figure 4-1 identified crystalline and amorphous phases of FA, PWP, MWP, and GWP, providing insight into their mineralogical compositions and potential suitability for AA-LWAC. The XRD pattern of FA shows a broad hump indicative of its highly amorphous nature, which is key in the alkali-activation process. The high silica and alumina content in FA make it a prime candidate for use in AAC, where these components react with the alkaline solution to form aluminosilicate gels, contributing to the binder formation. Crystalline phases of quartz (SiO_2), mullite ($Al_6Si_2O_{13}$), and calcite ($CaCO_3$) are present in FA. Still, these crystalline phases are less significant in alkali activation, as quartz and mullite may have limited reactivity in the alkaline environment. Thus, the pozzolanic reactivity of FA could be secondary to its role as a geopolymer precursor in AAC applications.

The XRD pattern for PWP shows a more significant presence of crystalline phases, primarily quartz (SiO_2) and albite ($NaAlSi_3O_8$), along with minor peaks for zeolites and other silicate minerals. The zeolites in pumice are especially important in AAC, as they enhance the material's reactivity in an alkaline environment, potentially improving the mechanical properties and durability of the resulting concrete. The high silica content of PWP supports the alkali-activation process, furthering its applicability as a supplementary material in AAC.

In the case of MWP, the XRD pattern reveals a high calcite content characteristic of marble. Calcite, while not directly reactive in the alkali-activation process, could influence the texture and durability of AAC, particularly in terms of carbonation resistance and the potential for CO_2 emissions during the decomposition of calcite. Minor peaks for dolomite and quartz reflect impurities in the marble material. As with traditional concrete, the environmental implications of high calcite content in AAC, especially regarding carbonation, warrant further investigation.

The XRD pattern of GWP shows a more complex mineral composition, with quartz, feldspar (potassium feldspar and albite), and mica as the primary phases. These minerals contribute to the heterogeneous granularity of granite waste powder. In AAC, the high silica content, especially from quartz, could enhance the reactivity of GWP with the alkaline activator, promoting the formation of a stable geopolymer structure. The feldspar and mica components might also influence the material's texture and mechanical performance, potentially enhancing AAC's durability against various environmental stresses.

The properties of these minerals suggest that the materials can be effectively used in alkali-activated concrete, especially in applications requiring durability and sustainability. FA’s amorphous structure makes it a suitable precursor for alkali activation, while PWP’s high silica and zeolite content can enhance reactivity. MWP, with its calcite content, may offer benefits in terms of carbonation resistance but requires further study regarding its influence on CO_2 emissions. GWP could enhance AAC's mechanical properties and durability with its diverse mineral content. These findings highlight the potential of these waste materials as green alternatives in producing alkali-activated concrete, promoting sustainability and durability. However, further research is needed to explore their long-term performance and environmental impact on AAC applications.

