

**T.C.
ISTANBUL GEDİK UNIVERSITY
INSTITUTE OF GRADUATE STUDIES**



**PERFORMANCE OF SLAG-VOLCANIC ASH-BASED
GEOPOLYMER COMPOSITES WITH DIFFERENT CURING
TEMPERATURES**

MASTER THESIS

Marwah Saad Hussein AL-SAEDI

Engineering Management Department

Engineering Management Master in English Program

**JUNE 2024
ISTANBUL**

**T.C.
ISTANBUL GEDİK UNIVERSITY
INSTITUTE OF GRADUATE STUDIES**



**PERFORMANCE OF SLAG-VOLCANIC ASH-BASED
GEOPOLYMER COMPOSITES WITH DIFFERENT CURING
TEMPERATURES**

MASTER THESIS

**Marwah Saad Hussem AL-SAEDI
(211281016)**

Engineering Management Department

Engineering Management Master in English Program

Thesis Advisor: Assoc. Prof. Dr. Redvan GHASEMLOUNIA

Thesis Second Advisor: Assist. Prof. Dr. Metin MEHMETOĞLU

Istanbul 2024



T.C.
İSTANBUL GEDİK ÜNİVERSİTESİ
Lisansüstü Eğitim Enstitüsü Müdürlüğü

Jüri Tez Onay Formu

..../...../2023

LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ MÜDÜRLÜĞÜ

Bu çalışma/...../2023 tarihinde aşağıdaki jüri tarafından Mühendislik Yönetimi Anabilim Dalı, Mühendislik Yönetimi (Tezli Yüksek Lisans) Programı Yüksek Lisans Tezi olarak kabul edilmiştir.

TEZ JÜRİSİ

Doç Dr. Redvan GHASEMLOUNIA

Danışman

İstanbul Gedik Üniversitesi

Üye (İmza)

İstanbul Gedik Üniversitesi

Üye (İmza)

İstanbul Gedik Üniversitesi

DECLARATION

I, Marwah Saad Hussem AL-SAEDI, declare that this thesis titled “Performance of Slag-Volcanic Ash-Based Geopolymer Composites with Different Curing Temperatures” is original work I completed this to receive my master's in civil engineering. I further declare that neither this thesis nor any part of it has ever been submitted to or presented for a research paper or other degree at any other university or institution. (05 /06/2024)

Marwah Saad Hussem AL-SAEDI



ACKNOWLEDGEMENTS

“He is one who is obedient during the night, prostrating and standing, fearing the Hereafter and hoping for the mercy of his Lord. Say: Are those who know equal to those who do not know? And only those of understanding remember”

[Az-Zumar: 9]

Is one who is devoutly obedient during periods of the night, prostrating and standing [in prayer], fearing the Hereafter and hoping for the mercy of his Lord, [like one who does not]? Say, "Are those who know equal to those who do not know?" Only they will remember [who are] people of understanding.

Alhamdulillah for this success, and I pray for success for all those pursuing the path of science. May Allah guide and bless their endeavors abundantly.

I express deep gratitude to the Republic of Iraq for its inspiration and support. May Allah grant peace and prosperity to our beloved nation once more.

I extend my warmest gratitude to the Republic of Turkey for its invaluable scientific and financial support during my studies. Thank you for believing in me.

"I am profoundly grateful to Assoc. Prof. Dr. Redvan GHASEMLOUNIA for his unwavering support and guidance during my studies. Working under his mentorship has been an honor and a privilege."

"I extend my sincere thanks to Assist. Prof. Dr. Metin MEHMETOĞLU for his invaluable contribution to the experimental studies. His wealth of experience, keen interest, and unwavering cooperation have been instrumental in every stage of our work together."

To my parents, your sacrifices and relentless dedication to my education have laid the foundation for my pursuit of knowledge. Your unwavering belief in my potential has fueled my determination, and I am deeply grateful for the countless sacrifices you've made to see me succeed.

To my friends, whose laughter and camaraderie have provided much-needed breaks and a sense of balance amid the academic rigor. Your support and encouragement have been a source of motivation, and I am fortunate to have you by my side.

This thesis is dedicated to each of you, a reflection of the collective efforts and sacrifices that have paved the way for my academic achievements. Your love and encouragement have been my driving force, and this accomplishment is as much yours as it is mine.

With heartfelt gratitude

Marwah Al-SAEDI



FOREWORD

In the realm of construction materials, the pursuit of sustainable and high-performance alternatives to traditional concrete has become imperative. This journey has led us to the fascinating world of geopolymers, where innovative combinations of fly ash, GGBFS, and volcanic ash have unlocked a realm of possibilities. The research presented in this body of work delves into the intricacies of geopolymer concrete, offering a comprehensive exploration of its properties and potential applications.

The amalgamation of environmental consciousness with engineering prowess is evident in the exploration of curing methods. The shift towards room conditions and freeze-thaw curing not only signifies a commitment to eco-friendliness but also unravels new dimensions in geopolymerization. The resilience of these geopolymers against high temperatures, coupled with the nuanced interplay of different material proportions, paints a vivid picture of a material poised for diverse applications.

As we navigate through the findings presented here, the optimization of mix ratios emerges as a delicate dance between enhancing compressive strength and mitigating potential strength loss. The promise of ground granulated blast furnace slag in geopolymer concrete beckons towards a future where sustainable construction materials can rival conventional counterparts.

This work does not merely exist within the confines of a laboratory; it sets the stage for future endeavors. The recommendations for future research laid out here pave the way for a deeper understanding of geopolymers-both in terms of their structural intricacies and their practical viability. From microstructural analyses to real-world field trials, the roadmap outlined here seeks to push the boundaries of what geopolymers can achieve.

In the hands of researchers, engineers, and practitioners, this work is not just a collection of findings but a catalyst for further innovation. It is an invitation to explore, question, and redefine the landscape of construction materials. The journey

towards environmentally friendly, high-performance concrete is an ongoing saga, and this body of work contributes a compelling chapter to that narrative.

May these insights spark curiosity, ignite discussions, and propel us toward a future where sustainable construction is not just a choice but a standard.



TABLE OF CONTENT

	<u>Page</u>
ACKNOWLEDGEMENTS	iv
FOREWORD	vi
TABLE OF CONTENT	viii
ABBREVIATIONS	x
LIST OF TABLES	xi
LIST OF FIGURES	xii
ABSTRACT	xiv
ÖZET	xvi
1. INTRODUCTION	1
1.1 Literature Review	1
1.2 Objective of the Thesis	6
1.3 Hypothesis	7
2. LITERATURE REVIEW	8
2.1 General	8
2.1.1 Literature on geopolymers made of volcanic ash in detail	9
2.1.2 A geopolymeric matrix's filler components	12
2.1.3 The impact of varying activator molarities	14
2.1.4 The role of curing temperature in geopolymerization and its impact on material qualities	16
3. MATERIALS AND METHODS	18
3.1 Introduction.....	18
3.2 Materials	18
3.2.1 Volcanic ash	18
3.2.2 Ground granulated blast furnace slag (GGBFS)	20
3.2.3 River sand	21
3.2.4 Chemical activators	21
3.3 Mixes Proportions and Plan Categorization	23

3.4 Experimental program.....	26
3.4.1 Procedures for mixing, molding, and curing	26
3.4.2 Test program	29
3.4.2.1 Strength tests	29
3.4.2.2 Ultrasonic pulse velocity test	31
3.4.2.3 Unite weight, Water Absorption and Voids Ratio.....	31
3.4.2.4 Freezing-thawing test.....	32
4. RESULTS AND DISCUSSION	34
4.1 General	34
4.1.1 Physical properties (water absorption, unit weight).....	34
4.1.2 Strength properties.....	35
4.1.3 Ultrasonic pulse velocity test	37
4.1.4 Elevated temperature test.....	40
4.1.5 Freezing-thawing test	53
4.1.6 Acid attack test.....	58
4.1.7 The correlation between upv and compressive strength.....	63
4.2 Conclusions.....	64
4.3 Recommendations for Future Work.....	65
REFERENCES	67
RESUME.....	76

ABBREVIATIONS

SEM	: Scanning Electron Microscopy
EDS	: Energy-dispersive X-ray Spectroscopy
OPC	: Ordinary Portland Cement
GPMs	: Geopolymer Mortars
TGA	: Thermal Gravimetric Analysis
XRD	: X-ray Diffraction
EDX	: Energy Dispersive X-ray
LCAs	: Life Cycle Assessments
ASR	: Alkali-Silica Reaction
SDGs	: Sustainable Development Goals
FTIR	: Fourier Transform Infrared spectroscopy
EE	: Energy Efficiency
VA	: Volcanic Ash
MSWI FA	: Municipal Waste Incineration Fly Ashes
EEC	: Embodied Energy Coefficients
CLSM	: Confocal Laser Scanning Microscopy

LIST OF TABLES

	<u>Page</u>
Table 3.1: Chemical composition of volcanic ash	19
Table 3.2: Ground granulated blast furnace slag	20
Table 3.3: Properties of sodium hydroxide	22
Table 3.4: Properties of sodium silicate	22
Table 3.5: Mixing compositions of produced geopolymer mortars (g)	23
Table 3.6: Details of the mixes	24
Table 4.1: Physical properties (water absorption, unit weight)	34
Table 4.2: Compressive strength (MPa).....	36
Table 4.3: Flexural strength (MPa).....	36
Table 4.4: UPV7- comp results	39
Table 4.5: UPV28- comp. results.....	39
Table 4.6: Results of strength after tests at 400 °C.....	41
Table 4.7: Results of strength after tests at 800 °C.....	45
Table 4.8: Results of strength properties before and after freezing-thawing	54
Table 4.9: Results of strength properties before and after acid attack test	59

LIST OF FIGURES

	<u>Page</u>
Figure 3.1: Volcanic ash sample.....	19
Figure 3.2: GGBFS sample	21
Figure 3.3: Sodium hydroxide.....	22
Figure 3.4: Sodium silicate.....	23
Figure 3.5: Mechanical mixer	24
Figure 3.6: Samples from trial mixes.....	25
Figure 3.7: Mixing procedure of the study.....	26
Figure 3.8: Sorting the samples	27
Figure 3.9: Vibrating sample apparatus	27
Figure 3.10: Samples prepared	28
Figure 3.11: A mixture of geopolymer samples.....	28
Figure 3.12: The samples' curing process	29
Figure 3.13: Flexural strength test.....	30
Figure 3.14: Compressive strength test.....	30
Figure 3.15: Ultrasonic pulse velocity test.....	31
Figure 3.16: Archimedes tool for physical tests.....	32
Figure 3.17: Freezing-thawing freezer.....	33
Figure 3.18: Samples of freezing-thawing test.....	33
Figure 4.1: Compressive strength results	37
Figure 4.2: Flexural strength results	37
Figure 4.3: Compressive strength loss	38
Figure 4.4: UPV 7-comp results.....	39
Figure 4.5: UPV 28-comp. results	40
Figure 4.6: Compressive strength results at 400 °C	42
Figure 4.7: Results of comp. strength loss at 400 °C.....	42
Figure 4.8: Flex. strength results at 400 °C.....	43
Figure 4.9: Flex. strength loss results at 400 °C.....	43
Figure 4.10: Weight loss results at 400 °C.....	44

Figure 4.11: UPV test results at 400 °C	44
Figure 4.12: Compressive strength results at 800 °C	45
Figure 4.13: Results of comp. strength loss at 800 °C.....	46
Figure 4.14: Flex. strength results at 800 °C.....	46
Figure 4.15: Flex. strength loss results at 800 °C.....	47
Figure 4.16: UPV test results at 800 °C.....	47
Figure 4.17: Weight loss results at 800 °C.....	48
Figure 4.18: Comp. strength values for different geopolymer mixes.....	49
Figure 4.19: Flex. strength at elevated temperatures.	50
Figure 4.20: UPV results for geopolymer concrete mixes.....	51
Figure 4.21: Results for comp. strength loss (400°C, 800°C).....	51
Figure 4.22: Results for flex. strength loss (400°C, 800°C)	52
Figure 4.23: Wight loss results at temperatures 400°C and 800°C	53
Figure 4.24: Comp. strength results after freezing-thawing test	55
Figure 4.25: Comp. strength loss results after the freezing-thawing test.....	55
Figure 4.26: Flex. strength results after freezing-thawing test.....	56
Figure 4.27: Flex. strength loss results after the freezing-thawing test	56
Figure 4.28: Weight loss results after freezing-thawing test.....	57
Figure 4.29: UPV-freezing-thawing test results.....	58
Figure 4.30: Comp. strength results after acid attack test.....	59
Figure 4.31: Com. strength loss results after acid attack	60
Figure 4.32: Flex. strength result after the acid attack.....	61
Figure 4.33: Flex. strength loss after acid attack.....	61
Figure 4.34: UPV test results after acid attack.....	62
Figure 4.35: Weight loss results after acid attack.....	62
Figure 4.36: Correlation relationship between comp. strength and UPV-7.....	63
Figure 4.37: Correlation relationship between comp. strength and UPV-28.....	63

PERFORMANCE OF SLAG-VOLCANIC ASH-BASED GEOPOLYMER COMPOSITES WITH DIFFERENT CURING TEMPERATURES

ABSTRACT

This topic focuses on investigating the performance of geopolymer composites using slag and volcanic ash as precursors, with an emphasis on how different curing temperatures affect their properties. Geopolymer composites, renowned for their sustainability and durability, have garnered considerable attention in the construction industry. This study delves into the performance of geopolymer composites utilizing slag and volcanic ash as primary precursors while exploring the influence of varying curing temperatures. The research aims to decipher the intricate interplay between curing temperature and material properties, focusing on mechanical performance, microstructural characteristics, and durability.

A comprehensive literature review sets the stage by summarizing the evolving landscape of geopolymer materials and the significance of curing conditions. Subsequently, the research objectives are delineated, including the assessment of compressive strength, flexural strength, ultrasonic pulse velocity, and freezing-thawing cycles, and the resistance of geopolymer composites to deleterious factors such as acid attack.

The methodology encompasses meticulous preparation of slag-volcanic ash-based geopolymer samples, employing a range of curing temperatures that span from ambient conditions to elevated levels. Mechanical tests, microstructural analyses, and durability assessments are conducted systematically. Results elucidate the intricate relationship between curing temperature variations and material properties, offering valuable insights into the optimization of geopolymer composites for sustainable construction applications.

The discussion section dissects the findings in the context of geopolymer composite performance, highlighting the implications of varying curing temperatures on mechanical strength, microstructure, and durability. Comparative analyses with existing literature augment the understanding of geopolymerization processes and curing temperature effects.

Geopolymer composites represent a paradigm shift in the construction industry, offering an eco-friendly and high-performance alternative to traditional cement-based materials. Their significance in sustainable construction is underscored by their reduced carbon footprint, efficient use of industrial by-products, enhanced durability, and potential to contribute to a more sustainable and resilient built environment. As the world grapples with the challenges of climate change and resource depletion, geopolymer composites offer a promising solution for a more sustainable future in construction.

Both slag and volcanic ash serve as promising precursors for geopolymerization in the creation of sustainable construction materials. Slag offers the advantage of being an industrial by-product, while volcanic ash is a naturally occurring material with low environmental impact. When activated with alkaline

solutions, these precursors can form geopolymeric matrices with excellent mechanical properties, durability, and resistance to environmental stressors, making them valuable components in the pursuit of greener and more resilient construction materials.

The choice of curing temperature in geopolymerization is a critical factor that influences various material properties, including compressive strength, microstructure, durability, setting time, and environmental impact. The selection of an appropriate curing temperature should align with the specific requirements of the construction application and the desired material properties.

Keywords: *Slag-Volcanic Ash Geopolymer, Geopolymer Composites, Curing Temperature, Compressive Strength, Flexural Strength, Acid Resistance, Pozzolanic Reaction.*



FARKLI KÜR SICAKLIKLARINDA CÜRUF-VOLKANİK KÜL BAZLI GEOPOLİMER KOMPOZİTLERİN PERFORMANSI

ÖZET

Bu konu, farklı kürlenme sıcaklıklarının özelliklerini nasıl etkilediğine vurgu yaparak, öncül olarak cüruf ve volkanik kül kullanan jeopolimer kompozitlerin performansının araştırılmasına odaklanmaktadır. Sürdürülebilirliği ve dayanıklılığıyla tanınan jeopolimer kompozitler inşaat sektöründe büyük ilgi görüyor. Bu çalışma, değişen kürlenme sıcaklıklarının etkisini araştırırken, birincil öncüller olarak cüruf ve volkanik kül kullanan jeopolimer kompozitlerin performansını araştırmaktadır. Araştırma, mekanik performansa, mikroyapısal özelliklere ve dayanıklılığa odaklanarak kürlenme sıcaklığı ile malzeme özellikleri arasındaki karmaşık etkileşimi çözmeyi amaçlıyor.

Kapsamlı bir literatür taraması, jeopolimer malzemelerin gelişen manzarasını ve kür koşullarının önemini özetleyerek sahneyi hazırlıyor. Daha sonra, basınç dayanımı, eğilme dayanımı, ultrasonik hız darbesi ve donma-çözülme döngülerinin ve jeopolimer kompozitlerin asit saldırısı gibi zararlı faktörlere karşı direncinin değerlendirilmesi de dahil olmak üzere araştırma hedefleri açıklanmaktadır.

Metodoloji, ortam koşullarından yüksek seviyelere kadar uzanan bir dizi kürlenme sıcaklığı kullanılarak cüruf-volkanik kül bazlı jeopolimer numunelerinin titizlikle hazırlanmasını kapsar. Mekanik testler, mikroyapısal analizler ve dayanıklılık değerlendirmeleri sistematik olarak yapılmaktadır. Sonuçlar, sertleşme sıcaklığı değişimleri ile malzeme özellikleri arasındaki karmaşık ilişkiyi aydınlatarak, sürdürülebilir inşaat uygulamaları için jeopolimer kompozitlerin optimizasyonuna ilişkin değerli bilgiler sunmaktadır.

Tartışma bölümü, bulguları jeopolimer kompozit performansı bağlamında ele alıyor ve değişen kürlenme sıcaklıklarının mekanik mukavemet, mikro yapı ve dayanıklılık üzerindeki etkilerini vurguluyor. Mevcut literatürle karşılaştırmalı analizler, jeopolimerizasyon süreçlerinin ve kürlenme sıcaklığı etkilerinin anlaşılmasını artırır.

Geopolimer kompozitler inşaat sektöründe bir paradigma değişimini temsil ediyor ve geleneksel çimento bazlı malzemelere çevre dostu ve yüksek performanslı bir alternatif sunuyor. Sürdürülebilir inşaatın önemi, azaltılmış karbon ayak izi, endüstriyel yan ürünlerin verimli kullanımı, artırılmış dayanıklılık ve daha sürdürülebilir ve dayanıklı bir yapıyı çevreye katkıda bulunma potansiyeli ile vurgulanmaktadır. Dünya iklim değişikliği ve kaynakların tükenmesi gibi zorluklarla boğuşurken, jeopolimer kompozitler inşaatla daha sürdürülebilir bir gelecek için umut verici bir çözüm sunuyor.

Hem cüruf hem de volkanik kül, sürdürülebilir inşaat malzemelerinin oluşturulmasında jeopolimerizasyon için umut verici öncüler olarak hizmet ediyor. Cüruf, endüstriyel bir yan ürün olma avantajını sunarken volkanik kül, çevresel etkisi düşük, doğal olarak oluşan bir malzemedir. Alkali çözeltilerle etkinleştirildiğinde, bu öncüller mükemmel mekanik özelliklere, dayanıklılığa ve çevresel stres faktörlerine

karşı dirence sahip jeopolimerik matrisler oluşturabilir, bu da onları daha yeşil ve daha dayanıklı inşaat malzemeleri arayışında değerli bileşenler haline getirir.

Jeopolimerizasyonda kürlenme sıcaklığının seçimi, basınç dayanımı, mikro yapı, dayanıklılık, sertleşme süresi ve çevresel etki dahil olmak üzere çeşitli malzeme özelliklerini etkileyen kritik bir faktördür. Uygun kürlenme sıcaklığının seçimi, inşaat uygulamasının özel gereksinimlerine ve istenen malzeme özelliklerine uygun olmalıdır.

Anahtar Kelimeler: *Cüruf-Volkanik Kül Geopolimeri, Geopolimer Kompozitleri, Kür Sıcaklığı, Basınç Dayanımı, Eğilme Dayanımı, Asit Dayanımı, Puzolanik Reaksiyon.*



1. INTRODUCTION

1.1 Literature Review

Cement is a widely used binding substance around the world. Nonetheless, one ton of cement manufacturing produces approximately one ton of CO₂. [1]. Clinker manufacturing is essentially linked to CO₂ emissions into the environment. Despite increasing worries about CO₂ emissions, substantial scientific research is being undertaken to produce sustainable alternative binder systems, with geopolymer technology being the most promising. Pozzolans are utilized as replacement materials in cement and as binders in waste solidification; they are also employed to build a block against harmful chemical transportation [2,3]. There are two types of pozzolans: natural and manufactured. Volcanic tuffs are the oldest and most plentiful natural stone resource. The structure of these includes a lot of silica and zeolite minerals. Zeolite is a microporous solid crystal structure that comprises aluminum, silica, and oxygen in its lattice structure, as well as alkaline or alkaline earth metals and water [4–6].

Aluminosilicate and an alkali activator solution, often sodium or potassium silicate, are used to form geopolymer binders. One notable example of an industrial by-product is blast furnace slag, which is used to make slag-based geopolymers. Scientists have investigated how different slag sources affect the characteristics of geopolymer composites. [7].

These binder solutions have several desirable engineering and durability characteristics, including as rapid drying, low shrinkage, high heat resistance, long-term durability, and low carbon dioxide (CO₂) emissions. In comparison to regular Portland cement, geopolymer binders may save CO₂ emissions by up to 80% when made under ideal circumstances. [8]. More and more people are concerned about CO₂ emissions, thus scientists are working hard to find environmentally friendly binder structures. Geopolymer technology is looking like the best bet at the moment. For example, pyroclastic rocks like volcanic ash, slag, fly ash, metakaolin, and

granite debris are some of the aluminosilicate materials that may be used to create geopolymer binders. (References 8, 9). A number of publications have highlighted the potential of using volcanic aluminosilicate minerals into geopolymer composite systems. [10,11].

Inorganic polymers, zeolitic precursors, and geopolymers are made by reacting an alkaline solution with aluminosilicate minerals extracted from GGBFS, fly ash, metakaolin, and other industrial waste products. There are a number of uses for geopolymers that could lessen the need for OPC (Ordinary Portland Cement) and the associated carbon dioxide emissions. Given their unique thermal behavior, geopolymers outperform composites made of OPC (Ordinary Portland Cement) in terms of fire resistance, according to the research. [12,13].