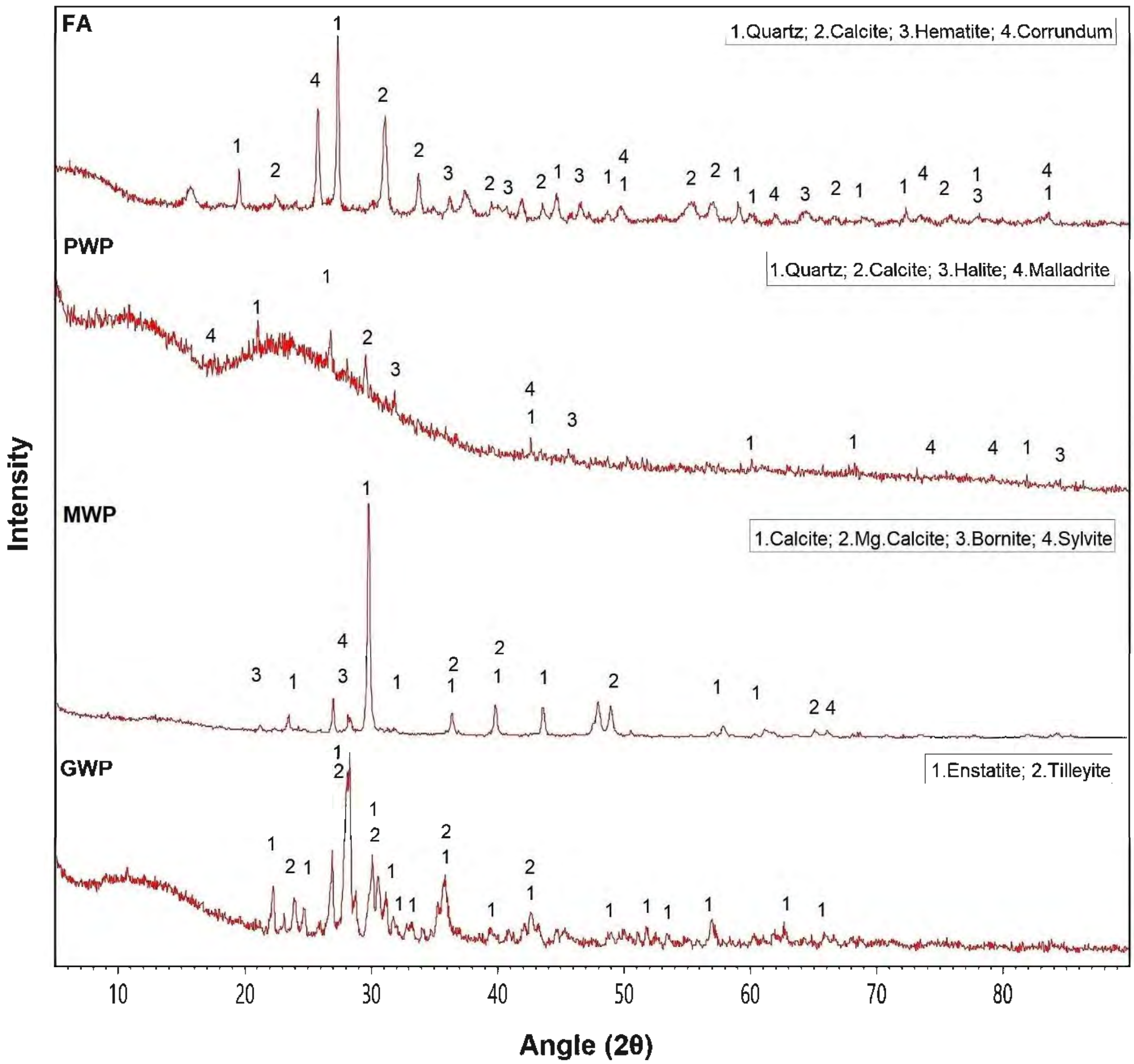

Figure 4-1: XRD for Precursors in AA-LWAC

4.2 Workability

The slump test was conducted to assess the workability of different concrete mixes. The results, presented in the bar chart, show the slump values (in mm) for various mix types.

- **CS (Control Sample)** achieved the highest slump value of 75 mm, indicating a relatively high workability and fluidity.

- **LCS (Lightweight Concrete Sample)** had a slump of 60 mm, showing a moderate decrease in workability compared to the control sample.
- **LFA100 (Lightweight Fly Ash 100%)** exhibited a slump value of 52 mm, reflecting a slight reduction in fluidity due to the increased use of fly ash.
- **LGWP (Lightweight Granite Waste Powder) mixes** showed a progressive reduction in slump, from 46 mm for 25% addition to 36 mm for 100% addition. This indicates a decrease in workability as the proportion of granite waste powder increased.
- **LMWP (Lightweight Marble Waste Powder) mixes** demonstrated a similar trend, with slump values ranging from 49 mm (25% addition) to 34 mm (100% addition), reflecting a decrease in workability as the marble waste powder content increased.
- **LPWP (Lightweight Pumice Waste Powder) mixes** showed a consistent decline in slump, from 55 mm (25%) to 35 mm (100%).

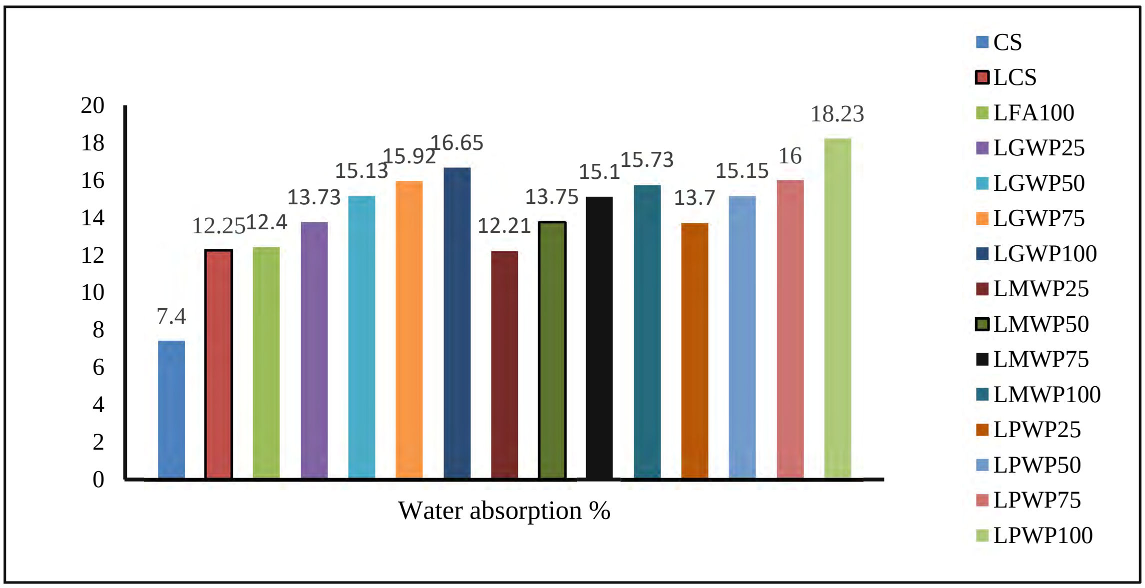

Figure 4-2: Workability of different mixes

4.3 Water absorption

The water absorption values for various concrete mixes were determined to assess the porosity and durability of the mixes. The results indicate that water absorption increases as the proportion of lightweight waste powders in the mix rises.

- **CS (Control Sample)** exhibited the lowest water absorption at 7.4%, reflecting the low porosity and better durability of the conventional concrete.
- **LCS (Lightweight Concrete Sample)** showed a significant increase in water absorption, reaching 12.25%, which suggests that the inclusion of lightweight aggregates results in higher porosity.
- **LFA100 (Lightweight Fly Ash 100%)** had a water absorption value of 12.4%, slightly higher than LCS, indicating that the high fly ash content leads to a marginal increase in porosity.
- **LGWP (Lightweight Granite Waste Powder) mixes** demonstrated a gradual increase in water absorption with increasing granite waste powder content, from 13.73% at 25% addition to 16.65% at 100% addition. This indicates that higher proportions of granite waste increase the porosity and water absorption of the concrete mix.
- **LMWP (Lightweight Marble Waste Powder) mixes** followed a similar trend, with water absorption ranging from 12.21% (25% addition) to 15.73% (100% addition), indicating an increase in porosity as more marble waste powder was added to the mix.
- **LPWP (Lightweight Pumice Waste Powder) mixes** showed the highest water absorption values, ranging from 13.7% (25%) to 18.23% (100%). This trend suggests that pumice waste powder significantly increases the porosity and water absorption, particularly when used in higher percentages.

In summary, the results show that the use of lightweight waste powders, including granite, marble, and pumice waste, increases the water absorption of concrete. This is indicative of increased porosity, which can impact the durability of the concrete, especially in exposed environments.

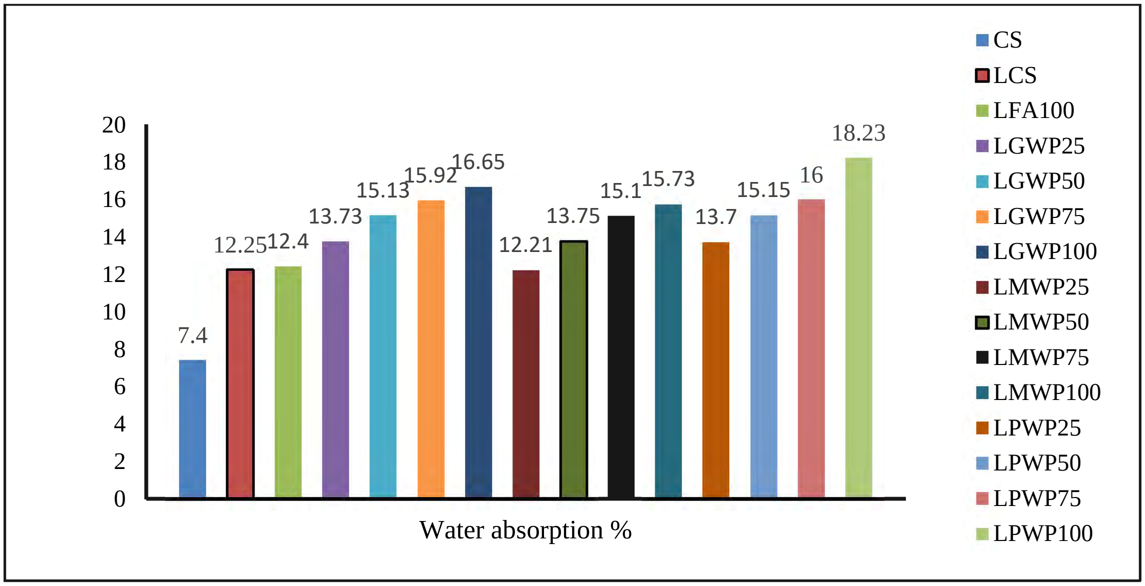

Figure 4-3: Absorption test results

4.4 Ultrasonic pulse velocity test

The Ultrasonic Pulse Velocity (UPV) test results highlight critical insights into the structural properties of different concrete mixes. The Control Sample (CS) displayed the highest UPV value of 4000 m/s, signifying the densest and most intact structure, making it the reference for comparison. The Lightweight Concrete Sample (LCS) and Lightweight Fly Ash (LFA100) mixes both exhibited a UPV of 3500 m/s, indicating slightly reduced compactness compared to the CS. Among the lightweight waste materials, the Lightweight Granite Waste Powder (LGWP) mixes showed a decline in UPV from 3300 m/s at 25% inclusion to 2500 m/s at 100%, reflecting a gradual loss in structural integrity. The Lightweight Marble Waste Powder (LMWP) mixes exhibited the lowest UPV values, ranging from 2800 m/s (25%) to 2100 m/s (100%), suggesting a highly porous structure. Conversely, the Lightweight Pumice Waste Powder (LPWP) mixes demonstrated relatively higher UPV values, ranging from 3400 m/s (25%) to 2700 m/s (100%), showing better structural performance compared to LGWP and LMWP. Overall, as the percentage of waste material increased, the UPV values decreased, indicating reduced density and compactness. Among the waste types, LPWP showed the least negative impact on structural properties, followed by LGWP and LMWP, respectively.