In a fire simulation, Shaikh and Vimonsatit [14] measured the compressive strength of geopolymer concrete made with fly ash. Fly ash geopolymer concrete performed very well at high temperatures, showing a compressive strength that was 110,000% more than its original value after fire exposure. The compressive strength of concrete prepared with ordinary Portland cement (OPC) was reduced to around 46.5% when calcium hydroxide ($\text{Ca}(\text{OH})_2$) was separated. The structure of the geopolymer, which was made of fly ash, remained unchanged below 600 °C, according to X-ray diffraction (XRD) and nuclear magnetic resonance (NMR) data.

Fernandez-Jimenez and Palomo.[15] delved into how geopolymers hold up under high temperatures, discovering that their flexural strength actually increased by 1.2 times after exposure to 600 °C. Likewise, Pan and colleagues.[16] observed a comparable trend, noting that the compressive strength of fly ash-based geopolymers improved significantly at the same temperature. Recent studies on geopolymer-based concrete have reinforced this pattern of strength enhancement post high-temperature exposure.

In their study, Fulin Qu and colleagues [17] explored how adding load-induced damage could actually enhance the heat resistance of geopolymer mortars (GPMs) made from fly ash and GGBFS. Their main goal was to understand how fire affects preloaded damaged structures. They looked at various physical properties of the geopolymer mortar before and after exposing it to high temperatures, including its appearance, strength, mass, and volume changes. They used techniques like

scanning electron microscopy (SEM) to examine the microstructure and thermal gravimetric analysis (TGA), X-ray diffraction (XRD), and SEM with energy dispersive X-ray (EDX) detection to measure phase shifts at high temperatures. These findings provide valuable insights into how fly ash/GGBFS geopolymer systems respond to fire damage after being subjected to loads, helping scientists better understand their behavior.

Vickers et al. [18] took a close look at geopolymer concrete made with fly ash and alumina aggregate. They found that adding alumina aggregate makes the concrete more likely to catch fire because it doesn't handle heat as well. Previous studies [15-18] didn't think about how mechanical stress affects geopolymer materials in fire tests. But in real life, buildings have to deal with more than just fire.

Geopolymers are a type of inorganic substance that may be formed by alkaline activation of aluminosilicate precursors. They are recognized for their ability to substitute traditional cement-based materials in a variety of applications [19].

Another well-studied precursor for geopolymerization is volcanic ash, which is also known as natural pozzolan [20]. It has been used for hundreds of years, and recent study has focused on making it more reactive and better knowing how it works in geopolymer compounds.

Researchers have found that geopolymer composites can have great mechanical properties, such as high compression and bending forces. The qualities depend a lot on the materials used, as well as the drying conditions. A lot of research has been done on geopolymers because they are strong, last a long time, and don't react badly with chemicals [21]. This makes them useful for many building projects.

XRD and SEM have been used in studies to look into the structures of geopolymer mixtures. Researchers have found that a microstructure that is thicker and has fewer holes can make something last longer, be more resistant to chemical attack, and let less water through [22].

The drying temperature is very important for geopolymerization. Strength, microstructure, and longevity are three geopolymer composite qualities that were studied in relation to the temperature at which they cured [23].

People think that geopolymer composites are better for the earth than regular cement because they use industry waste and have a smaller carbon footprint [24]. Because of this, there is more interest in how they can be used in green building.

Researchers have looked into geopolymer composites for many uses, such as precast concrete, building materials, and even 3D printing [25]. Researchers have been looking into how they might be used in infrastructure projects and building construction.

Even though they show potential, it is still hard to make more geopolymer composites while keeping their properties the same. Researchers are still working on ways to solve these problems and make them work better.

To encourage more use of geopolymer materials in the building business, groups that set standards have begun to create rules and standards for them.

Geopolymer composites could be a breakthrough in the search for environmentally friendly building materials [26]. These new materials are very different from traditional ones made of cement. They are better for the environment and last longer [27]. When aluminosilicate source materials are mixed with alkaline activators, usually sodium hydroxide (NaOH) or potassium hydroxide (KOH), they form geopolymers, which are artificial, amorphous to semi-crystalline materials [28]. The end result is a three-dimensional network that is chemically bound and has qualities that are similar to, or even better than, those of regular Portland cement-based materials.

It is a huge step forward that geopolymer composites are being used in building products. They might help lessen the damage that building does to the climate by using less energy and releasing less carbon dioxide than making Portland cement [29].

One of the main reasons people are interested in geopolymers is that they leave behind a lot less carbon [30]. Because limestone is heated to very high temperatures during traditional cement production, a lot of carbon dioxide (CO₂) is released into the air [31]. It is much cooler when geopolymers are made, and CO₂ is often not released during the process. In this way, they indicate a big drop in greenhouse gas production [32].

Industrial wastes like fly ash, slag, and volcanic ash can be used in geopolymers in a way that makes them useful. By using these materials in geopolymers, we not only cut down on trash, but we also lessen the damage that throwing them away does to the earth [33].

Slag, a waste product from the iron and steel industries, could be used to make geopolymer mixtures. It is pozzolanic and has a lot of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) in it [34]. Volcanic ash is a naturally found pozzolan that has been used by builders for a long time because it reacts well with alkali activators. The use of slag and volcanic ash as building materials in geopolymer composites gives us hope for green building materials [35].

The curing temperature is an important factor in geopolymerization because it has a big impact on the qualities of geopolymer products. A lot of research has been done on how the hardening temperature affects geopolymer composites. More often than not, higher hardening temps cause things to set faster and have higher early-age powers [36]. Because the initial materials dissolve faster and a thicker, more solid geopolymeric matrix forms, this is the case. But at higher temperatures, it may not be as easy to work with.

When it comes to longevity, geopolymer composites are better than traditional materials. They make things more resistant to tough weather conditions like chemical attack, being exposed to sulfates, and salt getting in. They are very good at working in harsh situations because of this, like naval and industrial settings [37].

As geopolymer materials gain acceptance in the construction industry, standardization efforts are emerging to develop guidelines and testing protocols. Sustainability is a significant driver of geopolymer research, with an increasing focus on life cycle assessments (LCAs) to determine and evaluate the environmental effect of these products with traditional alternatives [38].

The geopolymerization process typically requires less water compared to conventional concrete. This reduced water demand contributes to water conservation efforts and lowers transportation costs, particularly in arid regions [39].

Geopolymer composites have demonstrated excellent fire resistance properties. They maintain their structural integrity at high temperatures, making them suitable for applications in fire-prone areas [40].

Geopolymers can greatly increase the service life of buildings by resisting degradation processes such as alkali-silica reaction (ASR) and sulfate assault [41].

Geopolymer materials provide great early and ultimate compressive strength, as well as excellent workability. This makes them appropriate for a variety of building applications [42].

Responsible production and consumption, climate action, and sustainable cities and communities are only a few of the UN Sustainable Development Goals (SDGs) that are compatible with geopolymers [43].

This work aims to address certain gaps in the literature on geopolymer composites, despite the extensive research on the topic. To begin, studies that specifically investigate how curing temperature affects the performance of geopolymer composites based on slag and volcanic ash are few and far between. Second, there is a lack of information on the effectiveness of composites that include both slag and volcanic ash, as the majority of studies have focused on individual precursor elements. More in-depth microstructural investigation is required to learn how curing temperature affects the microstructure and, therefore, the characteristics of these composites. In addition, further research is needed to determine if these materials are environmentally sustainable, particularly when compared to standard cement-based materials.

1.2 Objective of the Thesis

Volcanic ash is considered a naturally occurring and sustainable material that may be used to generate an environmentally friendly binding matrix. Given this, it may be effectively assessed as a precursor in the geopolymeric matrix. The thesis will stress the following:

- 1- An investigation into the effect of replacing slag with volcanic ash on the researched attributes.

2- Examining the influence of different curing temperatures on the performance of the generated samples.

3- Evaluating the samples' performance in various durability situations such as high temperature, freezing-thawing, and acid attack.

4- Evaluating the correspondence of the results between the conducted mechanical and physical tests along with tests like compressive and flexural strength and Ultra pulse velocity test.

1.3 Hypothesis

The thesis aims to present a systematic summary of the research process. Following this introduction, Chapter 2 conducts a complete literature analysis, emphasizing current knowledge, gaps, and the research's contribution. Chapter 3 describes the materials utilized in the experiment, as well as the methods used and the results obtained. The thesis continues with Chapter 4, which covers data analysis, outcomes, and debates, culminating in practical recommendations and options for further study.

We hope that our research will provide vital insights to the increasing body of knowledge on geopolymer composites, allowing them to be used more effectively in sustainable construction methods.

2. LITERATURE REVIEW

2.1 General

The building sector is at the confluence of innovation and sustainability, demanding the development of materials that not only meet structural requirements but also align with environmental stewardship. In this context, Geopolymer composites have appeared as a possible alternative to traditional cement-based materials. As a result of alkali activation of aluminosilicate precursors, geopolymers are created. They offer a long-term answer by lowering the carbon footprint of building activities. As different geopolymerization materials are looked at, this study focuses on using slag and volcanic ash together. Slag and volcanic ash are waste items from nature and industrial processes, respectively.

Geopolymer mixtures are better than most materials in a number of ways. The process of making them uses less energy and releases less carbon dioxide than making Portland cement. This helps make sustainable building practices even more important. In addition to being good for the climate, geopolymers are also strong, durable, and resistant to many types of chemical attacks. This makes them appealing for many building uses.

The choice of predecessors is very important for figuring out the properties of geopolymer mixtures. Besides being good for the climate, geopolymers have great engineering qualities, last a long time, and are resistant to many types of chemical attacks. This makes them popular building materials for many uses. The goal of this study is to find out how mixing these ingredients changes the performance of geopolymer composites and, more importantly, how different hardening temperatures change this performance.

The review was broken up into different groups:

- Literature on geopolymers made of volcanic ash in detail.
- A geopolymeric matrix's filler components.
- The impact of varying activator molarities.

- The role of curing temperature in geopolymerization and its impact on material qualities.

2.1.1 Literature on geopolymers made of volcanic ash in detail

Djobo et al. [44] looked into the long-term mechanical and physical qualities of geopolymer blocks made of volcano ash. The temperatures at which these mortars cure and their ability to withstand hard conditions were both created separately. Over the course of six months, the physical and mechanical features were looked at to see how they changed. This report shows the outcomes of tests that looked at how long something could last. These tests included a wet-dry cycling test with 25 cycles and a sulfuric acid resistance test with 180 days. The process of sulfuric acid attack on manufactured samples has been figured out by studying their microstructure.

Using metakaolin and ash from volcanic events, Kouamo et al. [45] studied how to make geopolymers. They lowered the Si/Al ratio in geopolymers by adding Al_2O_3 as an extra source of aluminum. They then studied the changes. The properties of geopolymers made from both types of materials are studied. The manufactured geopolymers' compression strength was checked after 28 days. Analyzed using powder X-ray diffraction (XRD) and Fourier Transform Infrared spectroscopy (FTIR), the samples of solidified geopolymer cement paste were crushed into small particles after the compressive strength measurement. Investigating the properties of geopolymer pastes formed into cylindrical forms with a diameter of 10 mm and a height of 20 mm was done using the scanning electron microscope (SEM) method.

Geopolymer mortars made mostly from volcanic ash have their properties improved by Kouamo et al. [46]. To make the volcanic ash more reactive, scientists employed the alkali fusion technique. Various quantities of highly reactive metakaolin were used as supplementary sources of aluminosilicate (30%, 40%, 50%, and 60% MK by weight) to use up the excess alkali required for the fusion process. We compared the reactive phase and X-ray diffraction (XRD) patterns of the unfused volcanic ash (f-Z_G) with those of the fused ash (Z_G) to determine how the fusing procedure affected the reactivity of the ash. Testing procedures for the geopolymer mortars included compressive strength, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDS), linear shrinkage, and setting time.

Metekong et al. [47] examined the efficiency and long-lasting nature of geopolymer concrete produced from volcanic ash laterite. The researchers evaluated two variants, GL20 and GL40. The specimens were subjected to curing temperatures of 28, 60, and 80 degrees Celsius. Compressive and flexural strength of dry, wet, and wet-dry materials were assessed at 7, 28, and 90-day intervals.

The mechanical properties of geopolymer concrete made from the highly silicate Sinabung volcanic ash were investigated by Karolina et al. [48]. The resulting geopolymer concrete was 20 cm tall and 10 cm in diameter, giving it a cylindrical form. The combination of sodium hydroxide and sodium silicate served for an alkali activator. We tried four alternative durations of curing in an oven set to 60°C: four, eight, twelve, and twenty-four hours. The compressive strength and absorption value of a sample that was 7 days old were used to determine the mechanical properties, and a conversion procedure was used to get the expected value for a sample that was 28 days old.

Geopolymers were created by Tchakoute et al. [49] using unprocessed volcanic ash from two locations in Cameroon, Djoungo and Galim. The geopolymers were then dried at a steady temperature of 24 ± 3 °C. An analysis was conducted on the volcanic ash material, taking into account its chemical and mineralogical composition, the non-crystalline phase's chemical composition, the distribution of particle sizes, and the specific surface area. In order to make geopolymer cement paste, five different alkaline solutions were prepared with $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratios between 0.7 and 1.4. At the end of the 28-day trial, we compared the products' compressive strengths and setting times. In addition, X-ray diffraction and Fourier transform infrared were used to analyze powdered solidified geopolymer cement paste.

Churata et al. [50] looked into geopolymers that are made by mixing fly ash, pozzolan, metakaolin, industrial waste, and volcano ash in a 1:1 ratio. Acids and silica salts were used to get the reaction going. To describe the geopolymers, researchers used XRD, FTIR, and mechanical tests. These materials could be used as building blocks for geopolymer production, based on the results. The findings also showed that the compressive strength and geopolymerization process were changed by the mineralogy of the main materials when they were mixed. In particular, the compression strength of the mix of volcanic ash and pozzolan was 35 MPa.

Tchadjié et al. [51] studied the morphology and dynamic qualities of VA-GPC composites that had active bauxite added to them. Ball grinding was used to process bauxite by physically activating it. For geopolymer mortar compounds, between 0% and 25% by weight of volcanic ash and active bauxite were used. Measurements were used to check the geopolymer mortars' workability, shear strength, pore volume, and ability to absorb water. X-ray diffraction (XRD), optical microscopy, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) were some of the imaging methods used to look at the microstructure.

Tome et al. [52] talked about how VA was added to MSWI-FA to make up for the low amounts of silica and alumina. This made eco-friendly cement (Geopolymer), which helped recover this dangerous waste by making it stable and solid. Research was conducted to assess the activating solution's alkalinity and the impact of the VA dosage that was added.

Kupwade-patil et al. [53] provided several techniques to enhance the energy efficiency (EE) of buildings. They achieved this by comparing the EE of cement mixtures with VA substitution to the baseline scenario of traditional concrete. The Embodied Energy (EE) of a construction product is quantified in Mega Joules (MJ) per kilogram of material using Embodied Energy Coefficients (EEC). Take into account a cured cement paste including volcanic ash in the OPC, where the mean particle size is either 17 μm or 6 μm , and the volcanic ash content may reach up to 50%. Substituting OPC with volcanic ash reduces the EEC. However, in order to retain optimal mechanical strength, the mix design must take into account the characteristics of the volcanic ash.

Hamada et al. [54] examined the possible effects of VA on the mechanical, microstructural, and environmental characteristics of cement mortars and concretes as a supplementary cementitious material (SCM) and nanomaterial (NP), respectively.

In their study, Celik et al. [55] examined the impact of using limestone powder (LP) and basaltic volcanic ash (NP) as substitutes for Portland cement (PC) on the characteristics of fresh, mechanical, and physicochemical qualities of mortars and cement pastes. It was shown that both materials heightened the need for water.

LP had no significant impact on setup time, however NP had a noticeable rise. Both materials reduced the ultimate compressive strengths of the mortars, but to a lesser extent than their substitution levels.

Wilson et al. [56] summarized ash impacts on essential infrastructure, highlighted important sources of susceptibility and evaluated the relative sensitivity of different sectors to a variety of ash fall scenarios.

The physical and chemical properties of volcanic ash were detailed by Rafat Saddique [57]. Additionally, volcanic ash was tested for its effects on concrete collapse, compressive strength, porosity, permeability, and sulfate resistance.

The results of a research evaluating the corrosion resistance and degradation of twelve distinct concrete mixes subjected to a combination of sulfate solutions for forty-eight months were published by Hossain and Lachemi [58]. Buildings exposed to mixed sulfate environments that include magnesium, a prevalent element found in many places globally, may benefit from this study's recommendations for VA and VP-based blended cement.

2.1.2 A geopolymeric matrix's filler components

Papa et al. [59] created and characterized a novel class of geopolymer-zeolite materials by filling a geopolymer matrix with a commercial synthetic zeolite. Indeed, the key objective was to integrate zeolite's unique and defined microporosity with the geopolymer matrix's mesoporosity, as well as the ability to consolidate the zeolite powder.

Lazorenko et al. [60] conducted a study comparing the effects of different physical and chemical treatments on rubberized fly ash-based geopolymer composites. They used various solutions, such as NaOH, H₂SO₄, (CH₃)₂CO, and KMnO₄, as well as ultraviolet (UV-C) radiation. The aim was to assess how these treatments affected the compressive and flexural strength, as well as the microstructure, of the composites. The focus was on understanding the interaction between the geopolymeric matrix and the rubber filler material. The impact of pre-treatment on the surface characteristics of CR was investigated using water vapor adsorption, FTIR spectroscopy, and visual and confocal laser scanning microscopy (CLSM).

Kohout and Koutink [61] examined the impact of filler type on the thermomechanical characteristics of geopolymer composites based on meta-kaolinite. A comparison was made between the properties of four different fillers (sand quartz, chamotte, cordierite, and corundum) and the properties of the geopolymer binder without any fillers. A geopolymer binder was produced by using calcined claystone and a potassium alkaline activator.

Sahin et al. [62] examined the impact of polyvinyl alcohol fibers on geopolymers manufactured from metakaolin and other types of aggregates, including basalt sand, Rilem sand, and recycled concrete aggregate, individually.

In their study, Kovářik et al. [63] examined how the size and distribution of aggregates impact the shrinkage/expansion behavior and mechanical strength of geopolymer composites. The mineralogical phases, thermal behavior, dimensional stability, and mechanical properties of experimental specimens were evaluated both in their initial state and after being subjected to heat up to 1000 °C.

To study the mechanical properties and mechanism of flexibility of fiber-reinforced slag-fly ash geopolymer-agglutinated iron effluent infill materials, Zhang et al. [64] tested them using SEM, XRD, three-point bending, scanning electron microscopy, and macroscopic unrestricted compressive strength.

Natural rubber (NR) composites were experimented with by Yangthong et al. [65] using geopolymer particles (GP) as novelty fillers at varying loadings (0, 10, 20, 30, and 40 phr). Cured NR/geopolymer composites had their mechanical, dynamic, thermal, and morphological properties studied, as well as the impact of GP particles on these parameters. The curing properties and mechanical qualities were significantly affected by the inclusion of geopolymer particles.

Uysal et al. [66] investigated how four different fiber types affected the mechanical and microstructural characteristics of metakaolin and red mud geopolymer composites. Additionally, these composites included recycled aggregate and brick dust.

In their study, Ferdous et al. [67] investigated a novel method for designing geopolymer concrete mix and its use as a filler in structural hybrid composite beams. The viability of using this hybrid beam concept for a railway sleeper has also been evaluated and shown.

2.1.3 The impact of varying activator molarities

In their study, Felaous et al. [68] investigated the activation of volcanic pozzolan utilizing sodium silicate and sodium hydroxide as activators. Pozzolan rock is described in detail throughout the book, along with its microscopic features, chemical composition, and mineralogical makeup. Consideration and adjustment are given to the effects of the NaOH solution molarity and the mass ratio of Na_2SiO_3 to NaOH. References to earlier works provide context for an analysis and explanation of the microstructural, mechanical, and mineralogical properties of the geopolymers that are formed.

Activators ranging from 8 M NaOH to 5 M NaOH were used in GP pastes, and the effect of ambient temperature on their molarities was studied. Pundiend' and coworkers [69]. Alkaline activator solutions with a molarity below 8 M were the subjects of the experiment. Many writers believe that GP pastes need a larger quantity of water to get the appropriate fluidity; this opinion was taken into account in our experiment. A lower molarity is achieved by diluting the alkaline activator solution with more water, which lowers its concentration. Studies have shown that when compared to the alkaline activator, the extra water's composition might differ by as much as 30–35%.

Ibrahim et al. [70] found that the binder concentration and composition of alkaline activators affect the fresh and hardened properties of AAC.

The study investigated the impact of the concentration of NaOH, the ratio of Na_2SiO_3 to NaOH, and the ratio of alkaline activator to fly ash (AA/FA) on the current qualities (workability and wet density) and hardened properties (dry density, compressive strength, and flexural strength) of geopolymer concrete (GPC) cured at room temperature. The experiment included testing 45 different GPC mixes. Ghafoor et al. [71]

Ibrahim et al. [72] Identified the optimal combination of alkaline activator composition and SH concentration for creating NP-based AAC with enhanced mechanical and microstructural characteristics. In order to create the most optimal NP-based AAC, adjustments were made to the SS/SH ratio and SH intensity.

The effects of curing temperature and silica modulus on the microstructure and strength of alkali-activated LSP/VA mortar were studied. Research carried out

by Adewumi et al. [73] The study aims to further our comprehension of the effects of curing temperature and alkali-activated volcanic ash/limestone powder on the characteristics of mortars. When VA/LSP is used, less dangerous adhesives can be used, and less trash is made.

Researchers looked at how the compressive strength of geopolymer concrete changed with changes in the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio, the $\text{Na}_2\text{SiO}_2/\text{Na}_2\text{O}$ ratio in a solution of sodium silicate (Na_2SiO_3), the molarity of NaOH, and other factors. Reddy et al. [74] say that geopolymer mix designs can be made by changing the amount of alkali activator solution (AAS) to fly ash (FA) while keeping the amount of FA the same. This study looks into the compressive strength of geopolymer concrete, focusing on how different $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratios (2.0, 2.5, and 3.0) and NaOH molarities (8M, 10M, 12M, 14M, 16M, and 18M) work together. The compression strength is good when the ratio of SiO_2 to Na_2O in the Na_2SiO_3 solution is between 2.00 and 2.40, the ratio of Na_2SiO_3 to NaOH is 2.5, and 16M NaOH is used.