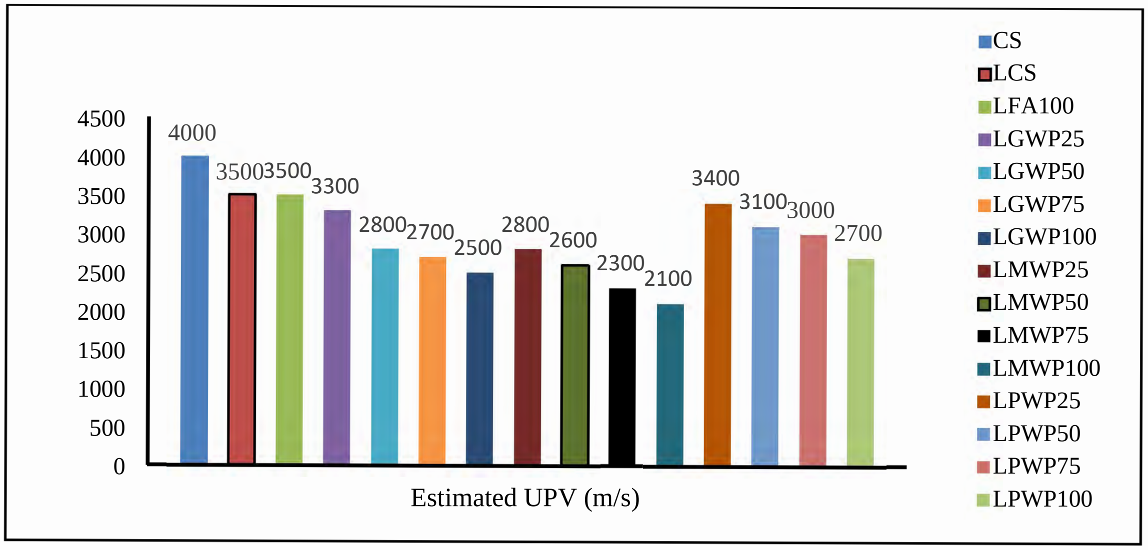

Figure 4-4: Ultrasonic pulse velocity results

4.5 Effects of Dust Replacement on Ultimate Compressive Strength

The compressive strength of the control sample (CS) using normal cement and coarse aggregate was measured at 22.48 MPa, which aligns with the expected results based on the design mix. However, when pumice stone was used as a replacement for the coarse aggregates, there was a notable reduction of 36.5%. This decrease is anticipated due to the higher porosity and lower density of lightweight aggregates, which ultimately diminishes the overall strength. Additionally, substituting the cement with alkali activators, specifically 100% fly ash (LFA100), led to a further decline in strength to 13.56 MPa, representing a 39.6% reduction compared to the CS. The small strength difference between LFA100 and LCS, which is only 0.71 MPa or 5%, highlights the highly amorphous nature of fly ash. This characteristic enhances its potential for alkali activation but may not entirely offset the loss of the binding properties typically provided by cement. These mixtures present considerable weight savings, making them ideal for non-structural applications where strength is not the main concern.

At a 25% replacement level, the strength remains relatively high at 12.51 MPa, which is only a 7% decrease compared to LFA100. This can be attributed to the significant silica content in granite waste powder (GWP), especially from quartz and feldspar, which plays a key role in the alkali-activation process. However, when the replacement levels increase to 50%, 75%, and 100%, there is a sharp decline in strength by 39.5%, 53.7%, and 65.0%, respectively. This reduction is due to the predominance of quartz and feldspar phases; while they aid in geopolymer formation, their reactivity decreases at higher replacement levels, compromising structural integrity. The findings indicate that GWP is most effective when its replacement is kept to 25% or less in AA-LWAC. Exceeding this limit results in significant strength loss, rendering it unsuitable for load-bearing applications.

Marble waste powder (MWP) mainly serves as a filler because of its high calcite content, which is not very reactive in the alkali-activation process. As a result, there is a notable decrease in strength at all replacement levels—38.3%, 61.9%, 74.9%, and 81.3% for 25%, 50%, 75%, and 100% replacements, respectively. This considerable reduction indicates that the filler effect of calcite is not enough to preserve structural integrity, and the limited reactivity of MWP components like dolomite and quartz further restricts its ability to enhance strength.

In contrast, using pumice powder (PWP) as a replacement for cement shows significantly better results, with only an 8.6% reduction in compressive strength. Even at higher replacement levels (LPWP50–100), the remaining strength surpasses that of LGWP and LMWP, highlighting the superior performance of PWP. This enhanced performance is due to the high silica and alumina content in pumice, along with the presence of zeolites, which greatly improve its reactivity in the alkali-activation process, making it a more effective material for AA-LWAC applications.

4.6 Effects of Dust Replacement on Stress-Strain Curves

The descending part of the stress-strain curves shows how the material behaves after it has reached its ultimate compressive strength. This area is crucial for assessing the material's ductility and energy absorption capacity. At lower replacement levels (LGWP25), the decline in stress after the peak was gradual, suggesting that some load-bearing capacity was retained. This behavior indicates a relatively ductile failure mode, likely due to adequate gel formation and cohesion within the microstructure. As the GWP replacement increased (LGWP50, LGWP75), the slopes after the peak became steeper, indicating a shift towards brittle failure. The weaker interfacial bonds and reduced cohesion in these mixes led to a sudden loss of load-carrying capacity once the peak stress was reached. At 100% replacement (LGWP100), the material showed a distinctly brittle failure mode, with a nearly vertical drop in stress following the peak. This behavior suggests that the matrix could not support loads without sufficient gel phase formation.