A recent study looked at what happens to the microstructures and mechanical qualities of GPMs when the molarity of the NH solution is changed. The author is given as Huseien et al. [75]. These Glass Powder Materials (GPMs) are made from broken bottles, FA, GBFS, and ceramics, which are mixed together at certain hardening temperatures. We look at the microstructural features of these GPMs using X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS). The ASTM C109/109M standard is used to find out how strong GPM is when compressed. Finding the right amounts of NH molarity in Na_2O , H_2O , solution modulus ($\text{SiO}_2:\text{Na}_2\text{O}$), and $\text{Na}_2\text{O}:\text{Al}_2\text{O}_3$ is important for getting the best compression strength.

There is a study into how the water-to-binder ratio and the SS/SH ratio affect low molarity (4 M and 6 M) geopolymer concrete. Singh et al. [76]. In addition, the study will look at how the drying schedule affects the strength growth of the low-molarity geopolymer concrete that is made. Furthermore, this study investigates the influence of three different mix compositions, each with compressive strengths varying between 30 and 2 MPa, on the elastic modulus, sorptivity, and chlorine migration. The investigation has focused on inelastic strain and the loss of strain energy at lower stress levels.

2.1.4 The role of curing temperature in geopolymerization and its impact on material qualities

Mo et al. [77] concentrated on creating kinetic models and evaluating mechanical properties; nevertheless, the correlation between curing temperature and geopolymerization has not been extensively studied. The main objective of the research is to examine the impact of curing temperature and duration on the dissolution, polymerization, and reprecipitation processes involved in the geopolymerization reaction. The study examines the impact on both the duration of solidification and the physical and mechanical characteristics of the geopolymer samples.

Rovnaník et al. [78] Examined the mechanical properties of geopolymer mortars produced from metakaolin, considering changes in curing temperatures and durations. The compressive and flexural strength data were interpreted in terms of microstructure changes noticed during the hardening process using mercury intrusion porosimetry and FTIR spectroscopy, respectively. The composition of the geopolymer under investigation was derived by empirical knowledge gained from various kinds of geopolymer materials produced at room temperature. The goal was to create a combination that exhibited the most favorable mechanical characteristics over a 28-day period.

Aredes et al. [79] Examined the structure of geopolymer made from meta kaolinite at different curing temperatures. The primary objective is to enhance comprehension of quick curing at elevated temperatures in geopolymer synthesis, with the aim of producing superior quality products and optimizing the geopolymerization process for real-world use. The mechanical property data were examined by the analysis of microstructure alterations.

According to Sajan et al. [80], Built on earlier studies by doing an extensive experimental analysis of how the three main components affected the mechanical properties of geopolymer as a whole. Compressive strength, Poisson's ratio, and Young's modulus are three mechanical properties of geopolymers that are investigated in this study. Several factors are taken into account, such as three different amounts of alkaline concentration, four different cure temperatures, and three different curing times. Microscopy is also used to look at the relationship

between the mechanical properties and the regulatory parts described above and make sure it is real. There will be useful information for using geopolymer goods made from fly ash that comes from this in-depth trial.

The goal of Nagral et al. [81] was to make GPC cubes with a specific strength of 50MPa. To do this, they added fly ash and GGBS to a 12M NaOH solution to help the chemicals stick together. Curing times of 12 to 24 hours took place at temperatures between 80 and 100 degrees Celsius. Researchers used this data to find the best temperature and length of time for geopolymer concrete to cure, which is what gives it its high compression strength. Researchers dug deeper to find out how adding water to geopolymer concrete at the right setting temperature and time changes how it can be used and how well it holds up against compression.

The main goal of Zribi et al.'s study [82] was to make phosphate-based geopolymers at two different hardening temperatures: room temperature and a slightly higher temperature (60°C). Researchers use a variety of methods to look into the speed at which geopolymers form, their compression strength, and their structure.

3. MATERIALS AND METHODS

3.1 Introduction

A thorough discussion of the materials utilized in this research, together with an explanation of the tests that were undertaken, will help to make sense of the experimental results that were produced.

3.2 Materials

3.2.1 Volcanic ash

Volcanic ash is a natural pozzolan derived from volcanic activity, possessing unique characteristics that make it a valuable material in the construction industry. Unlike traditional fly ash from coal combustion, volcanic ash originates from volcanic eruptions, providing an alternate supply of aluminosilicate material for the manufacture of cementitious materials including concrete and geopolymer composites.

Volcanic ash is a result of volcanic eruptions where molten lava fragments into fine particles during the eruption process. These airborne particles cool rapidly in the atmosphere and form a glassy, amorphous structure. The composition of volcanic fly ash varies based on the type of volcano and the minerals present in the original lava. Common constituents include silica (SiO_3), alumina (Al_2O_3), iron oxide (Fe_2O_3), and other trace minerals.

Fly ash from volcanic eruptions has a high pozzolanic reactivity, which is an important property. Cementitious materials benefit from the addition of volcanic fly ash, which, like other pozzolans, interacts with calcium hydroxide ($Ca(OH)_2$) in the presence of moisture to produce extra binding phases. The C-S-H gel that is created during the pozzolanic process is responsible for the cohesiveness and strength of the concrete.[83]

Table 3.1 displays the chemical composition of volcanic ash, which is a basaltic substance of the scoria type. as the SiO_2 , content is less than 52.5%. The major oxides are SiO_2 , Al_2O_3 , and Fe_2O_3 , with the sum of $SiO_2 + Al_2O_3 + Fe_2O_3$ equal to 83.08 wt. The minor oxides present are CaO, MgO, SO_3 , and Na_2O with a total sum of 16.9 wt. %. The components utilized to prepare the mixes included ground granulated blast furnace slag, sand, sodium silicate, and sodium hydroxide. Figure 3.1 depicts a sample of the utilized volcanic ash.

Table 3.1: Chemical composition of volcanic ash

Oxides	Content (%)
SiO_2	49.47
Al_2O_3	18.67
Fe_2O_3	14.94
CaO	8.61
MgO	3.65
Na_2O	4.64
LOI	8.67



Figure 3.1: Volcanic ash sample

3.2.2 Ground granulated blast furnace slag (GGBFS)

The iron and steel industry produces a byproduct known as Ground Granulated Blast Furnace Slag (GGBFS). It is created when the iron slag that has been melted in a blast furnace is cooled quickly with water or steam. The pozzolanic and latent hydraulic characteristics of GGBFS make it a popular supplementary cementitious material; these properties enhance concrete quality and make buildings more sustainable.[84]

GGBFS is primarily composed of amorphous silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), along with other oxides present in varying amounts based on the specific steel production process. It is made when melted iron slag is quickly cooled down, which turns the slag into very small glassy particles. After being broken up into small pieces, this material is turned into a fine powder, which is GGBFS.[85]

It is a flexible cementitious material that stands out because it has a unique mix of pozzolanic and latent hydraulic properties. Pozzolanic reactions happen when calcium hydroxide ($\text{Ca}(\text{OH})_2$) and GGBFS are mixed with water. This makes a C-S-H gel. At the same time, because it has inactive hydraulic action, it makes hydrated calcium aluminate phases. Because of its dual nature, concrete is more durable and lasts longer. Figure 3.2 displays the sample, and Table 3.2 details the chemical make-up of crushed granulated blast furnace slag.

Table 3.2: Ground granulated blast furnace slag

oxides	Content (%)
SiO_2	40.55
Al_2O_3	12.83
Fe_2O_3	1.10
CaO	35.58
MgO	5.87
Na_2O	0.79
LOI	0.03
SO_3	0.18
Cl ⁻	0.0143



Figure 3.2: GGBFS sample

3.2.3 River sand

River sand is a naturally occurring granular material derived from riverbeds that is an essential component of the building industry. Its diverse qualities make it a necessary component in the manufacturing of concrete, mortar, and other construction products.

3.2.4 Chemical activators

The geopolymerization process, a sustainable alternative to traditional cement-based materials, relies on chemical activators to initiate the transformation of aluminosilicate precursors into geopolymers. Sodium silicate and sodium hydroxide are essential chemical catalysts that significantly contribute to the formation of robust and high-performing building materials.

Sodium silicate is a water-soluble compound consisting of sodium oxide (Na_2O) and silica (SiO_2).

Sodium hydroxide dissociates in water to provide hydroxide ions (OH⁻) essential for the geopolymerization reaction.

Chemical activators, such as sodium hydroxide and sodium silicate, were used to initiate the geopolymeric process. A company called Merck Chemicals Company was bought the chemicals. The chemical samples are shown in Figures 3.3 and 3.4, and their technical data is provided in Tables 3.3 and 3.4.

Table 3.3: Properties of sodium hydroxide

NaOH (%)	Na ₂ CO ₃ (%)	Cl (%)	SO ₄ (%)	Al (%)	Fe (%)
99.1	0.3	≤ 0.01	≤ 0.01	≤ 0.002	≤ 0.002

Table 3.4: Properties of sodium silicate

Na ₂ O (%)	SiO ₂ (%)	Density (20° C) (g/ml)	Fe (%)	Heavy metals (as Pb) (%)
8.2	27.0	1.360	≤ 0.005	≤ 0.005

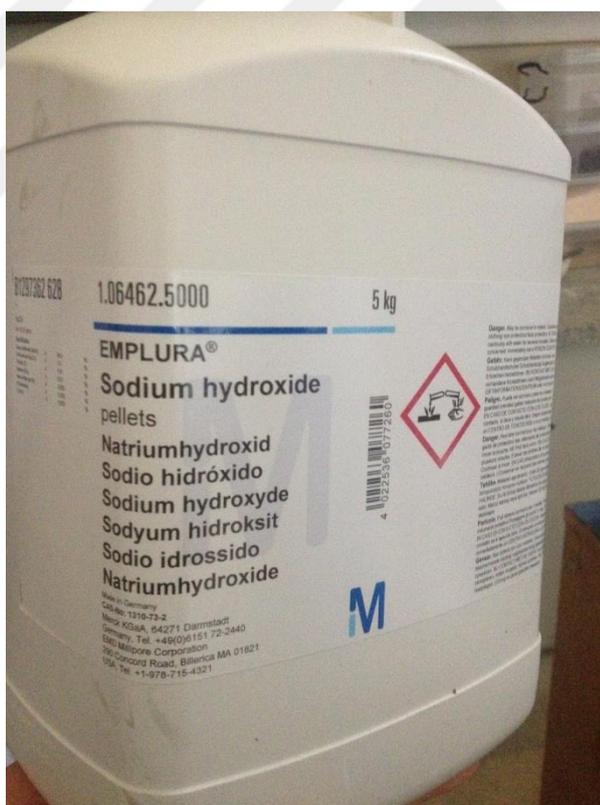


Figure 3.3: Sodium hydroxide

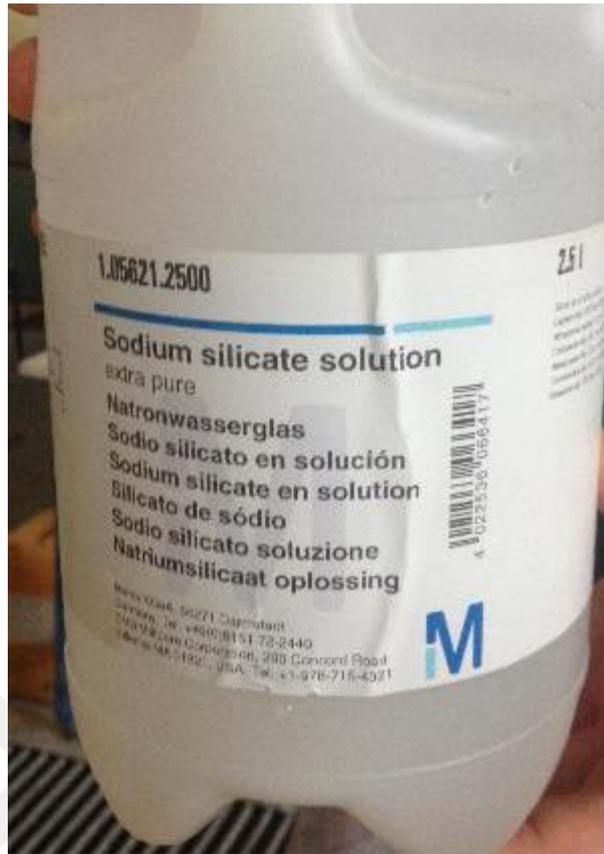


Figure 3.4: Sodium silicate

3.3 Mixes Proportions and Plan Categorization

The volcanic ash was mixed with slag and river sand in different percentages by adding chemical activators Na_2SiO_3 and NaOH (10 M) as shown in the table 3.5 below.

Table 3.5: Mixing compositions of produced geopolymer mortars (g)

Mix ID	GGBS	Volcanic Ash	Na_2SiO_3	NaOH (10 M)	River sand
Reference	450	0	210	105	1012.5
25%	337.5	112.5	210	105	1012.6
50%	225	225	210	105	1012.7
75%	112.5	337.5	210	105	1012.8

Ratio of chemical activator to binder = 0.7

Ratio of sodium silicate to sodium hydroxide = 2:1

Ratio of sand to activator = 2.25:1

The ability of the manufactured samples to harden in natural conditions was evaluated using varying amounts of slag and volcanic ash. The prism-shaped trial mix samples had dimensions of 40×40×160 mm, as seen in Figure 3.6. Figure 3.5 shows the original method of mixing, which used a small mechanical mixer. The enormous number of specimens required for the investigation's methodology, however, rendered the use of this mixer impractical. So, to combine, an electric drilling device was used in conjunction with a blending rod. In table 3.6, you can see all the details about the combinations.

Table 3.6: Details of the mixes

Code	%	Curing Temp.
Control	100% GGBS	Room temp.
75G25V-R	25% VA + 75% GGBS	Room temp.
50G50V-R	50% VA + 50% GGBS	Room temp.
25G75V-R	75% VA + 25% GGBS	Room temp.
75G25V-60	100% GGBS	60°C
50G50V-60	25% VA + 75% GGBS	60°C
25G75V-60	50% VA + 50% GGBS	60°C
75G25V-100	75% VA + 25% GGBS	100°C
50G50V-100	100% GGBS	100°C
25G75V-100	25% VA + 75% GGBS	100°C



Figure 3.5: Mechanical mixer



Figure 3.6: Samples from trial mixes

In addition, meeting with Joseph Davidovits during the 9th geopolymer camp in Saint Quentin, France, to learn the precise process for making geopolymer composites was a huge help in directing the planned study in the correct direction. With this background information in hand, the real investigation recorded and took into account the following details. There are a number of issues with the mixing procedure that must be resolved:

- Volcanic ash should be dried before combining.
- Slag ought to be utilized for fast hardening.
- It is recommended to prevent adding a chemical filler in the mixing procedure.
- To get the optimum reaction of the proposed mix, sodium hydroxide ought to be prepared a minimum of one day ahead of time, it is necessary to add sodium silicate to sodium hydroxide before combining.
- Davidovits' ideas advise that volcanic ash be combined with chemical activators to determine the proper reaction process. Slag is next supplied to the substance, and finally, filler ingredients are added to complete the mixing process.
- Manual high-shear mixers are ideal for mixing geopolymers than standard mechanical mixers.

- Weather conditions have a crucial effect on the manner of mixing. Specifically, it is highly recommended to combine at an elevation of around 23°C and a level of moisture of around 50%.

Concerning the procedure of drying and detaching the mold, early studies indicated a few factors:

- The oven proved to be the optimal curing procedure regarding quick strength progress and chemical stability.
- To reach the necessary strength, cure for at least 10 hours.
- Grease oil was deemed the most effective technique to coat the molds to facilitate the demolding process.

3.4 Experimental program

3.4.1 Procedures for mixing, molding, and curing

Following the steps outlined in the flow diagram in Figure 3.7, the blending process was executed. At least one day before the mixing day, sodium hydroxide was manufactured. On that particular day, sodium hydroxide and sodium silicate were mixed. The first step of geopolymerization was initiated after the addition of the metasilicate solution to the slag. In order to complete the geopolymeric mixing process, the resulting paste is mixed with sand and then added to volcanic ash. As indicated earlier, a rod-attached manual drilling machine was used to get the necessary homogeneity in the finished mixture.

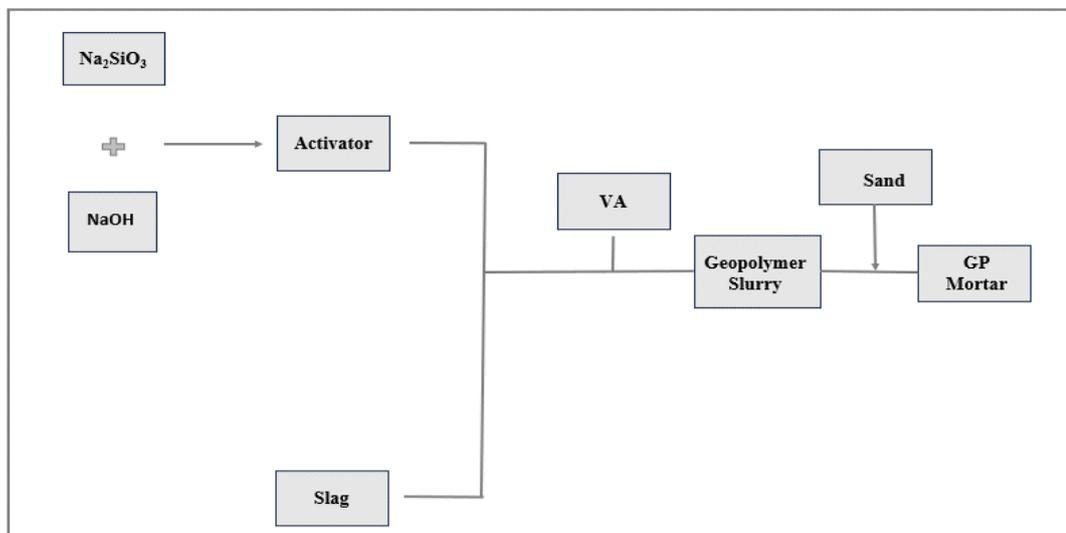


Figure 3.7: Mixing procedure of the study

When the mixture was let aside for a little while, the containers formed. The specimens could be easily removed from the molds because of the thick coatings applied to them. Molding was accomplished by pouring two layers of the compound into the molds in a certain order and then stirring them to release any trapped air during casting. The flow table was analyzed by taking a small proportion from each combination. Casting prisms with dimensions of 40×40×160 mm was part of this project. After that, the samples were heat-cured for 24 hours in an oven set to temperatures higher than 80°C. Methods for mixing, molding, and curing are shown in Figures 3.8-3.12.



Figure 3.8: Sorting the samples



Figure 3.9: Vibrating sample apparatus



Figure 3.10: Samples prepared



Figure 3.11: A mixture of geopolymer samples



Figure 3.12: The samples' curing process

3.4.2 Test program

3.4.2.1 Strength tests

In order to conduct compressive and flexural strength tests according to ASTM E4 10002-2 [86], this inquiry made use of a 35-ton load-measuring device that has a displacement accuracy of $\pm 1\%$ mm and a precision of $\pm 0.2\%$ mm. For the purpose of compressive strength testing, the standards ASTM C109 [87] and ASTM C 348 [88] were used. At 7 and 28 days of age, the specimens were tested separately. Prism samples of $40 \times 40 \times 160$ mm were used for compressive and flexural strength testing. The flexural strength was calculated using the following equation in order to meet the standards set by ASTM:

$$\text{Flexural Strength} = 0.0028 P \quad (3.1)$$

P stands for the maximum stress exerted on the specimen under test, in kilonewtons (KN), and MPa is the unit of measurement for flexural strength.

Using ASTM standards, compute compressive strength values. Compressive strength may be calculated using the formula shown below.

$$\text{Compressive Strength} = P/A \quad (3.2)$$

Finding the area (A) of the assessed plate divided by the specimen's highest load (P) in kilonewtons (KN) yields the compressive strength in megapascals (MPa). Compressive and flexural strength evaluations are shown in Figures 3.13 and 3.14, respectively.

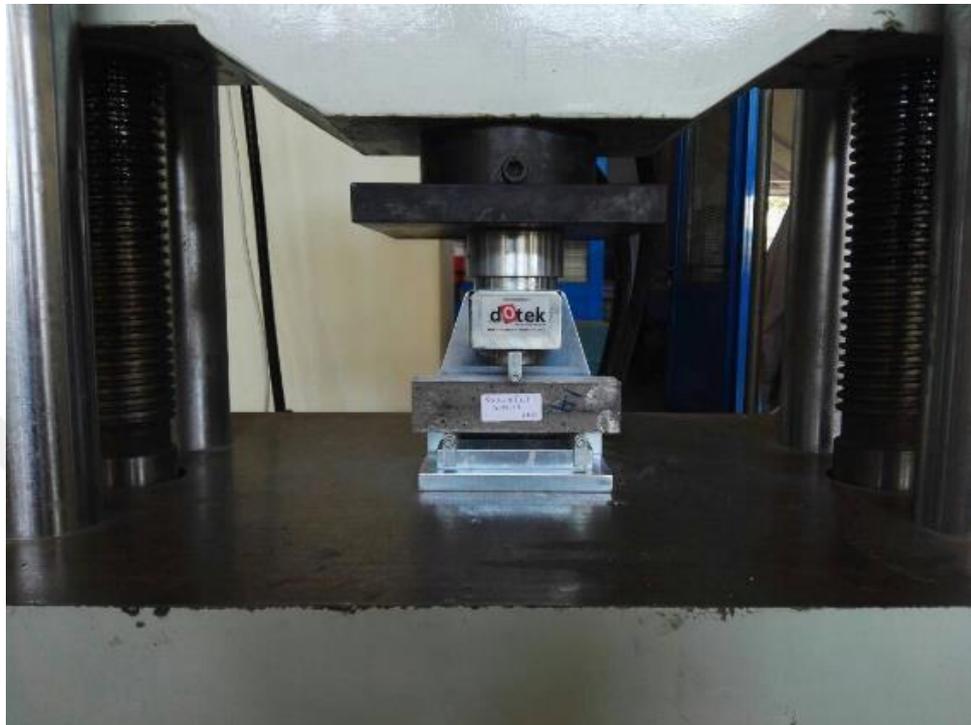


Figure 3.13: Flexural strength test



Figure 3.14: Compressive strength test

3.4.2.2 Ultrasonic pulse velocity test

Ultrasonic pulse velocity studies are often used to find any defects or cracks in the manufacturer's composition and to assess its consistency. To evaluate the effectiveness of the matrix utilizing the studied variables and classifications, ultrasonic pulse velocity tests were performed on the generated specimens in this investigation. Figure 3.15 shows the results of the study's ultrasonic pulse velocity studies.