The post-peak response of LMWP25 resembled that of the control mix, with a gradual stress decrease, indicating a ductile failure mode. This suggests that at lower replacement levels, MWP does not significantly change the failure characteristics of the mix. The fine particle size of MWP likely improved the packing density of the mix, offsetting the reduction in cement content and leading to performance similar to the control mix. At 50% and 75% replacement, the post-peak decline became steeper, indicating a transition to more brittle behavior. The diminished cohesion in the matrix, due to lower hydration product formation, is likely a contributing factor. The LMWP100 mix exhibited a highly brittle failure mode, with a sharp drop in stress after the peak. The insufficient hydration products and a weaker microstructure played a role in this behavior, rendering the mix unsuitable for applications that require energy dissipation or ductile performance.

The LPWP25 mix showed a post-peak trend similar to the control, with a steady reduction in stress. This indicates that at low LPWP content, the matrix can still redistribute stresses and handle further deformation. However, as the LPWP content increased, the post-peak behavior became more brittle, marked by a sharper decline in stress. This suggests a weaker matrix where cracks spread quickly once the ultimate load is reached. The LPWP100 mix demonstrated a sudden and significant drop in stress after the peak, indicating a brittle failure mode. Its porous and weak microstructure offered little resistance to crack propagation beyond the peak stress. In contrast, the post-peak response of LPWP25 resembled that of the control mix, showing a gradual decline in stress. This implies that at low replacement levels, LPWP does not greatly affect the mix's capacity for plastic deformation after reaching the peak load.

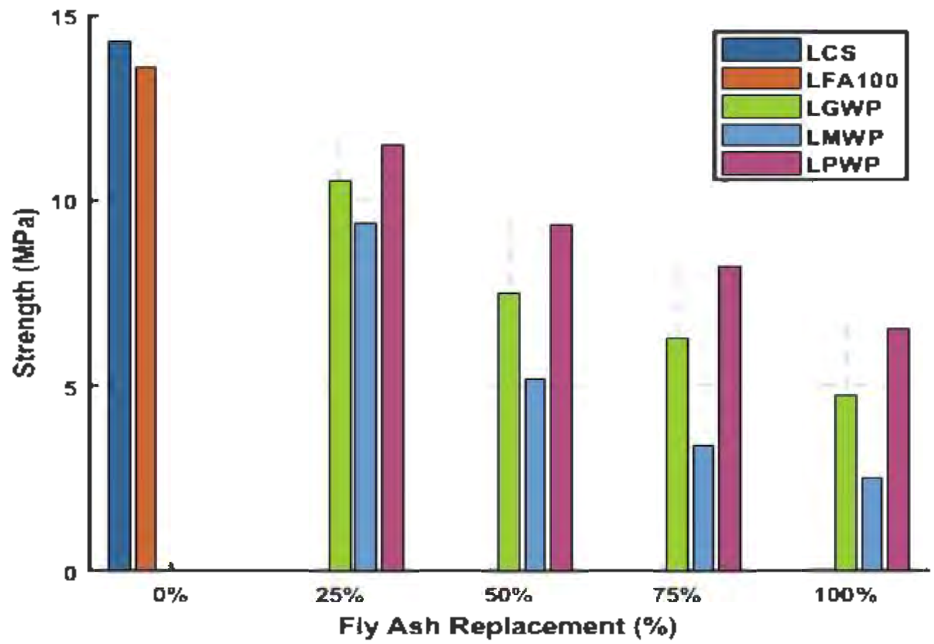

Figure 4-5: Ultimate Compressive Strength of AA-LWAC with replacement of FA precursor with waste stone dust

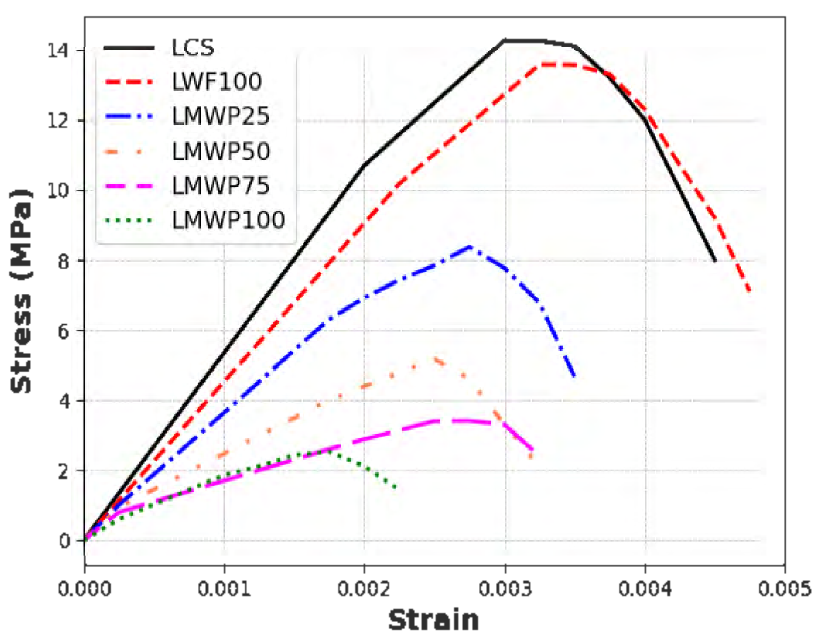

Figure 4-6: Marble waste powder replacement Stress-Strain results

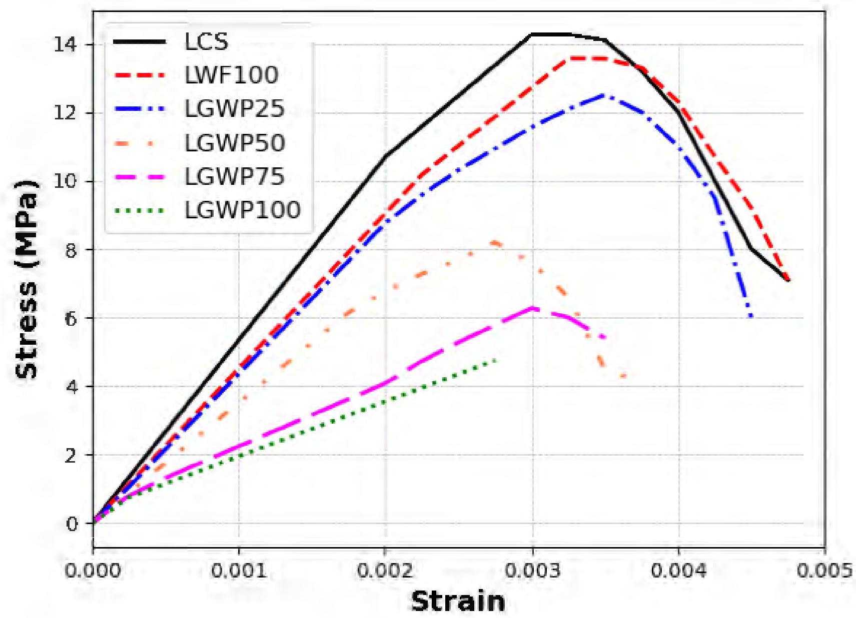

Figure 4-7: Granite waste powder stress-strain curves

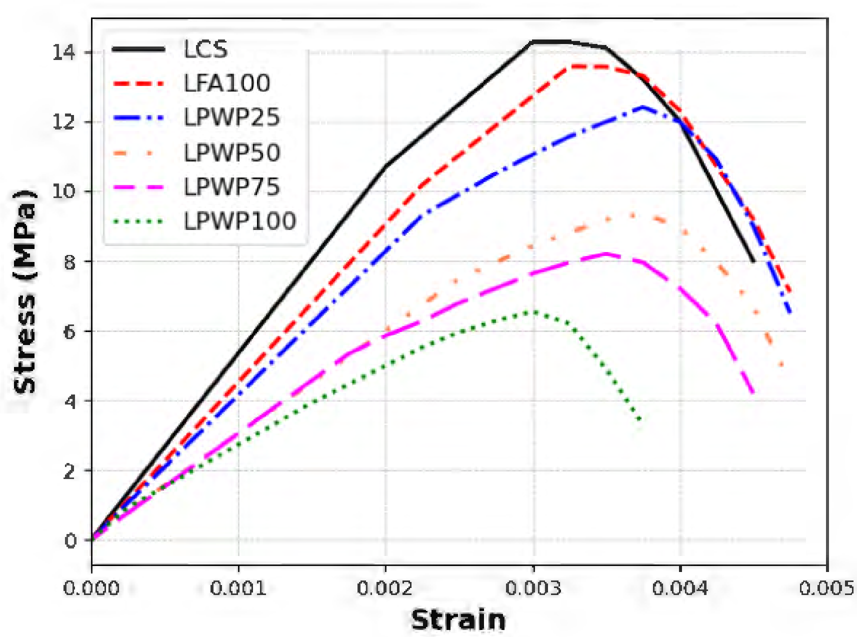

Figure 4-8: Pumice stone waste powder

The stress-strain behaviour of the different waste powders, a comparison of their performance at similar replacement levels is shown in Figure 4-9, Figure 4-10, Figure 4-11and Figure 4-12. As observed, at a 25% replacement, LGWP and LPWP exhibit nearly identical stress-strain curves, showing similar ultimate strengths and strain values. However, LMWP displays a marked reduction in both strength and strain capacity, as evident from its distinctively lower ultimate strength and strain values compared to LGWP and LPWP. At the 50% replacement level, LPWP shows better performance, offering both higher strength and enhanced ductility, with an ultimate strain value of approximately 0.0035 at the peak strength. In contrast, LGWP shows a similar ultimate strength but with a reduced strain value of 0.0027, reflecting lower ductility.

When replacement levels reach 75% to 100%, all waste powders exhibit a notable decrease in performance, particularly in terms of strength and ductility. Nevertheless, in applications involving low-strength and lightweight concrete where strength is not the main focus, LPWP emerges as a suitable material because it effectively maintains ductility and has a lower density. This underscores the promise of LPWP as a sustainable option, especially in situations where strength is less critical compared to factors like lightweight characteristics or cost-effectiveness.