Figure 3.15: Ultrasonic pulse velocity test

3.4.2.3 Unit weight, Water Absorption and Voids Ratio

Physical characteristics are very important in determining the structure of produced specimens. The unit weight, water absorption, and void ratio of the mixes have been investigated to analyze the impact of different molarities and types of aggregates on their physical characteristics. The specimens were first heated in the oven for 48 hours before being tested in the Archimedes pool, This is connected to the digital scale. Figure 3.16 depicts the test devices, and the following equations were used to determine the property values:

$$\text{Unit weight (gm/cm}^3\text{)} = A / (A-C) \quad (3.3)$$

$$\text{Voids ratio (\%)} = [(B-A) / (B-C)] \times 100 \quad (3.4)$$

$$\text{Water absorption} = [(B-A)/A] \times 100 \quad (3.5)$$

Here ,

A: oven dry weight (g)

B: saturated surface dry weight (g)

C: weight of soaked sample in water (g)



Figure 3.16: Archimedes tool for physical tests

3.4.2.4 Freezing-thawing test

There were 56 cycles of freezing and thawing of the mixes. With each cycle, the freezing phase lasted 90 minutes and the thawing period 30 minutes. A temperature range of 4 to 18 degrees Celsius was used for the scientific experiments. After each cycle ended, the specimens were tested for compressive and flexural strengths, weight loss ratios, and comparisons to specimens that had not been frozen and thawed. Figure 3.17 shows the equipment used for freezing and thawing, whereas Figure 3.18 shows the specimens that are being examined.



Figure 3.17: Freezing-thawing freezer



Figure 3.18: Samples of freezing-thawing test

4. RESULTS AND DISCUSSION

4.1 General

The results were presented and discussed according to the categories intended for the study so that the integrity of the investigation's procedures about the elements that were evaluated could be preserved. The parts of this chapter will be addressed as follows:

- Physical properties (water absorption, unit weight)
- Strength properties.
- Ultrasonic pulse velocity test.
- Elevated Temperature Test.
- Freezing-Thawing Resistance.
- Acid Attack Test.
- The Correlation Between UPV and Compressive Strength.

4.1.1 Physical properties (water absorption, unit weight)

In general, all of the produced samples outperformed the control samples, The findings exhibited enhancement in comparison to the cementitious control specimens, as seen by the data presented in Table 4.1. Moreover, the enhanced percentages for water absorption also demonstrated improvement.

Table 4.1: Physical properties (water absorption, unit weight)

	Code	(%) Water absorption	Unit weight (gr/cm ³)
1	Control	12.5	2.16
2	75G25V-R	14.64	2.24
3	50G50V-R	15.27	2.34
4	25G75V-R	15.18	2.55
5	75G25V-60	11.37	2.71
6	50G50V-60	12.81	2.82
7	25G75V-60	12.12	2.63
8	75G25V-100	12.37	3.19
9	50G50V-100	11.41	3.27
10	25G75V-100	11.91	3.14

4.1.2 Strength properties

For concrete, its compressive strength is a key indicator of its mechanical performance over time. For this analysis, we averaged the compressive strengths of three samples drawn from 10 different combinations. Specifically, the proportion of ground granulated blast furnace slag and volcanic ash that cured at various temperatures was the primary variable examined. There were 28-day compressive tests conducted on the mixture. Figure 4.1 displays the compressive strengths of the series both before and after being exposed to high temperatures. When added to geopolymer made from fly ash, GGBFS increases the material's compressive strength. Nevertheless, the compressive strength was 4.744% more than the control mix at room temperature after 28 days of age with adding 75% GGBFS and 25% Volcanic ash. Increased compressive strength of about 11.35 % is achieved when 50% GGBFS and 50% volcanic ash are used. At room temperature, the amount increased by 8.452% compared to the control mix while using 25% GGBFS and 75% volcanic ash. when the mixture is cured at 60°C with 25% GGBFS and 75% volcanic ash, the compressive strength is around 3.214 % more than the control mix, and when the mixture is 50% GGBFS and 50% volcanic ash, it is about 7.25 % higher. Nonetheless, the compressive strength was 3.21 % greater than the control mix after 28 days of age when the increase was 25 % volcanic ash and 75 % green screened ballast. When the mixture is cured at 100°C with 75% GGBFS and 25% volcanic ash, the compressive strength drops 5.989% compared to the control mix. A further 2.54% drop is observed with 50% GGBFS and 50% volcanic ash at 100°C. Lastly, a 7.07% drop is observed when compared to the control mix with 25% GGBFS and 75% volcanic ash.

After 7 and 28 days, the specimens were tested for compressive and flexural strengths, and then compared to the control specimens made of cement. The findings are shown in Figures 4.1,4.2 and Tables 4.2,4.3, respectively.

Table 4.2: Compressive strength (MPa)

#	Code	7 days (MPa)	28 days (MPa)
1	Control	23.65	38.57
2	75G25V-R	27.34	40.40
3	50G50V-R	30.17	42.95
4	25G75V-R	28.29	41.83
5	75G25V-60	25.13	39.88
6	50G50V-60	28.62	41.37
7	25G75V-60	26.36	39.81
8	75G25V-100	21.77	36.26
9	50G50V-100	24.42	37.59
10	25G75V-100	20.83	35.84

It recognized that 50G50V for all temperatures gives the highest values for compressive and flexural strength, for other mixes low values occur because the increasing of volcanic ash decreases the strength, and decreasing slag lowers the strength for compressive and flexural as mentioned also in many research as Metekong et al. (2021) [94] found that Flexural and compressive strengths increased with curing temperature from 28 to 80°C, resulting in high solid precursor dissolution and a dense, compact structure.

Table 4.3: Flexural strength (MPa)

#	Code	7 days (MPa)	28 days (MPa)
1	Control	5.46	7.24
2	75G25V-R	6.31	8.11
3	50G50V-R	7.43	9.06
4	25G75V-R	6.79	8.67
5	75G25V-60	6.47	8.14
6	50G50V-60	7.12	8.98
7	25G75V-60	6.82	8.19
8	75G25V-100	5.89	6.88
9	50G50V-100	6.46	7.21
10	25G75V-100	6.17	6.79

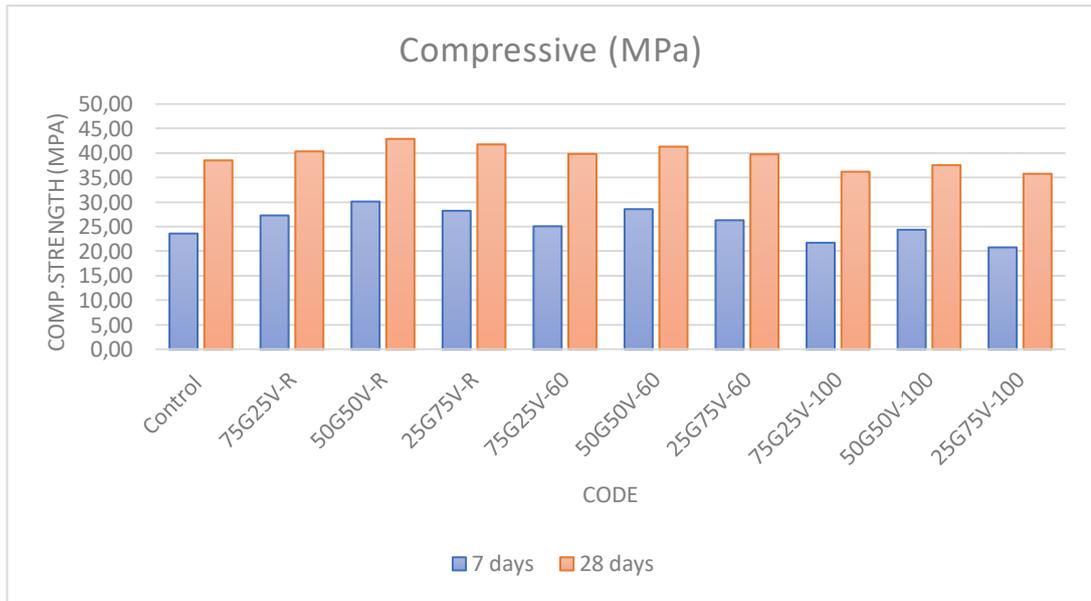


Figure 4.1: Compressive strength results

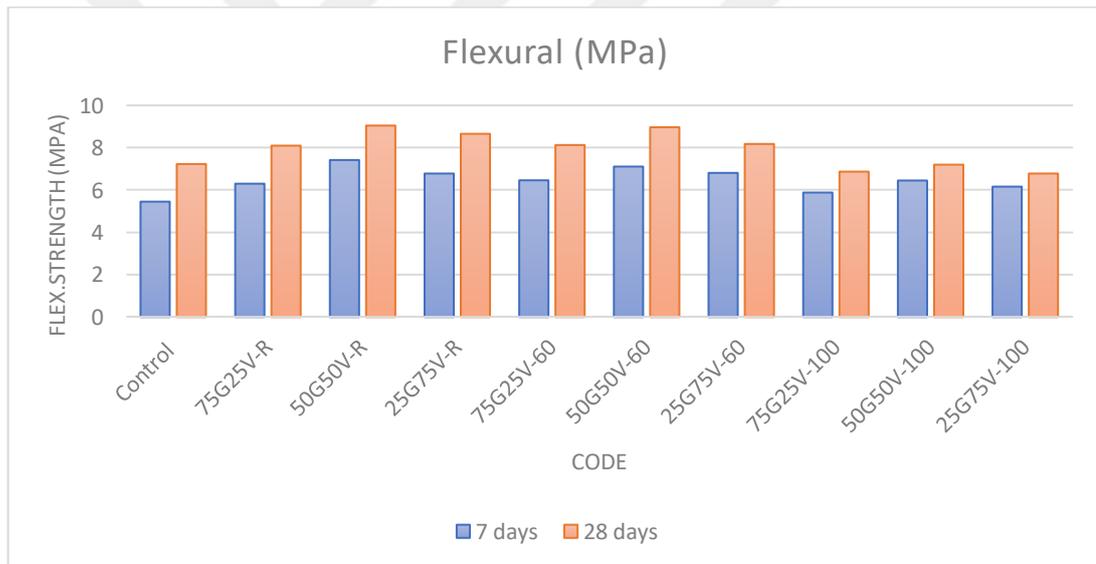


Figure 4.2: Flexural strength results

4.1.3 Ultrasonic pulse velocity test

A non-destructive method for checking for material discontinuities, defects, and internal fissures as well as the matrix's homogeneity is the ultrasonic pulse velocity. The results suggested that geopolymer composites' compressive behavior might be evaluated using the UPV test.

The UPV test was used as a non-destructive method to evaluate geopolymer specimens for variations in homogeneity. Figure 4.5 displays the UPV data collected after high-level exposure, together with the results obtained 28 days later. All things

considered, the results were in line with the strength findings when evaluated as a whole. Curing at room temperature reduced the UPV results because the binding components dissolved more slowly than in conditions with higher curing temperatures. But the thick structure and the freeze-thaw curing helped the UPV results come out better.

This tiny structure showed remarkable endurance after being exposed to extreme temperatures. Evaporation of water and expansion of the pore network were both accelerated by the temperature increase. New spaces were also created as a result of the shrinkage. Lower UPV levels were the outcome of this disorder. Moreover, micro-cracks caused by temperature reduction were shown to reduce the density of the composites. Topçu and Karakurt (2008) found that this situation led to longer propagation times for ultrasonic velocity waves and lower UPV values. As the temperature rose over 500°C, the rate of fracture propagation accelerated and fiber melting occurred, resulting in a longer propagation of the ultrasonic velocity wave and lower values. As shown by Arslan et al. (2019) and Celik et al. (2018), both basalt fibers and PVA had a higher modulus of flexibility, which had some limits in this case.

The UPV test found is shown in Tables 4.4 and 4.5, as well as Figures 4.3, 4.4, and 4.5.

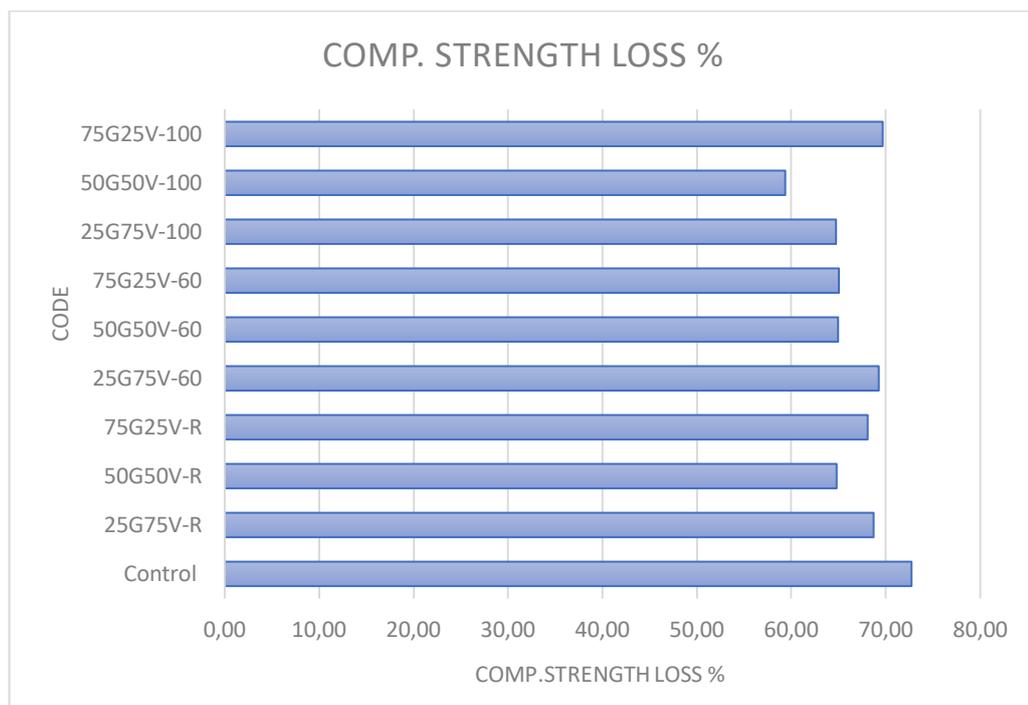
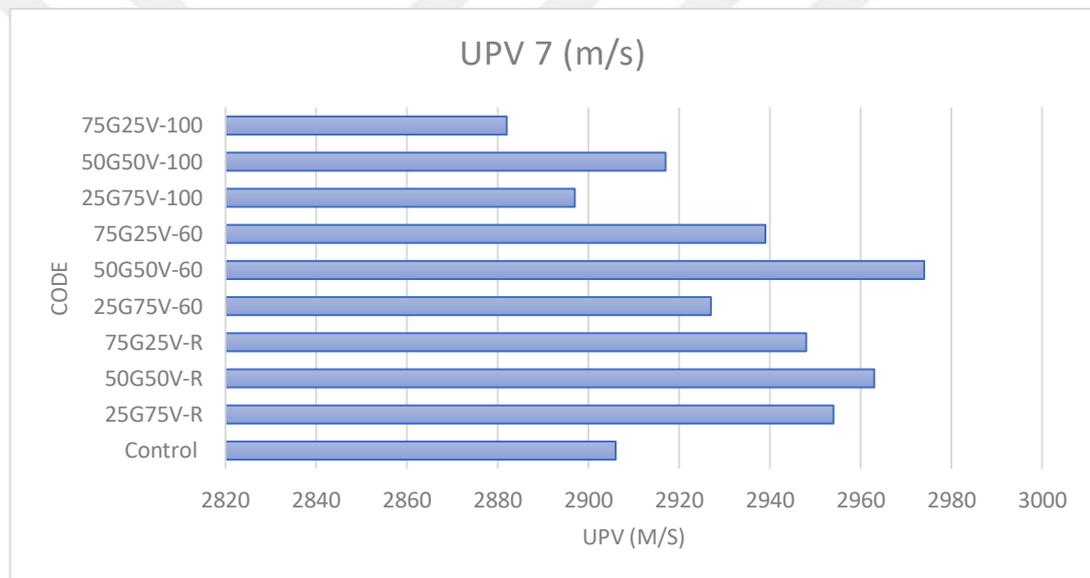


Figure 4.3: Compressive strength loss

Table 4.4: UPV7- comp results

#	Code	7 Compressive (MPa)	7 UPV (m/s)
1	Control	23.65	2906
2	25G75V-R	27.34	2954
3	50G50V-R	30.17	2963
4	75G25V-R	28.29	2948
5	25G75V-60	25.13	2927
6	50G50V-60	28.62	2974
7	75G25V-60	26.36	2939
8	25G75V-100	21.77	2897
9	50G50V-100	24.42	2917
10	75G25V-100	20.83	2882

**Figure 4.4: UPV 7-comp results****Table 4.5: UPV28- comp. results**

#	Code	28 Compressive (MPa)	28 UPV (m/s)
1	Control	38.57	3331
2	75G25V-R	40.40	3351
3	50G50V-R	42.95	3426
4	25G75V-R	41.83	3388
5	75G25V-60	39.88	3361
6	50G50V-60	41.37	3400
7	25G75V-60	39.81	3349
8	75G25V-100	36.26	3276
9	50G50V-100	37.59	3331
10	25G75V-100	35.84	3305

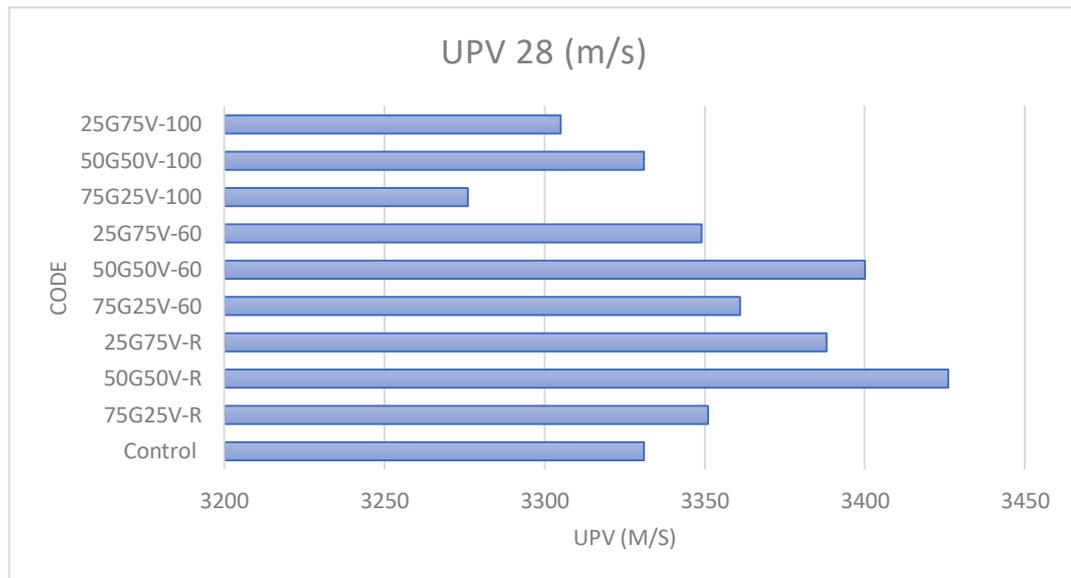


Figure 4.5: UPV 28-comp. results

UPV results for 7 and 28 days increased so it means low voids which means there is a compact sample containing these voids and this will increase the speed of crossing the wave through the sample.

4.1.4 Elevated temperature test

The impact of elevated temperatures on geopolymer mortars has been the subject of mixed findings in the scientific literature. Strength findings varied among research, with some seeing an increase and others a loss in the 200-400 °C range. According to prior research, the activator type (Cheng &Chiu, 2003), curing conditions (Nasr et al., 2018; Türker et al., 2016), and activator concentration (Nasr et al., 2018; Rashad et al., 2016) all have a role in how geopolymer mortars react to heat stresses. After the increased temperature test was conducted, the strength findings in this research fell. Water evaporation and dehydration due to heat reactions above 500 °C were the primary causes of this condition (Zhang et al., 2012). It would be helpful to define the steam effect in order to provide a clearer explanation for the strength reduction that occurs over 500 °C. Strength decreased with rising temperatures, and the main cause for this was the steam effect.

By exposing them to different temperatures, namely 60 °C and 100 °C, the thermal behavior of 25V75G-60, 50V50G-60, 75V25G-60, 25V75G-100, 50V50G-100, and 75V25G-100 were evaluated. To see what percentage of weight loss there was, look at Table 4.6. At 100 °C, both materials lost about the same amount of

weight (12.7%). This could be because some of the water in the pores evaporates, some of the water in the reaction products physically bonds with them, and some of the organic matter (carbon) given by FA partially evaporates. This loss is thought to be caused by dehydration, a process where the structure removes water when the temperature is high.

Table 4.6: Results of strength after tests at 400 °C

	Code	28day (MPa)	Comp. After test (MPa)	Comp. strength loss %	28 flexural (MPa)	flex. After test (MPa)	Flex. strength loss %	weight loss (%)	UPV (m/s)
1	Control	38.57	20.21	47.60	7.24	2.51	65.33	5.29	1807
2	75G25V-R	40.40	23.84	40.99	8.11	3.21	60.42	3.23	1874
3	50G50V-R	42.95	26.57	38.14	9.06	3.37	62.80	3.06	1916
4	25G75V-R	41.83	22.62	45.92	8.67	2.62	69.78	4.38	1832
5	75G25V-60	39.88	21.81	45.31	8.14	3.42	57.99	4.46	1830
6	50G50V-60	41.37	25.43	38.53	8.98	3.57	60.24	3.79	1925
7	25G75V-60	39.81	23.76	40.32	8.18	2.83	65.40	4.36	1802
8	75G25V-100	36.26	22.33	38.42	6.88	2.77	59.74	5.2	1821
9	50G50V-100	37.59	25.18	33.01	7.21	3.28	54.51	4.87	1895
10	25G75V-100	35.84	21.49	40.04	6.79	2.91	57.14	5.19	1840

At 400°C again in compliance with the results of compressive and flexural strength both flexural and compressive strength results for elevated temperatures 400°C showed the same compliance for 50G50V samples because they maintained to show less loss after flexural and compressive strength and compared other samples like 75G25V and 25G75V for all temperatures showed also good results when compared to control sample with 100 % slag which means, in general, the addition of volcanic ash was beneficial in this temperature.

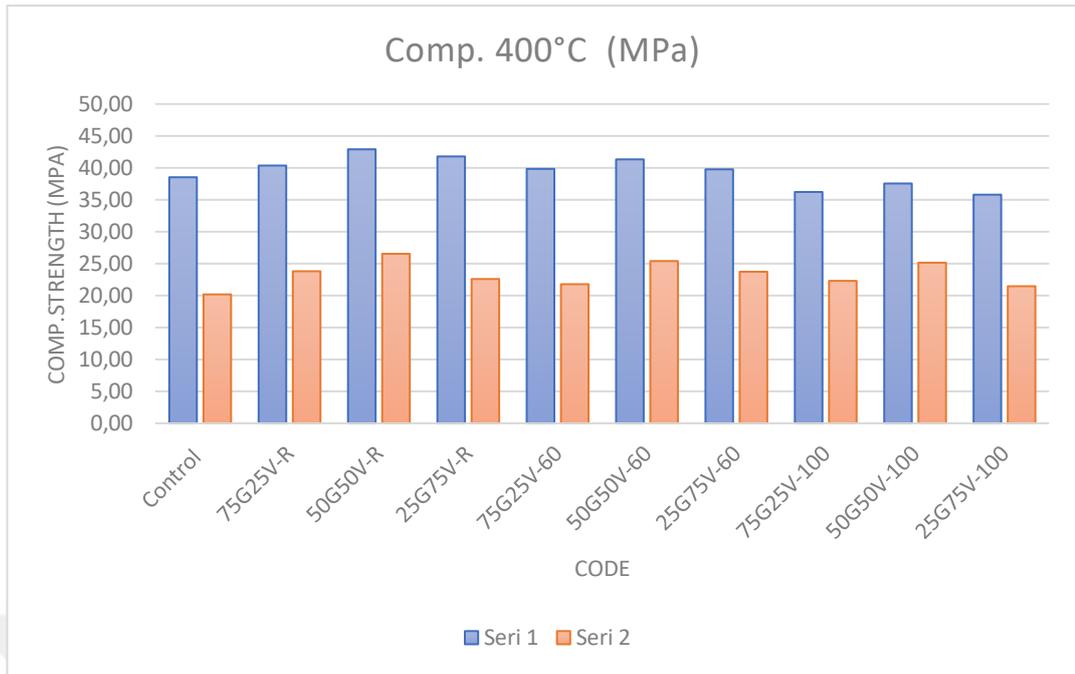


Figure 4.6: Compressive strength results at 400 °C

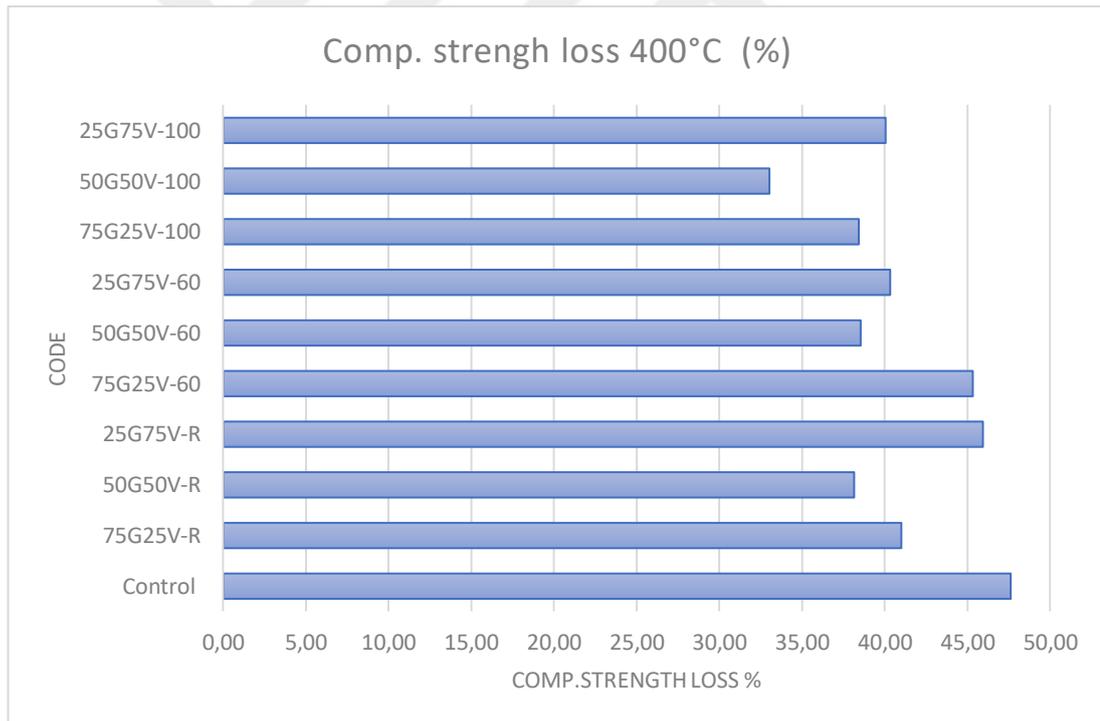


Figure 4.7: Results of comp. strength loss at 400 °C

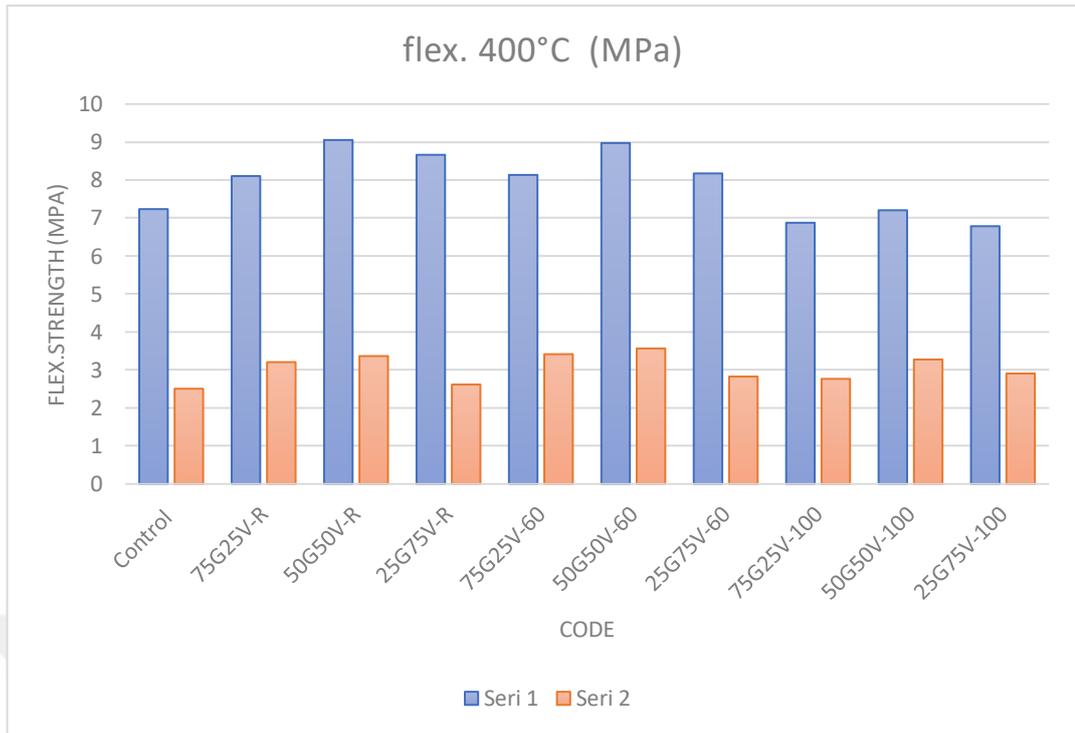


Figure 4.8: Flex. strength results at 400 °C

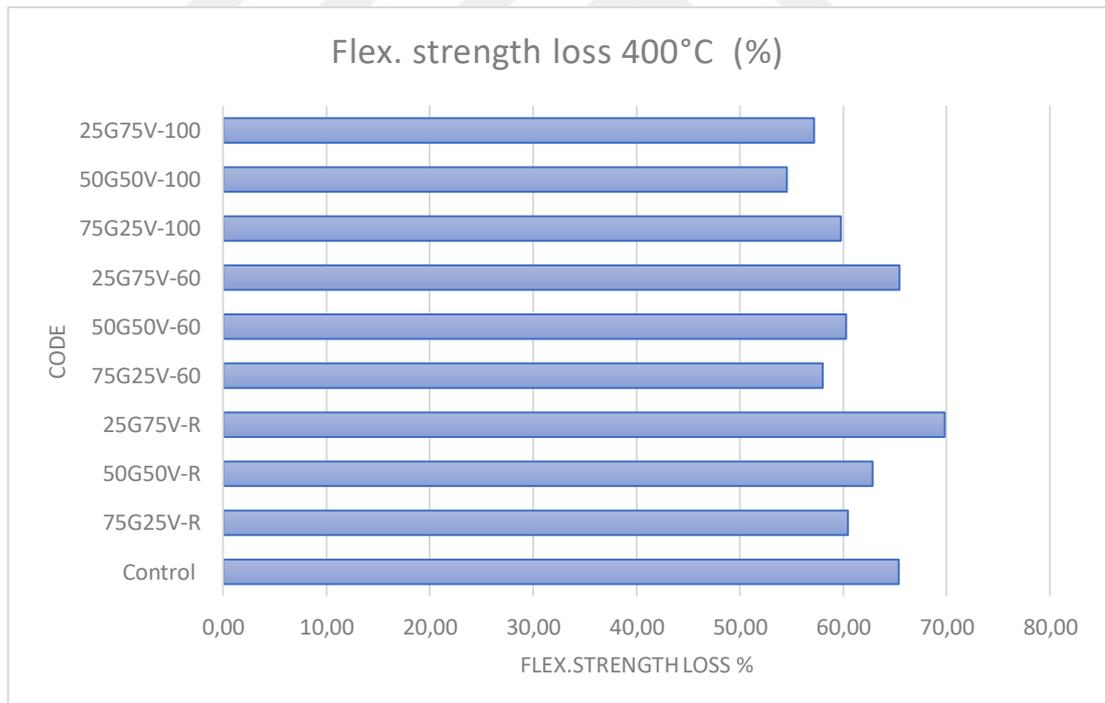


Figure 4.9: Flex. strength loss results at 400 °C

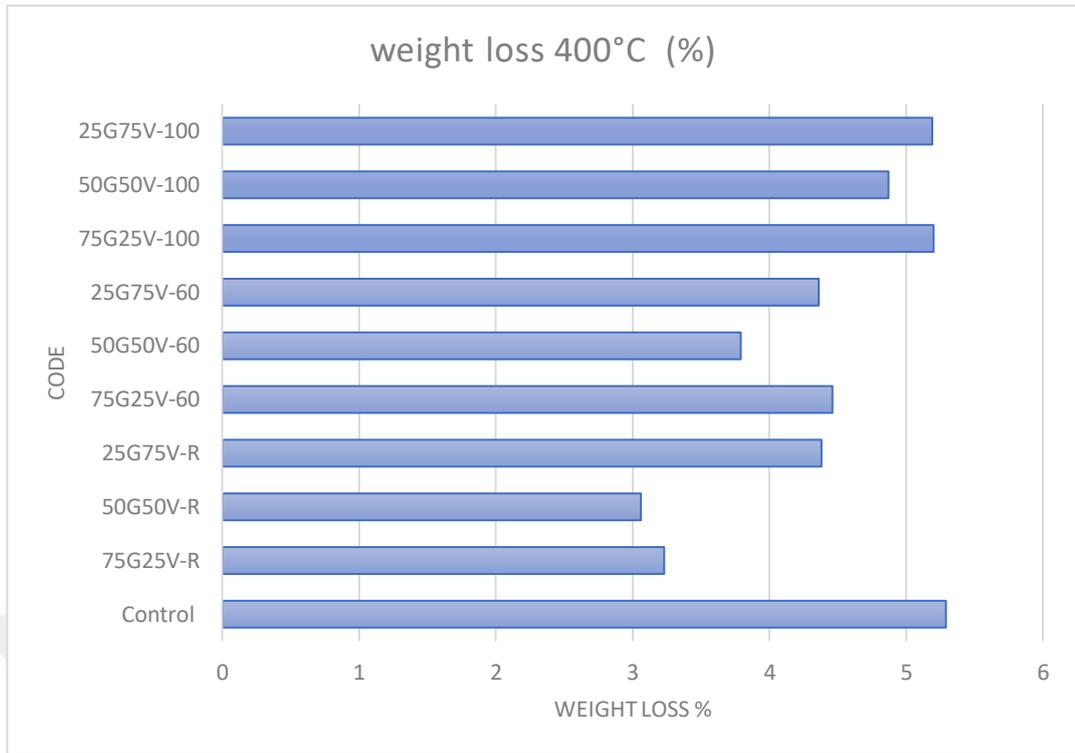


Figure 4.10: Weight loss results at 400 °C.

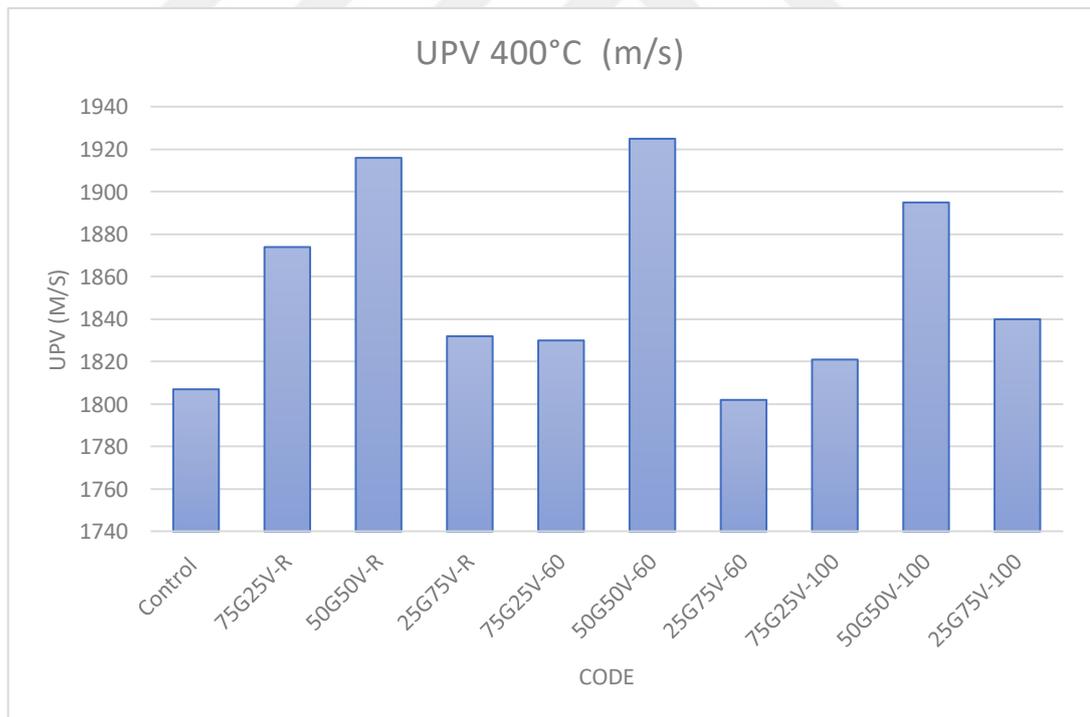
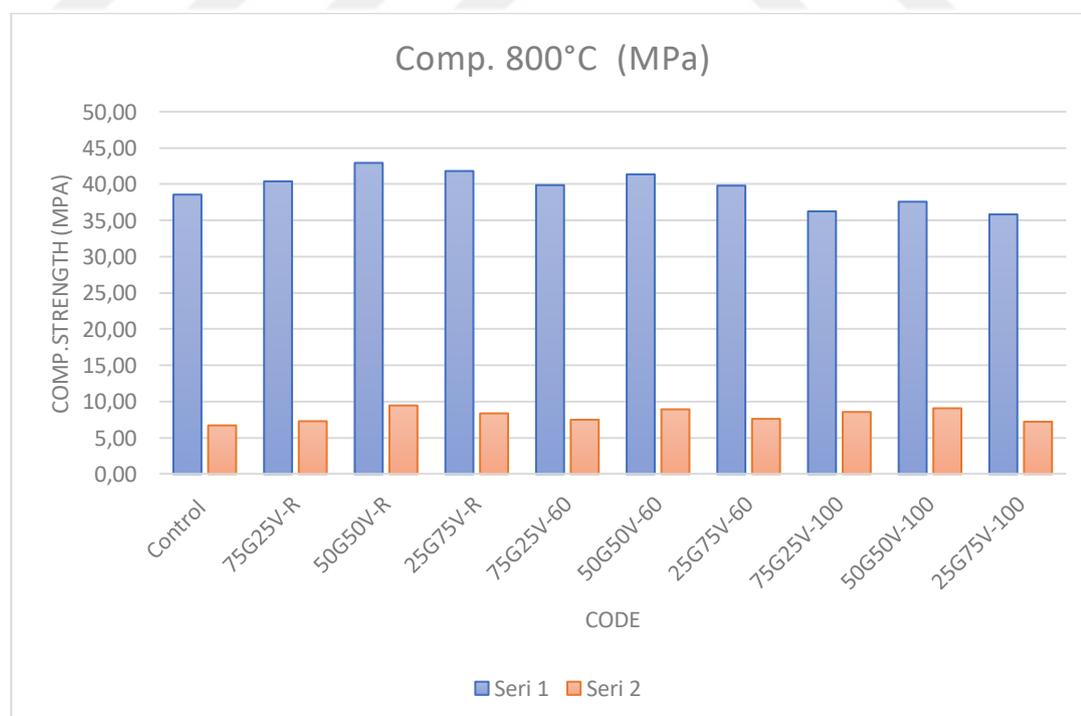


Figure 4.11: UPV test results at 400 °C

Table 4.7: Results of strength after tests at 800 °C

	Code	28day (MPa)	Comp. After test (MPa)	Comp. strength loss %	28 flexural (MPa)	flex. After test (MPa)	Flex. strength loss %	weight loss (%)	UPV (m/s)
1	Control	38.57	6.71	82.60	7.24	0.81	88.81	7.61	970
2	75G25V-R	40.40	7.29	81.96	8.11	0.97	88.04	7.28	1147
3	50G50V-R	42.95	9.46	77.97	9.06	1.36	84.99	6.96	1261
4	25G75V-R	41.83	8.37	79.99	8.67	0.85	90.20	7.16	1193
5	75G25V-60	39.88	7.49	81.22	8.14	0.95	88.33	8.57	1213
6	50G50V-60	41.37	8.93	78.41	8.98	1.41	84.30	7.71	1272
7	25G75V-60	39.81	7.61	80.88	8.18	0.84	89.73	8.16	1110
8	75G25V-100	36.26	8.56	76.39	6.88	1.35	80.38	7.23	1012
9	50G50V-100	37.59	9.07	75.87	7.21	1.46	79.75	6.42	1059
10	25G75V-100	35.84	7.22	79.85	6.79	0.82	87.92	7.74	1007

Coming to 800°C temperature we know that after 800°C serious damage will happen to the sample but again the same thing can be said for the samples 50G50V at room temperature, 60°C and 100°C and the same performance can be said about 75G25V and 25G75V because they were all good when compared to control as mentioned by Aygörmez et al. (2022). [98]