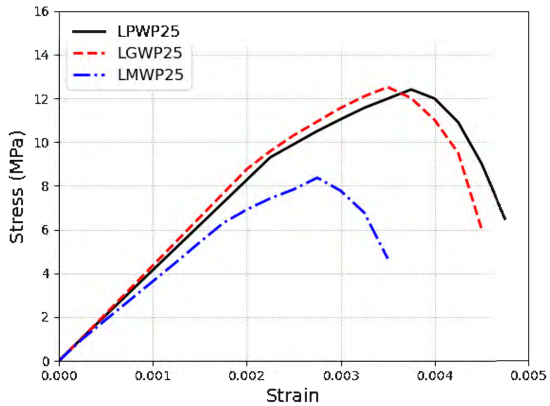

Figure 4-9: 25% Replacement

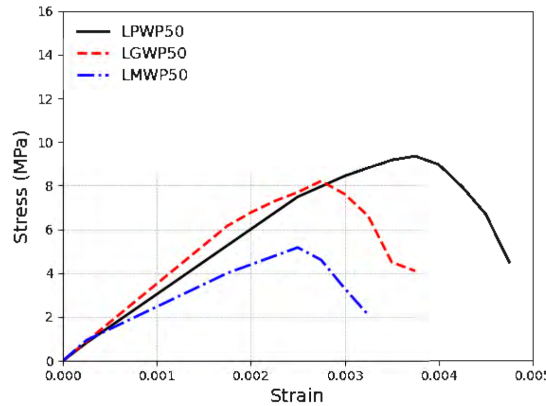

Figure 4-10: 50% Replacement

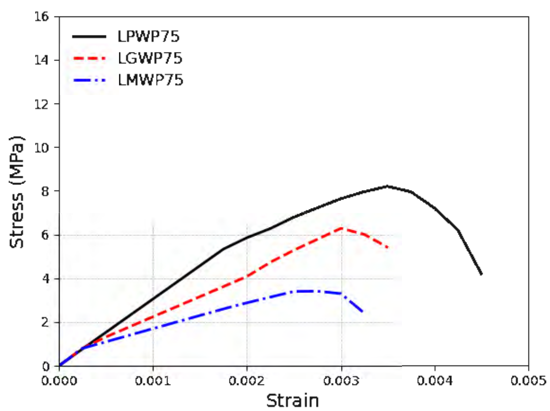

Figure 4-11: 75% Replacement

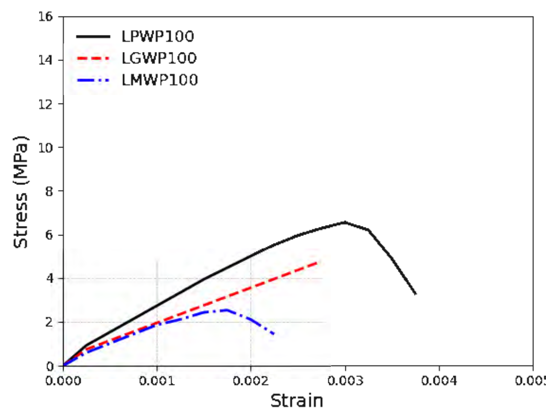

Figure 4-12: 100% Replacement

4.7 Effects of Dust Replacement on Secant Stiffness

The stiffness of a material is often assessed using the secant modulus, which is usually calculated from the slope of the stress-strain curve that connects the origin to 40% of the ultimate strength. This modulus offers a good estimate of the material's stiffness in the elastic region, which is crucial for understanding how well the material can resist deformation when loads are applied. In this study, we present the secant modulus for various samples at different replacement levels, shown in percentage form relative to the LCS, which is set at 100% (see Figure 4-13).

As illustrated in Figure 4, the LCS exhibits the highest secant modulus at a 0% replacement level, indicating superior stiffness compared to the other samples. With an increase in the replacement level, the secant modulus for the different waste powders shows a decline, reflecting a decrease in material stiffness. Among the waste powders, LGWP experiences the most pronounced reduction in secant modulus as the replacement level rises, with values falling from 81.7% at 25% replacement to 36.5% at 100% replacement, indicating a significant loss of stiffness at higher replacement levels. Likewise, LMWP shows a steady decrease in stiffness, with values dropping from 68.0% at 25% replacement to 38.2% at 100% replacement. In contrast, LPWP maintains more stable stiffness values, with a moderate reduction from 77.5% at 25% replacement to 51.1% at 100% replacement.

A higher secant modulus signifies increased stiffness, indicating that the material can better withstand strain when stress is applied. The observed decrease in secant modulus with higher waste powder content implies that although these waste powders may enhance other attributes like sustainability and lightweight features, they compromise the material's stiffness. This reduction in stiffness can be critical in scenarios where rigidity is essential, such as in structural components that demand high load-bearing capacity and minimal deformation.

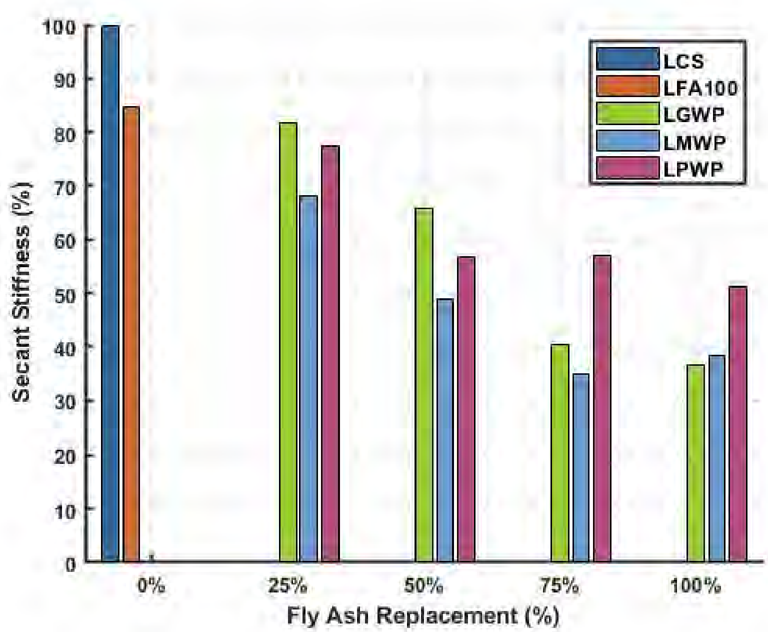

Figure 4-13: Secant Stiffness

5 Conclusion

This experimental study comprehensively investigated the mechanical performance of lightweight concrete incorporating different types of industrial waste powders; Lightweight Granite Waste Powder (LGWP), Lightweight Marble Waste Powder (LMWP), and Lightweight Pumice Waste Powder (LPWP) as partial replacements for Fly-Ash (FA) precursor in the Alkali-activated Lightweight Aggregate Concrete (AA-LWAC). The primary objective was to evaluate the effect of these waste powders on the compressive strength, stress-strain behaviour, and secant modulus of lightweight concrete. Based on the experimental findings, the following conclusions can be drawn:

- At lower replacement levels (25-50%), LGWP and LPWP performed better than LMWP. Notably, LPWP at 50% replacement showed the highest strength among all samples, achieving ultimate strengths that were nearly on par with the control sample (LCS). However, at higher replacement levels (75-100%), all waste powders experienced significant reductions in strength, with LGWP and LMWP showing more severe declines than LPWP. These performance trends indicate that LPWP is a promising alternative for lightweight concrete in non-load-bearing applications where some reduction in strength is acceptable.
- The stress-strain responses indicated that LPWP surpassed LGWP and LMWP in ductility and strain capacity, especially at the 50% replacement level, where LPWP reached an ultimate strain of 0.0035. LGWP had similar strength but lower ductility, with an ultimate strain of 0.0027. At higher replacement levels, all samples showed reduced ductility and a notable drop in peak strength, yet LPWP maintained relatively better performance compared to the other waste powders. This implies that LPWP could be a suitable choice for applications that require moderate ductility, such as non-structural concrete elements.
- The secant modulus, measured at 40% of the ultimate strength, consistently decreased as the replacement levels of waste powders increased, indicating a decline in stiffness. LPWP showed more stable stiffness compared to LGWP and LMWP, especially at higher replacement levels. The notable drop in stiffness for LGWP and LMWP at 75-100% replacement levels restricts their use in applications that require high rigidity. On the other

hand, LPWP retained moderate stiffness, making it a better option for lightweight and non-load-bearing structures.

- LPWP stood out as the best-rounded material among the waste powders examined, showcasing a favorable mix of compressive strength, ductility, and stiffness. Its excellent performance at 50% replacement underscores its potential as a sustainable and lightweight choice for moderate-strength concrete applications. While LGWP and LMWP displayed acceptable performance at lower replacement levels, they experienced significant declines in stiffness and strength at higher replacements. These materials may be better suited for non-structural or insulating applications where high mechanical performance is not essential.
- Using these waste powders in concrete offers an environmentally friendly way to cut down on cement use, reduce carbon emissions, and encourage the recycling of industrial byproducts. However, it's essential to optimize the levels of replacement to find the right balance between sustainability and mechanical performance. LPWP, in particular, holds potential for lightweight construction applications, including partition walls, precast elements, and insulation panels, where its moderate strength and improved ductility can be effectively utilized.

5.1 Future recommendations

- While this study focused on replacing Fly Ash (FA) with varying proportions of industrial waste powders, future research should explore the potential of replacing Granulated Blast Furnace Slag (GGBFS) as well. Since GGBFS has been commonly used as a precursor in alkali-activated concretes, investigating its replacement with waste powders, such as marble, granite, and pumice stone powders, could provide additional insights into their suitability for diverse concrete applications.
- Additionally, this study primarily focused on lightweight concrete for moderate-strength applications. Further research is needed to develop high-strength lightweight alkali-activated concrete (LW-AAC). This would involve optimizing the mix proportions and identifying suitable combinations of waste powders and aggregates to achieve the necessary mechanical properties for structural applications in high-rise buildings or other

demanding constructions.

- Finally, while the findings of this study are promising, practical implementation of alkali-activated concrete incorporating waste powders requires more research to address challenges related to production scalability, material consistency, and long-term performance in field applications. Investigating the durability, workability, and cost-effectiveness of these materials at a larger scale is crucial to facilitate their adoption in the construction industry. Field trials and real-world applications should be explored to better understand how these materials perform under various environmental and loading conditions.

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