**Figure 4.12:** Compressive strength results at 800 °C

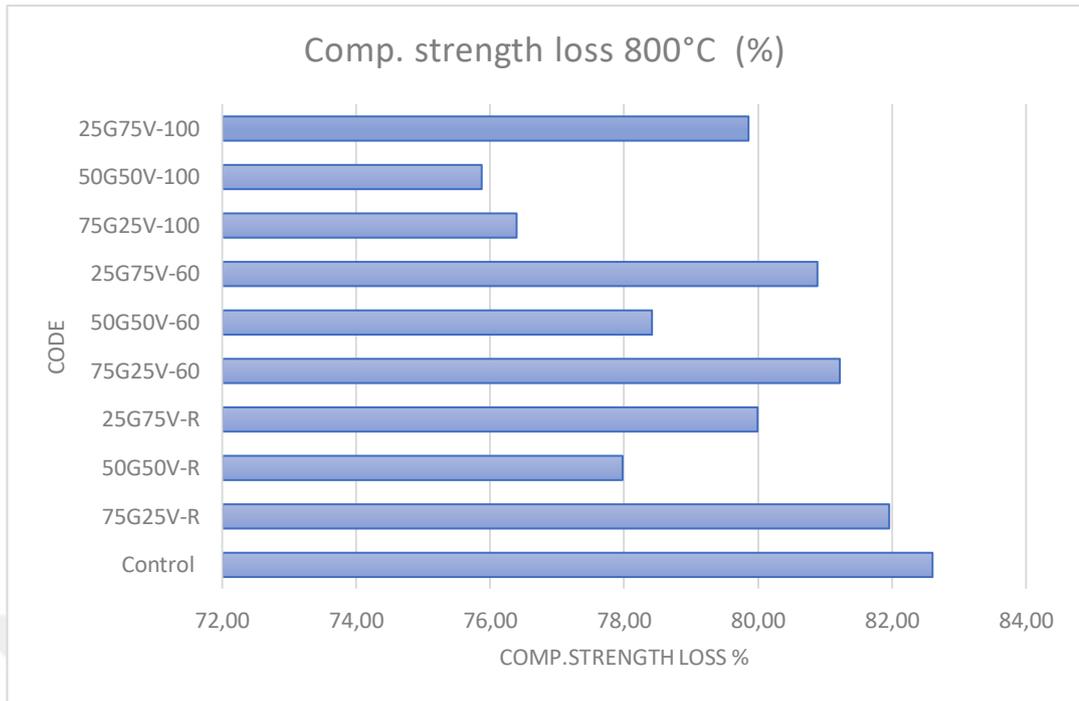


Figure 4.13: Results of comp. strength loss at 800 °C

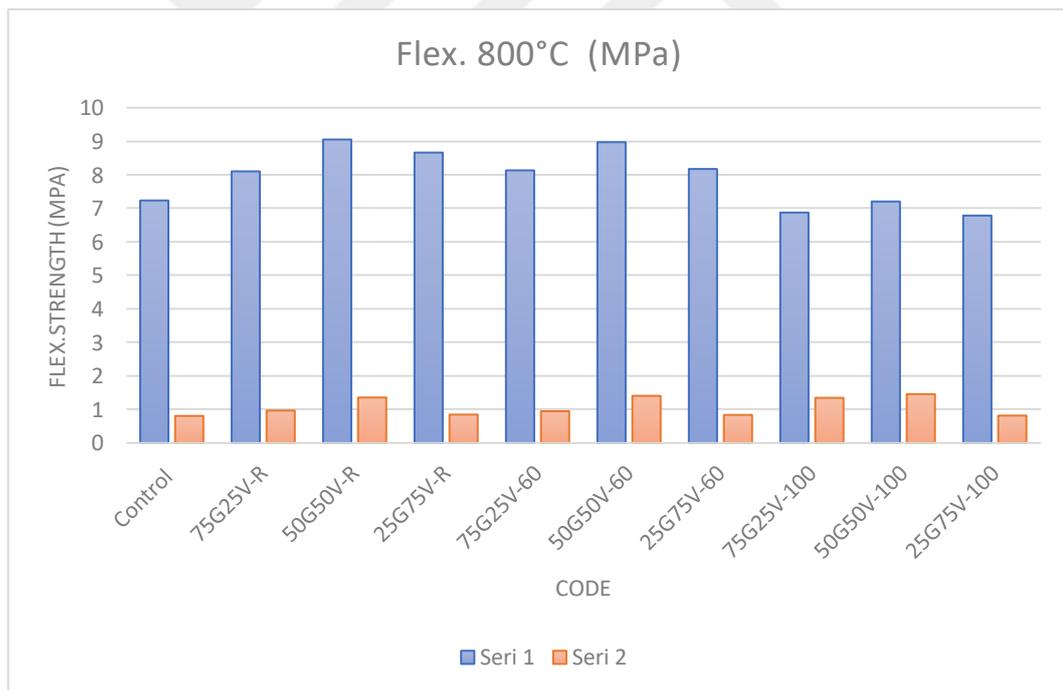


Figure 4.14: Flex. strength results at 800 °C

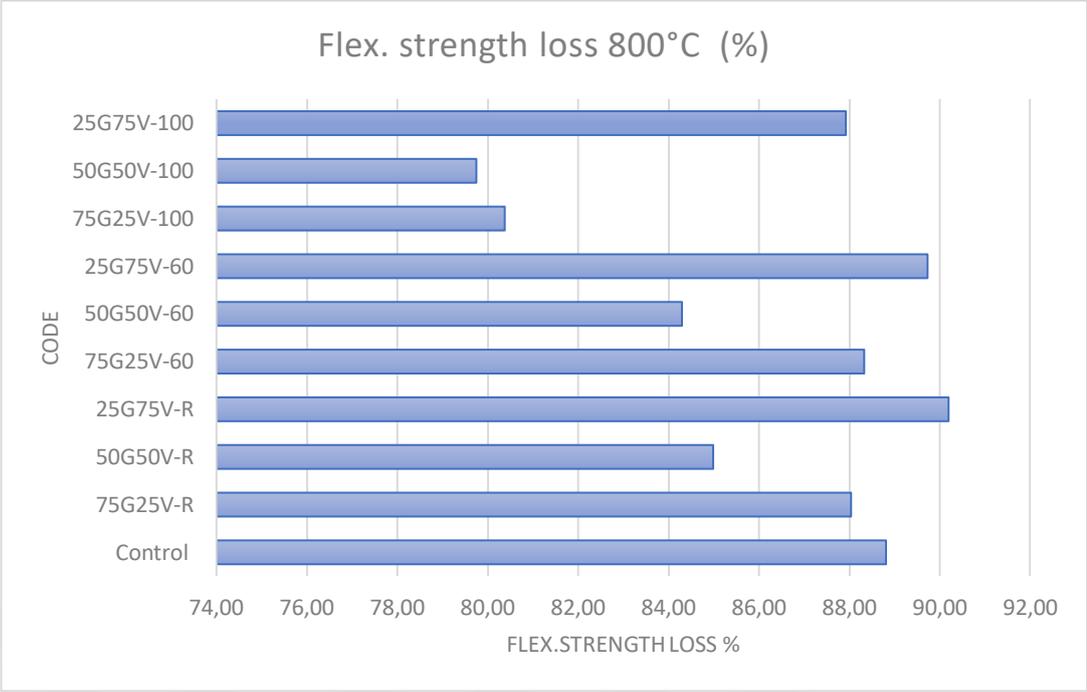


Figure 4.15: Flex. strength loss results at 800 °C

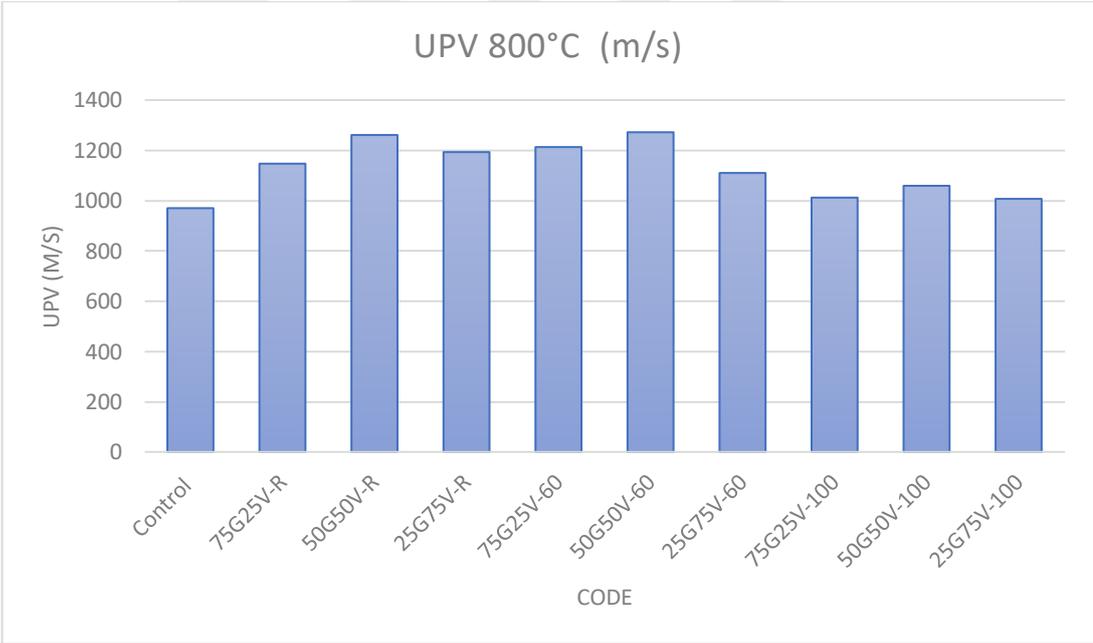


Figure 4.16: UPV test results at 800 °C

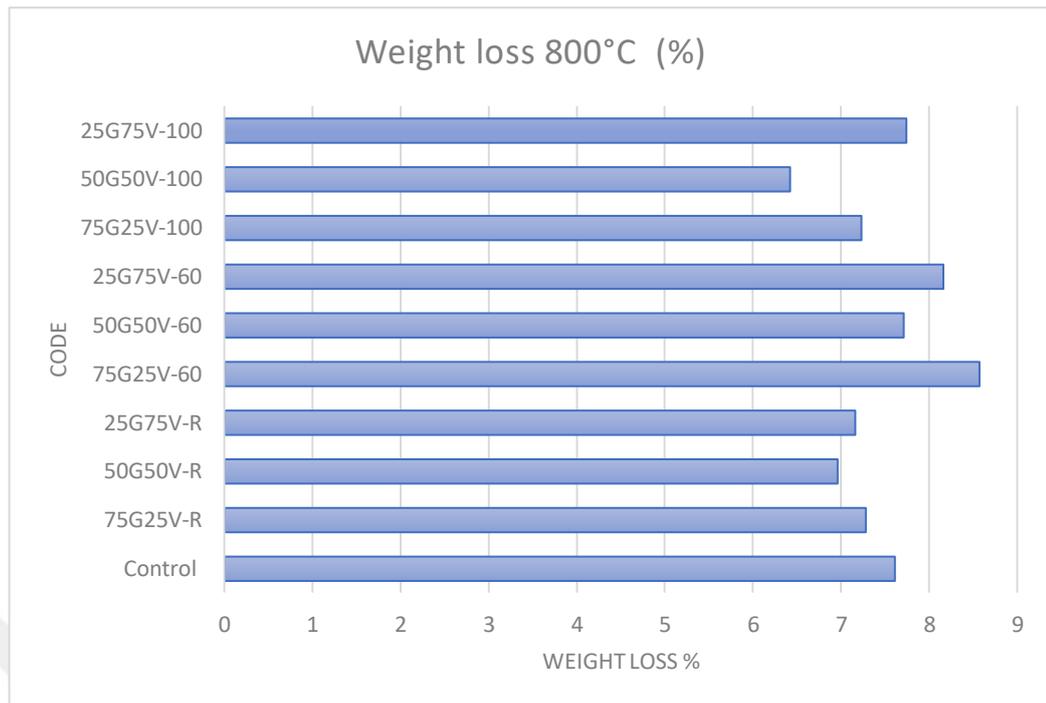


Figure 4.17: Weight loss results at 800 °C

The compressive strength generally increases with higher proportions of GGBFS in the mix. Notably, the 50G50V-R mix exhibits the maximum compressive strength under normal ambient conditions, 60°C, and 100°C. As shown in Figure 4.18. This suggests that an equal combination of GGBFS and volcanic ash tends to produce optimal strength across different curing conditions as mentioned also by Tayeh et al. (2021). [95]

In some cases, like 25G75V-60, the compressive strength is higher at 60°C compared to room temperature, indicating the positive influence of elevated curing temperatures.

However, at 100°C, the compressive strength tends to decrease for most mixes, possibly due to excessive heat affecting the structure. Some mixes, such as 75G25V-60, exhibit reduced strength at higher curing temperatures, suggesting that the material might face challenges under prolonged exposure to elevated temperatures.

Typically, when comparing compressive strength, the geopolymer mixes show that GGBFS and volcanic ash can improve the material's characteristics, surpassing the control mix.

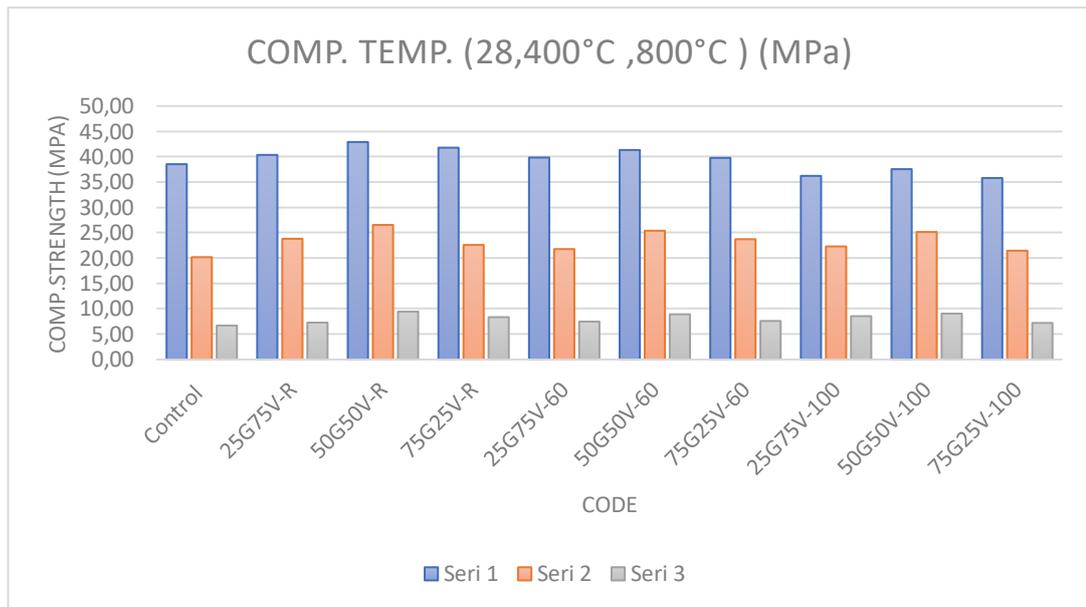


Figure 4.18: Comp. strength values for different geopolymer mixes

Similar to compressive strength, mixes with higher GGBFS content tend to show higher flexural strength at room temperature.

The 50G50V-R mix again stands out as having the highest flexural strength, showcasing its versatility across different mechanical properties. As shown in Figure 4.19.

The impact of curing temperature on flexural strength varies across mixes. For some, like 50G50V-60, there is an increase in flexural strength at 60°C, indicating the positive influence of elevated curing temperatures.

However, at 100°C, the flexural strength tends to fluctuate, with some mixes showing a decrease. This could be attributed to the potential adverse effects of prolonged exposure to high temperatures as shown also by Yong-Sing et al. (2022). [96]

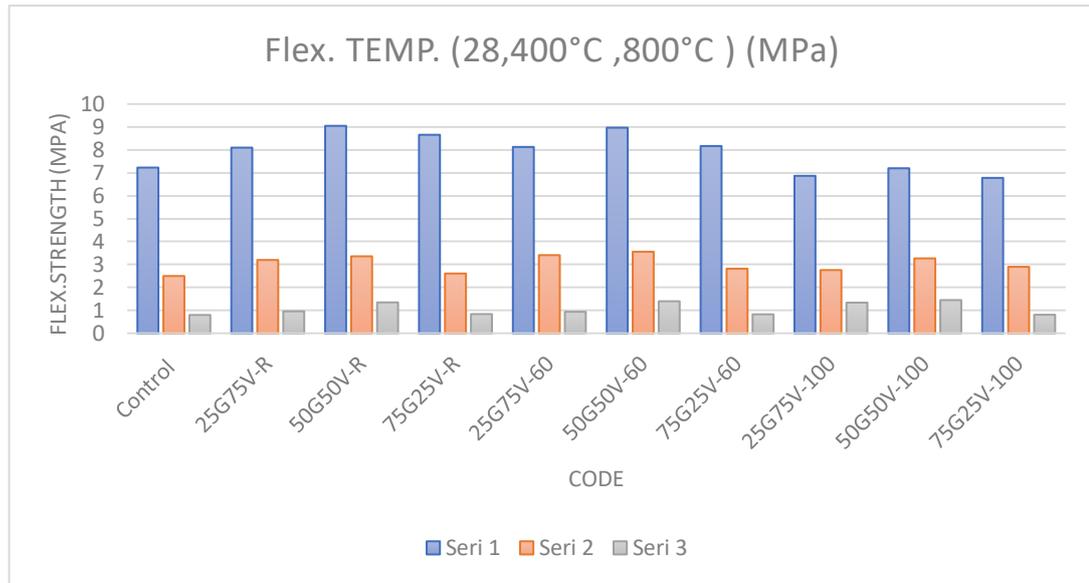


Figure 4.19: Flex. strength at elevated temperatures.

Referring to Figure 4.20. The 50G50V-R blend has the best UPV at room temperature (3426 m/s), which indicates that the structure is well-compacted and that the interior quality is excellent.

Generally, all mixes show reasonably high UPV values at room temperature, indicating sound internal integrity.

The 50G50V-60 mix maintains a high UPV (1925 m/s) even at 60°C, indicating its ability to retain internal quality under elevated curing temperatures. The 75G25V-60 mix performs well, suggesting that geopolymer concrete can maintain its UPV under moderate heat exposure.

The 50G50V-100 mix shows resilience with a relatively high UPV (1059 m/s) at 100°C, emphasizing its ability to withstand higher temperatures. The 75G25V-100 mix has a slightly lower UPV (1012 m/s), indicating potential challenges in maintaining UPV at prolonged high temperatures.

For general observations, the 50G50V mix consistently exhibits superior UPV values, suggesting a more uniform and well-compacted internal structure as mentioned also by Omer et al. (2015). [97]

Elevated curing temperatures have varying effects on UPV, with some mixes maintaining resilience and others showing slight reductions.

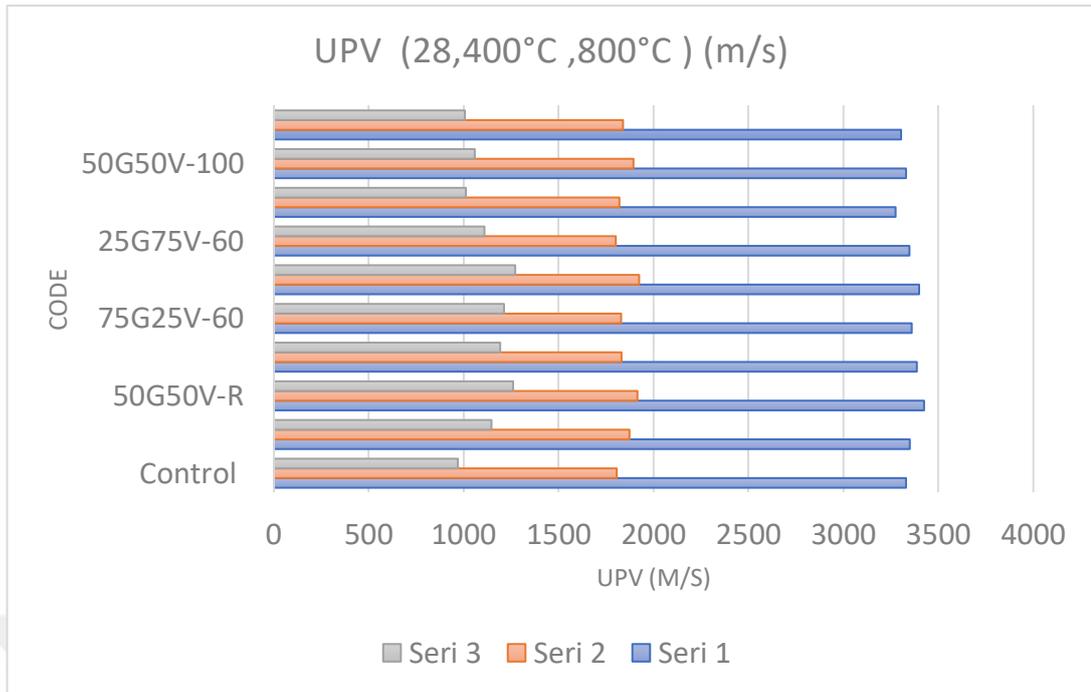


Figure 4.20: UPV results for geopolymer concrete mixes

As shown in Figure 4.21, The mixes show varying compressive strength loss and the lowest result was with 50G50V-100 for both 400 and 800 °C because when curing at high temperature gives a good compacted sample as we mentioned before so the compressive strength loss will be less.

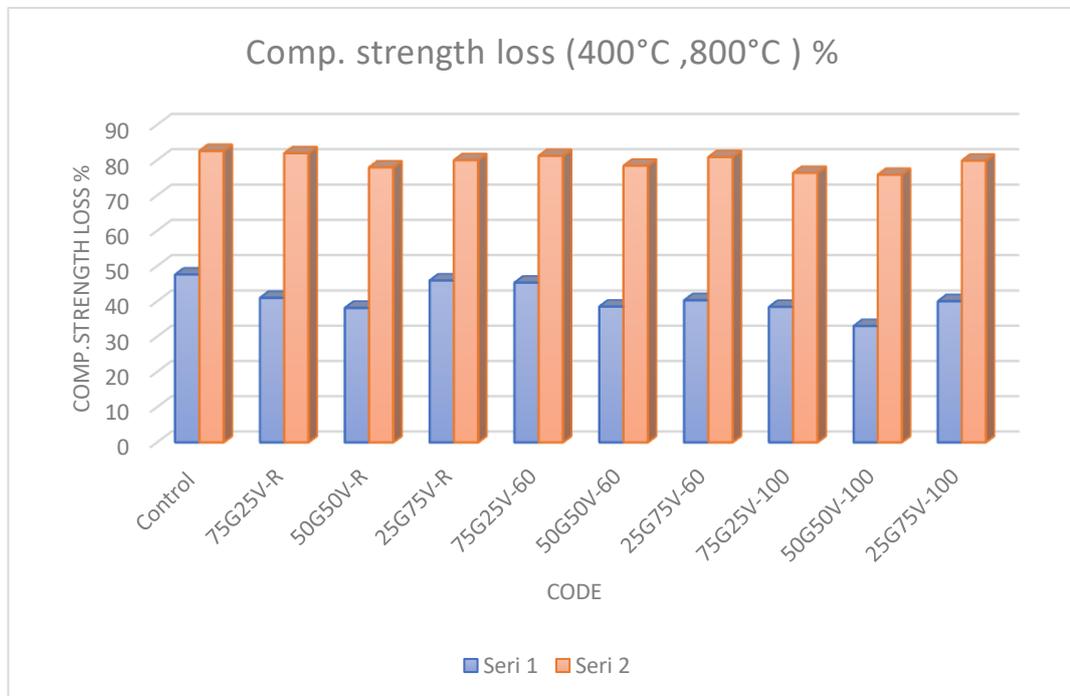


Figure 4.21: Results for comp. strength loss (400°C, 800°C)

As shown in Figure 4.22, Mixes with varying proportions of GGBFS and volcanic ash show a range of flexural strength loss at 400 and 800°C.

The mix 50G50V-100 again gives the minimum value for the flexural strength loss as mentioned by Hussin et al. (2015) [99], BAG concrete samples' zeolite-like N–A–S–H binder gel system produced thermally stable structures like hydrosodalite and analcime at 200–800 C. This increased geopolymer crystallinity till 200–400 C and maintained structure up to 800 C. XRD showed it recrystallized to nepheline or albite.

Temperature effects influence flexural strength differently for each mix, indicating the importance of mix composition in determining the high-temperature behavior of geopolymers.

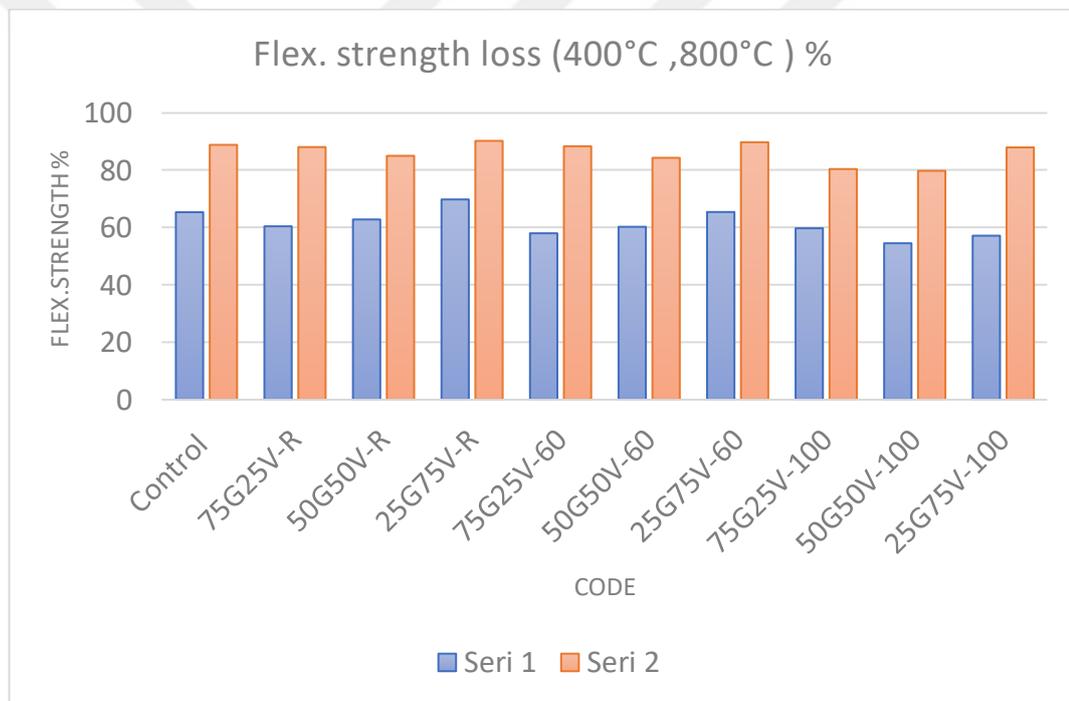


Figure 4.22: Results for flex. strength loss (400°C, 800°C)

As shown in Figure 4.23. The mix 50G50V-R generally shows lower weight loss, suggesting improved thermal stability at 400 °C. As mentioned also by Metekong et al. (2021).

The 75G25V-60 mix exhibits the highest weight loss at 800°C (8.57%), possibly due to its specific composition and proportions.

The mix 50G50V-100 at 800°C gives the lower weight loss and tends to well a compacted sample at high temperature so the voids will be very low in this case. As

the researcher Lemouagna et al. (2013) [100] mentioned There is a sudden jump in weight loss between 500 and 600°C. This portion is explained by some structural water in the geopolymer matrix being dehydrated or dehydroxylated.

It has been observed that hydroxy sodalite loses weight almost consistently between 100 and 800 °C.

The composition of the combination, especially the inclusion of GGBFS, affects the weight loss at higher temperatures.

One way in which GGBFS can improve geopolymers' thermal stability is by aiding in the production of binding products.

The control mix experiences significant weight loss, indicating that it may undergo more pronounced decomposition under high temperatures.

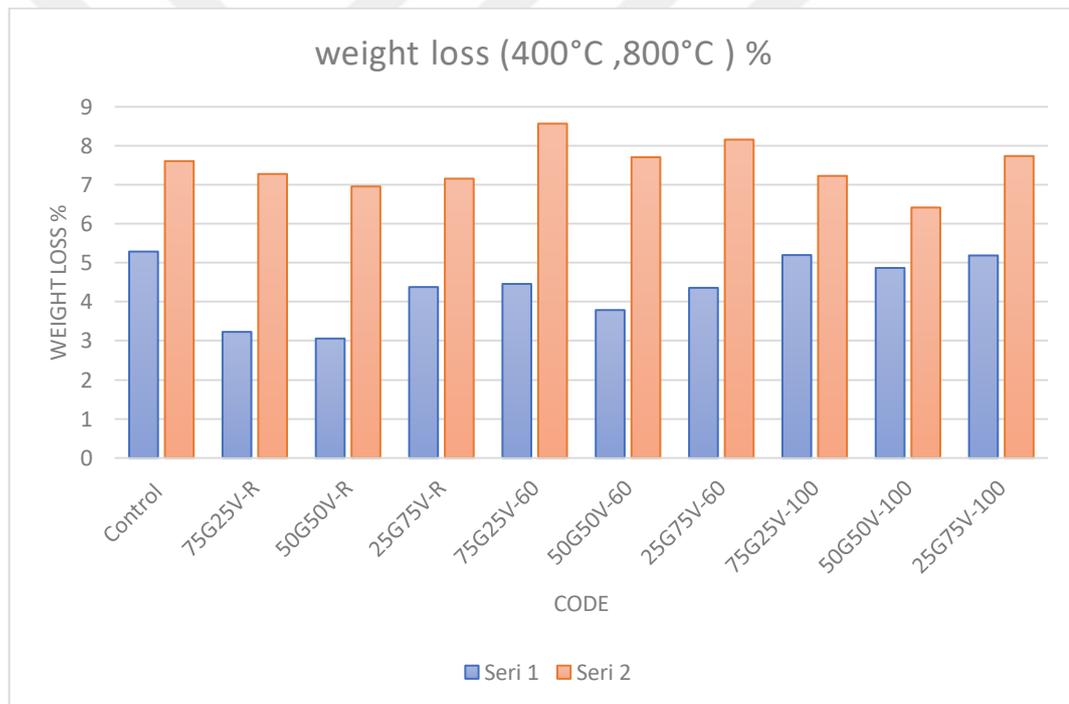


Figure 4.23: Wight loss results at temperatures 400°C and 800°C

4.1.5 Freezing-thawing test

The percentage of compressive strength loss was used as an attribute metric to assess the impact of freeze-thaw cycling on the variation in compressive strength of the samples. The findings of strength characteristics before and after 25 and 50 freezing-thaw cycles are presented in Table 4.8. Figure 4.24 clearly demonstrates that the 50G50V-R mixture has the maximum compressive strength at 28 days, measuring 42.95 MPa, surpassing the control condition. Generally, mixes with a

higher proportion of GGBFS (Ground Granulated Blast Furnace Slag) tend to exhibit higher 28-day compressive strengths. Also, the 50G50V-R mix maintains the highest compressive strength after testing (38.74 MPa), indicating good resilience.

The compressive strength after testing is crucial for assessing the durability and long-term performance of the concrete mixes.

The figure 4.25 shows Mixes with a balanced combination of fly ash and GGBFS (50G50V-R) demonstrate both high early strength and good resistance to strength loss after testing.

The selection of mix proportions and extra cementitious elements significantly influences the performance of geopolymers, particularly in terms of achieving favorable early strength development. The substitution of volcanic ash with slag has a beneficial impact on reducing the decline in compressive strength of geopolymer. The compressive strength loss percentage in the mixes 25V75G-R, 50V50G-R, and 75V25G-R was decreased to 5.51%, 10.9%, and 6.73% correspondingly, compared to the control sample subjected to 25 and 50 freezing-thaw cycles. The use of Volcanic ash significantly enhanced the durability. Also, 25V75G-60, 50V50G-60, and 75V25G-60 mixes were reduced to 4.76 %, 10.69 %, and 10.57% concerning the control sample. Also, 25V75G-100,50V50G-100, and 75V25G-100 mixes were reduced to 10.99%,18.37%, and 4.19% respectively concerning the control sample. Zheng et al. (2023). [101]

Table 4.8: Results of strength properties before and after freezing-thawing

#	Code	28day (MPa)	Comp. After test (MPa)	strength loss (%)	28 flexural (MPa)	flex. After test (MPa)	strength loss (%)	weight loss (%)	UPV (m/s)
1	Control	38.57	32.3	16.26	7.24	6.8	6.08	3.9	3070
2	75G25V-R	40.40	35.43	12.30	8.11	7.2	11.22	3.7	3147
3	50G50V-R	42.95	38.74	9.80	9.06	8.18	9.71	3.55	3161
4	25G75V-R	41.83	34.27	18.07	8.67	7.75	10.61	3.6	3123
5	75G25V-60	39.88	32.82	17.70	8.14	7.17	11.92	3.76	3103
6	50G50V-60	41.37	35.58	14.00	8.98	8.14	9.35	3.69	3152
7	25G75V-60	39.81	31.7	20.37	8.19	7.1	13.31	3.86	3120
8	75G25V-100	36.26	30.71	15.31	6.88	5.8	15.70	2.9	3012
9	50G50V-100	37.59	32.77	12.82	7.21	6.2	14.01	2.4	3059
10	25G75V-100	35.84	29.37	18.05	6.79	5.5	19.00	2.3	3007

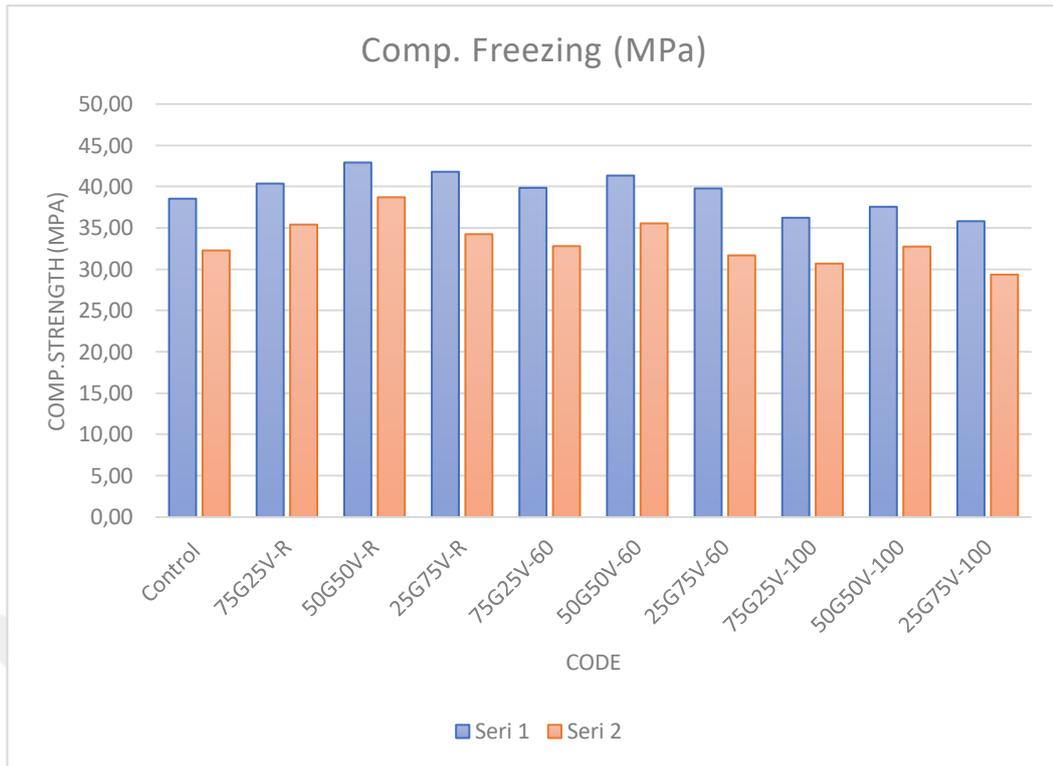


Figure 4.24: Comp. strength results after freezing-thawing test

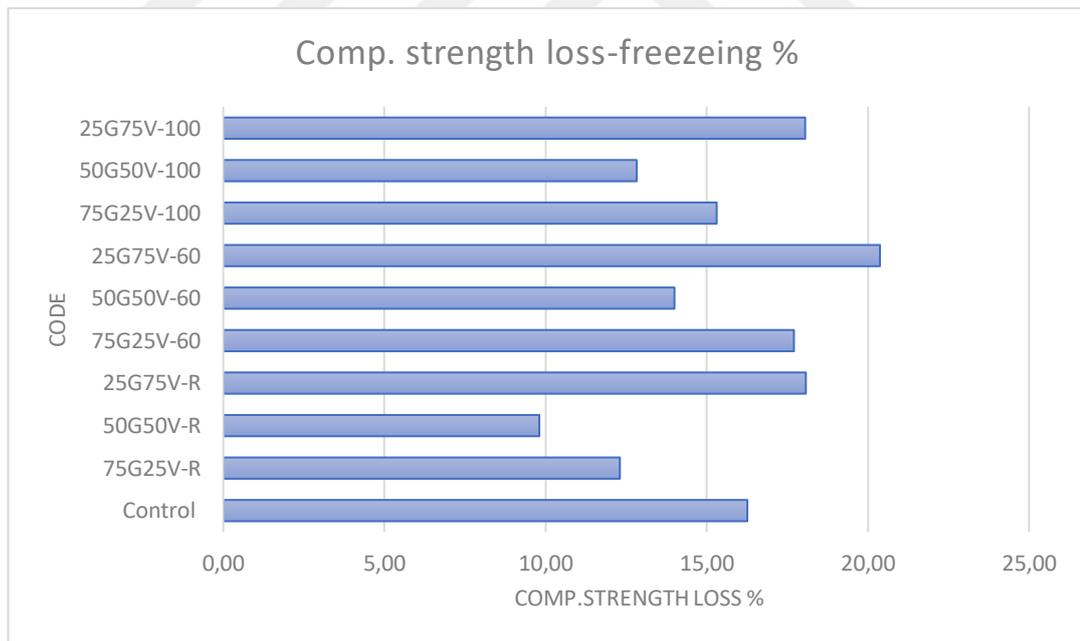


Figure 4.25: Comp. strength loss results after the freezing-thawing test

The 50G50V-R mix as shown in Figure 4.26 has the highest flexural strength at 28 days (9.06 MPa), indicating good early flexural strength development. Mixes with a higher proportion of GGBFS (Ground Granulated Blast Furnace Slag) tend to exhibit higher 28-day flexural strengths. The 50G50V-R maintains the highest

flexural strength after testing (8.18 MPa), demonstrating good resilience. Flexural strength losses are more pronounced in mixes with lower proportions of GGBFS, such as the Control mix as mentioned also by Zhang et al. (2023). [102]

When it comes to flexural performance, geopolymers are very sensitive to mix proportions and the addition of cementitious elements.

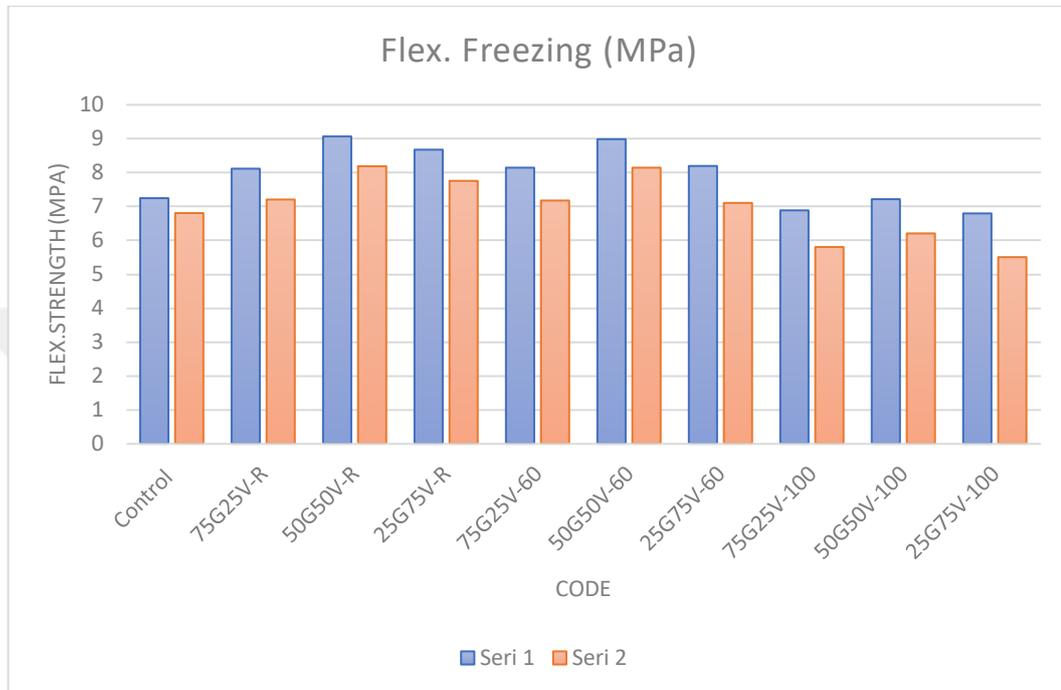


Figure 4.26: Flex. strength results after freezing-thawing test

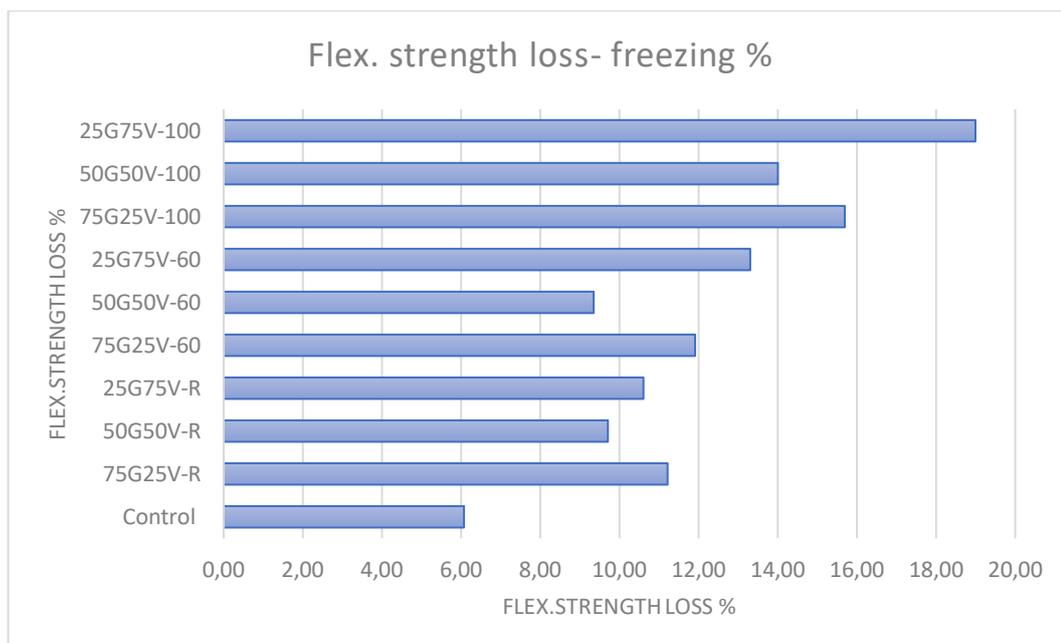


Figure 4.27: Flex. strength loss results after the freezing-thawing test

Mixes with higher proportions of GGBFS (Ground Granulated Blast Furnace Slag) generally show lower weight losses after the freezing-thawing test in Figure 4.28. 50G50V-R has lower weight loss than the control condition, also 50G-50V-60 is lower weight loss from other mixes, But The 25G75V-100 mix has the lowest weight loss (2.3%), suggesting enhanced durability under freezing-thawing conditions as mentioned by Djobo et al. (2017). [20]

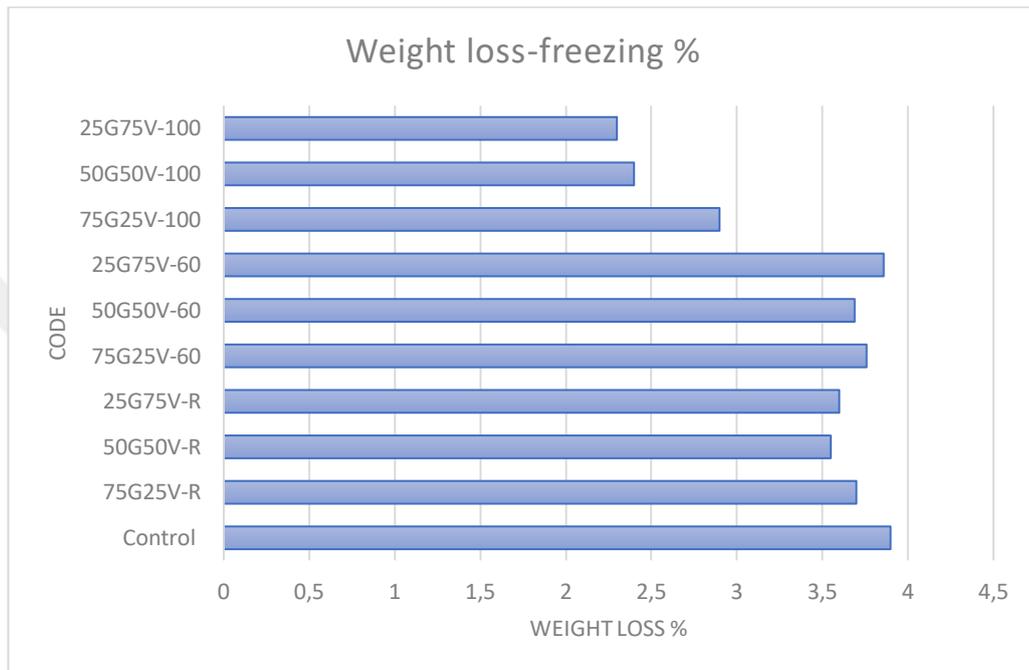


Figure 4.28: Weight loss results after freezing-thawing test

The UPV values provide insights into the integrity and quality of the concrete specimens after the freezing-thawing test. Generally, higher UPV values indicate better structural integrity and reduced damage due to freezing-thawing cycles.

Mixes with higher proportions of GGBFS, such as 50G50V-R, tend to exhibit relatively highest UPV value, indicating better resistance to freeze-thaw damage. The mix 50G50V-60 has a good UPV value compared to other mixes in the same temperature and is higher than the control mix because of lower voids when cured at high temperatures. But when increasing the temperature to 100 for the mixes we recognized that the UPV values were very low and this could be because of the cracks that occurred in the samples as mentioned by Özdal et al. (2021) [103]. The SGC samples' UPV and RDEM values increased as the GGBFS ratio raised. The samples subjected to 300 F-T cycles showed maximum drop rates of 25.6 and 44.7% in the RDEM and UPV values, respectively.

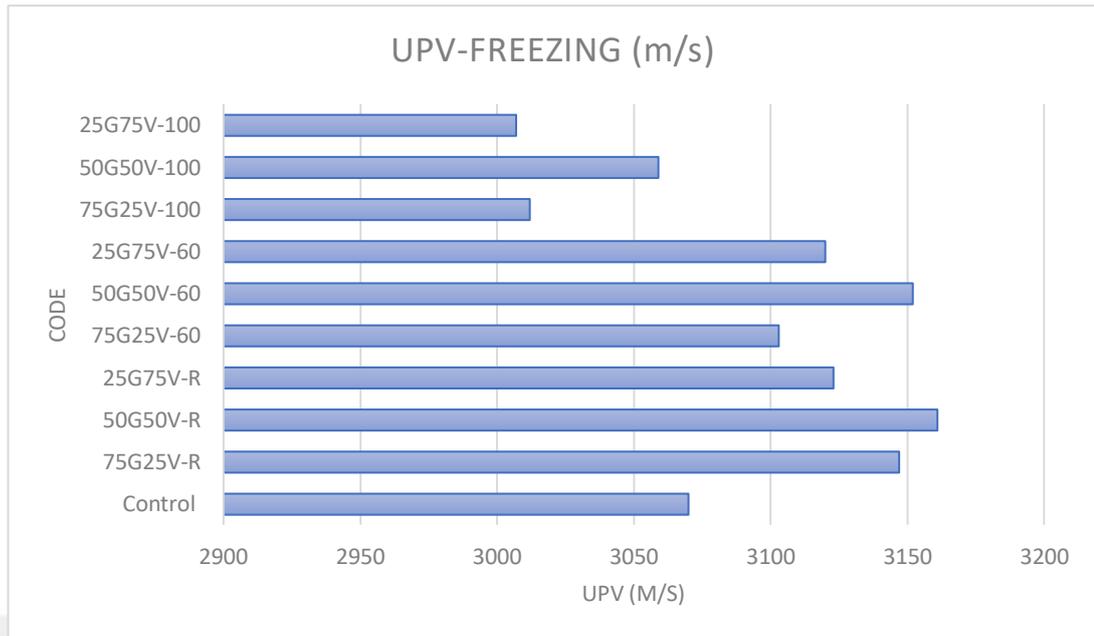


Figure 4.29: UPV-freezing-thawing test results

4.1.6 Acid attack test

It was shown that bottom ash geopolymer mortars were less affected by the H_2SO_4 attack than PC mortars. There was less than a 3.6% decrease in weight for the bottom ash geopolymer mortars. In their study, Ganesan et al. [90] found that geopolymer concrete containing steel fiber saw a significant increase in weight loss after being exposed to a 3% sulfuric acid solution for 180 days. Deb et al. [91] found that after 90 days immersed in 3% H_2SO_4 , the average weight losses of the geopolymer mortars were reduced. Adding 2% nano-silica reduced the weight reduction from 6% to 1.9%. Upon exposure to a 5% H_2SO_4 solution, the weight loss of geopolymer mortars composed of volcanic ash fell by 3.51% and 3.1%, respectively, according to the research conducted by Djobo et al. [44]. Cured samples of geopolymer mortar at 27 °C and 80 °C, respectively, showed these outcomes. The weight loss of the specimens increased in proportion to the amount of PC replacement in geopolymer concretes subjected to a 2% H_2SO_4 solution, according to Mehta and Siddique [92]. Samples submitted to HCl solutions lost weight ranging from 1 to 5%, according to Kwasny et al. [93], whereas specimens exposed to H_2SO_4 solutions lost weight ranging from 2 to 8%. After looking over the studies, it's clear that acid treated geopolymers lost some of their weight. Consistent with other research, our investigation confirmed that acid exposure reduced the weight of geopolymer concretes.

Table 4.9: Results of strength properties before and after acid attack test

#	Code	28day (MPa)	Comp. Strength After test	Strength loss %	28 flexural (MPa)	Flex. Strength after test	Strength loss %	UPV 2 months (m/s)	weight loss 2 months %
1	Control	38.57	10.51	72.75	7.24	1.51	79.14	847	9.37
2	75G25V-R	40.40	12.63	68.74	8.11	2.22	72.63	923	8.1
3	50G50V-R	42.95	15.11	64.82	9.06	3.13	65.45	981	7.35
4	25G75V-R	41.83	13.34	68.11	8.67	1.76	79.70	926	9.26
5	75G25V-60	39.88	12.25	69.28	8.14	2.86	64.86	903	8.41
6	50G50V-60	41.37	14.49	64.97	8.98	2.91	67.59	958	7.29
7	25G75V-60	39.81	13.91	65.06	8.18	1.81	77.87	913	7.71
8	75G25V-100	36.26	12.78	64.75	6.88	2.44	64.53	862	8.21
9	50G50V-100	37.59	15.27	59.38	7.21	2.70	62.55	909	7.16
10	25G75V-100	35.84	10.86	69.70	6.79	2.15	68.34	857	9.39

In figure 4.30 Mixes with a higher proportion of GGBFS, such as 50G50V-R and 50G50V-100, exhibit relatively higher compressive strengths after acid attack.

The Control mix shows a compressive strength of 10.51 MPa after acid attack, indicating some susceptibility to acid-induced degradation.

Mix (25G75V-100) shows a lower compressive strength of 10.86 MPa after acid attack, suggesting potential challenges in acid resistance.

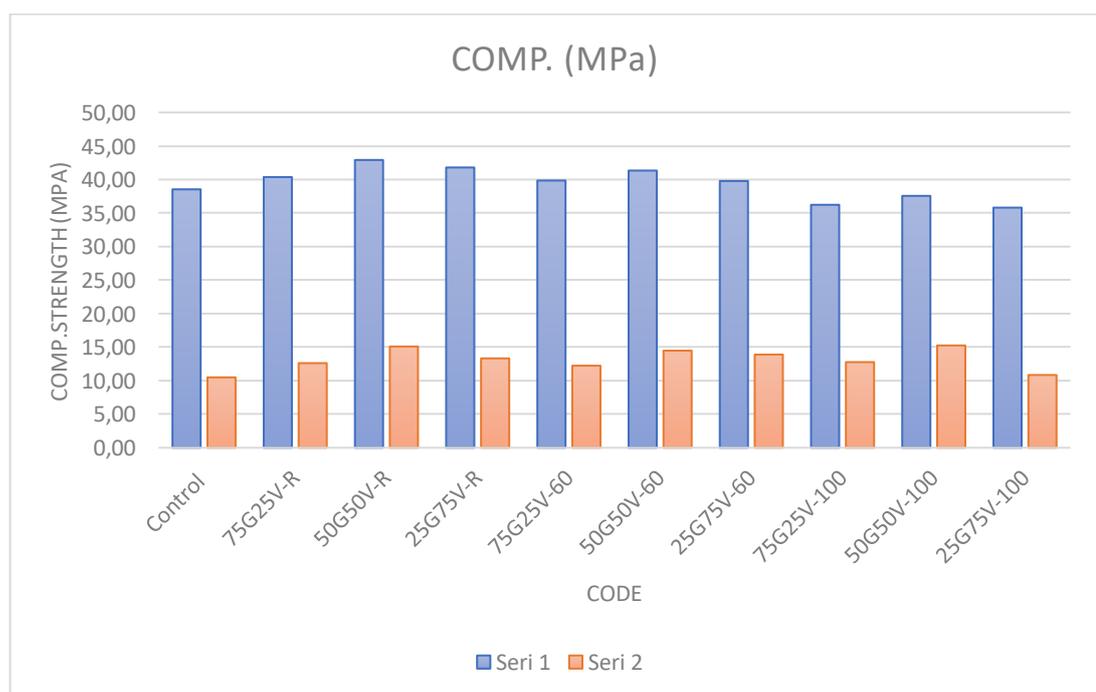


Figure 4.30: Comp. strength results after acid attack test

In Figure 4.31 The strength loss percentage represents the reduction in compressive strength after exposure to acid attack, indicating the susceptibility of mixes to acid-induced degradation. Mixes with higher proportions of GGBFS, such as 50G50V-R, 50G50V-100, and 50G50V-60, show lower strength loss percentages after acid attack. Mix (50G50V-100) exhibits a relatively lower strength loss of 59.38%, suggesting enhanced acid resistance compared to other mixes.



Figure 4.31: Com. strength loss results after acid attack

In Figure 4.32, we can see how the concrete samples' flexural strengths changed after being attacked by acid. This shows how well the mixes resisted acid-induced deterioration in terms of their flexural performance. After being attacked by acid, mixes with a larger percentage of GGBFS, including 50G50V-R, 50G50V-100, and 50G50V-60, exhibit comparatively higher flexural strengths. Following acid assault, Mix (50G50V-R) shows an increased flexural strength of 3.13 MPa, indicating better flexural performance in acidic environments.

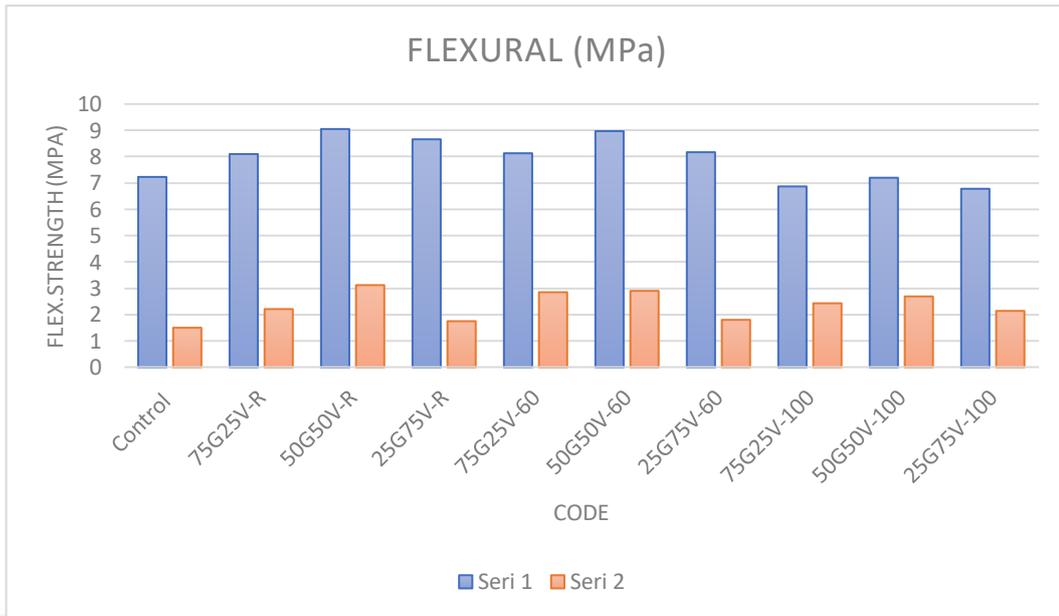


Figure 4.32: Flex. strength result after the acid attack

In Figure 4.33 Mixes with varying GGBFS and volcanic ash ratios show different levels of strength loss after acid attack. Mixes (50G50V-R) and (50G50V-100) exhibit lower strength loss percentages, suggesting improved acid resistance.

The Control mix and Mix (25G75V-R) experience relatively higher strength loss percentages, indicating greater vulnerability to acid-induced deterioration.

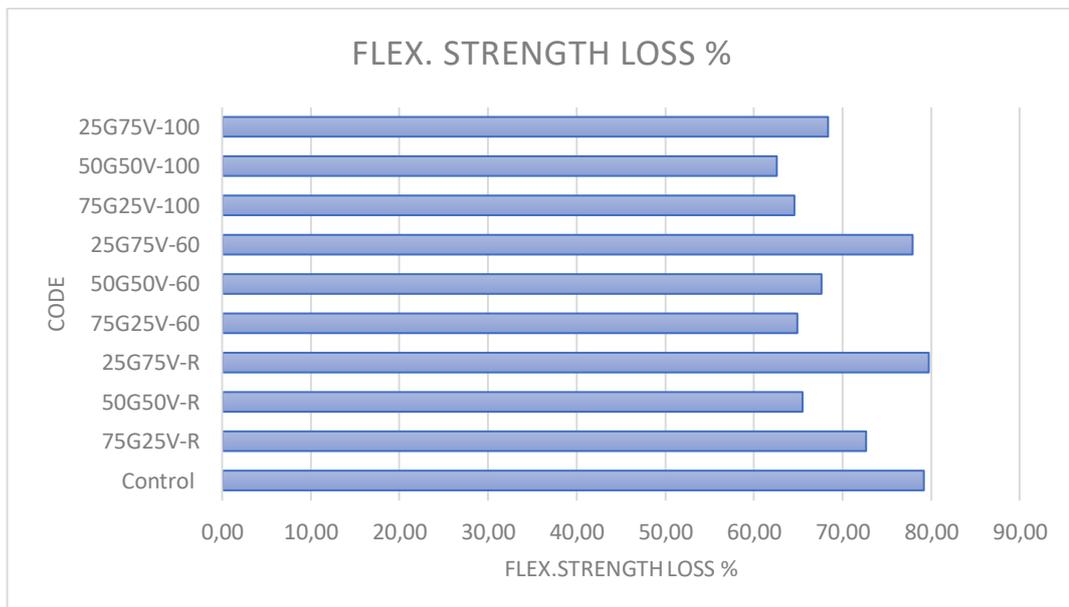


Figure 4.33: Flex. strength loss after acid attack

Mixes (50G50V-R) and 6 (50G50V-60) demonstrate higher UPV values, suggesting better integrity and less deterioration after acid attack. The Control mix

and Mix (75G25V-60) exhibit slightly lower UPV values, indicating some degree of deterioration in acoustic properties as shown in figure 4.34.

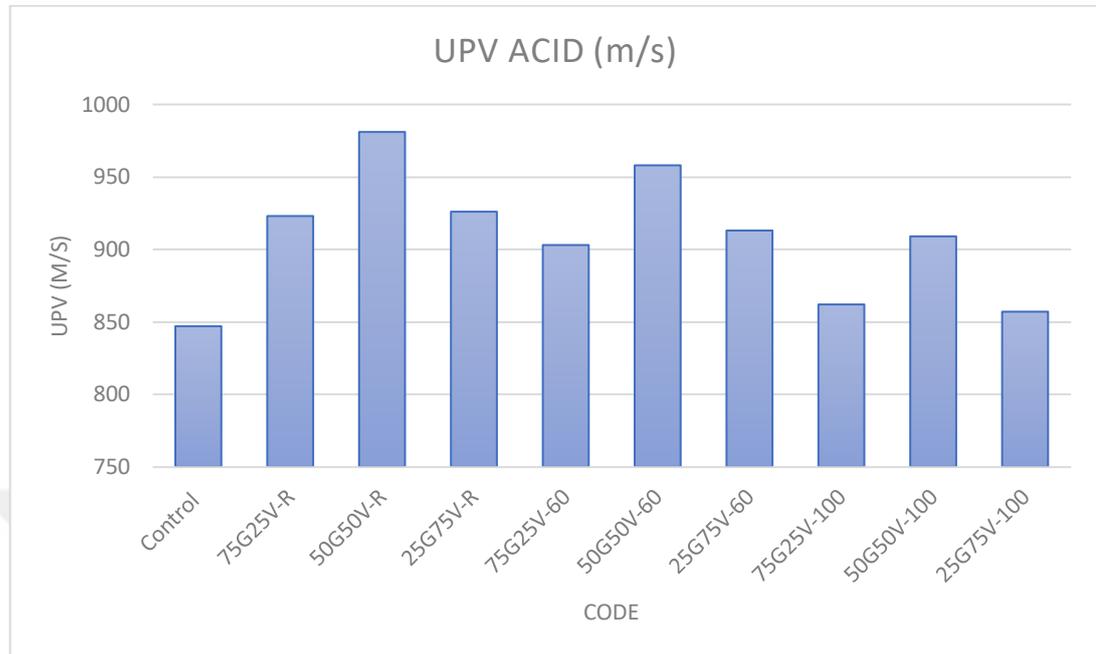


Figure 4.34: UPV test results after acid attack

Mixes (50G50V-R) and 6 (50G50V-60) show lower weight loss percentages, suggesting better resistance to mass reduction. Mixes (25G75V-R) and (25G75V-100) experience higher weight loss percentages, indicating greater susceptibility to acid-induced mass reduction as shown in figure 4.35.



Figure 4.35: Weight loss results after acid attack

4.1.7 The correlation between upv and compressive strength

It is an attempt to find a link between the results of compressive and UPV results. Whenever the regression coefficient is more than 0.75, the results are better for 7 and 28 days, and this is consistent with the results published by Al-Mashhadani et al. (2018). [104]

Between the objects' compression values and their UPV, you can see in Figures 4.8 and 4.9. In their study [89], Omer et al. used Equation to find the link between UPV and compression strength.

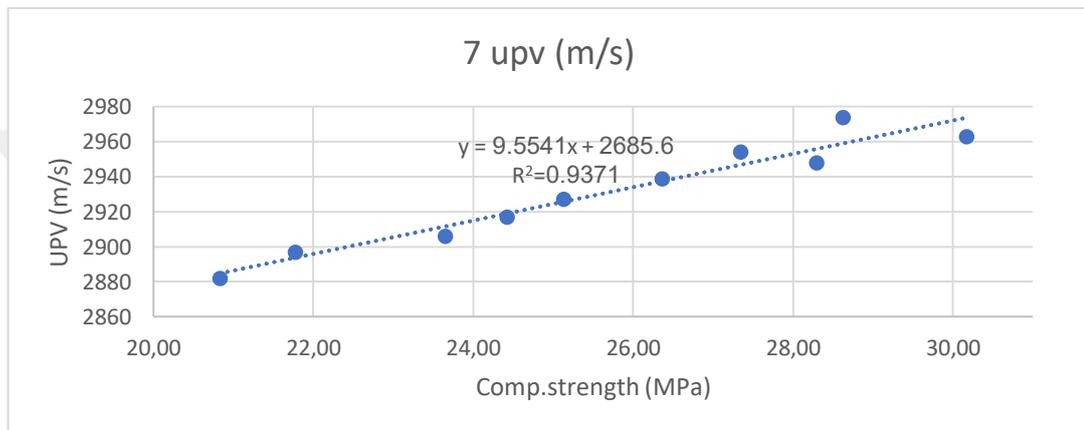


Figure 4.36: Correlation relationship between comp. strength and UPV-7

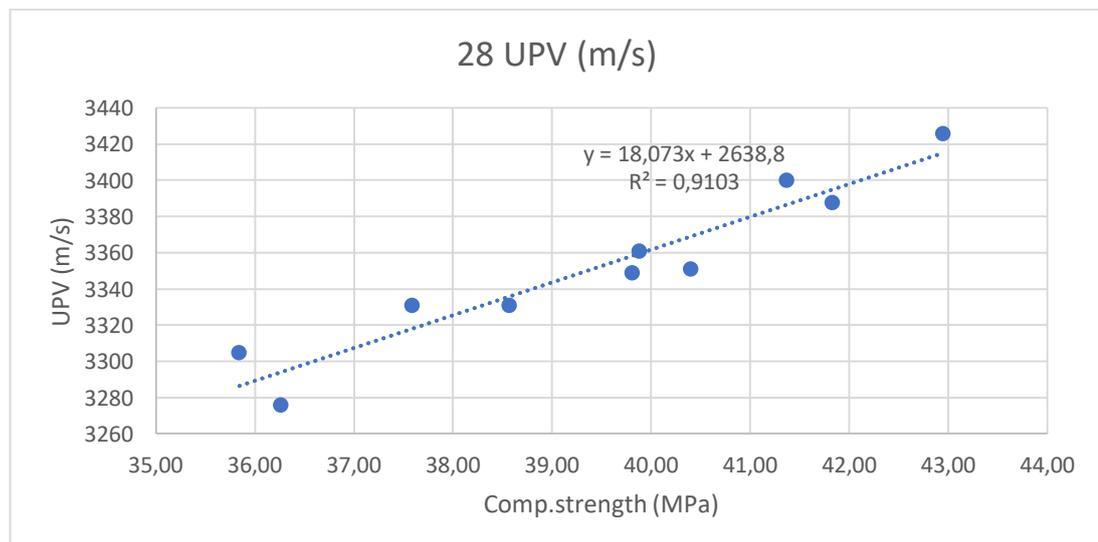


Figure 4.37: Correlation relationship between comp. strength and UPV-28

4.2 Conclusions

This research conducted an examination to examine the impact of including in summary:

- Geopolymer based on fly ash has an increased compressive strength after adding GGBFS. However, increasing the fraction of strength degradation may occur as a consequence of enhancing the GGBFS composition.
- An environmentally friendly geopolymer has been successfully manufactured by using an innovative method that replaces heat curing with a 28-day ambient curing period followed by a 21-day freeze-thaw curing period. In the moist environment of the freeze-thaw test, binding compounds, such as low activation slag, created binding products, which aided the continuing geopolymerization process. A physical power spike has resulted from this.
- High-temperature influences affected the mechanical characteristics of geopolymer composites. Applying the novel curing process retained the durability of the geopolymer samples against the 100C temperature impact.
- When 50% Volcanic Ash and 50% Ground Granulated Blast Furnace Slag (GGBFS) are added, the compressive strength is increased by around 11.35%. In comparison to the control mix at room temperature, the compressive strength increased by 8.452% with the addition of 25% GGBFS and 75% volcanic ash. The compressive strength of the combination containing 25% GGBFS and 75% Volcanic ash was 3.214% more than that of the control mix when cured at 60°C. In addition, the compressive strength increased by 7.25 percent in the combination that included 50 percent GGBFS and 50 percent volcanic ash.
- One promising material for geopolymer concrete is ground granulated blast furnace slag. In terms of strength, geopolymer concrete produced using ground granulated blast furnace is about on par with regular concrete produced using Fly Ash, a volcanic substitute. An eco-friendly and potentially game-changing substance for future construction, geopolymer concrete has just come to light.
- Geopolymers exhibiting excellent mechanical characteristics were effectively synthesized using a low-reactivity combination of volcanic ash

and slag at ambient temperature, 60°C, and 100°C. The inclusion of slag was shown to positively impact the compressive strength.

4.3 Recommendations for Future Work

- Try mixing GGBFS and volcanic ash in different ways to find the best mix ratios that give the best compression strength with the least amount of possible strength loss.
- Look into and compare the benefits of different ways of curing, such as heat curing, freeze-thaw curing, and room temperature curing. Check to see how they will affect the mechanical qualities of geopolymers in the long run.
- More research needs to be done on how well geopolymers can handle high temperatures. Look into changing the drying temperature and length of time to see how the material reacts to different temperatures.
- Check how long geopolymers last in the real world by looking at things like chemical contact, damage, and the structure's ability to stay stable over time. This can give us clues about how well geopolymers work in real-world building situations.
- Use advanced microstructural analysis tools, like SEM (Scanning Electron Microscopy) and XRD (X-ray Diffraction), to get a better idea of how the bonds work and how the structures change at the tiny level. This can help us learn more about the qualities of the object.
- Comparing the effects of geopolymer concrete to regular concrete on the environment should be done in detail. Think about things like the material's carbon footprint, how much energy it uses, and how its resources are used over its whole lifetime.
- Think about whether it would be possible to make more geopolymer concrete for big building projects. Look into possible problems and chances for business usage, such as how cost-effective it is and how easy it is to use.
- Investigate the potential of adding other types of industrial trash to the geopolymer mix to make it last longer. As part of this, the use of recycled rocks or other extra cementitious materials could be looked into.

- Research ways to make geopolymers' mechanical properties, like their tensile and bending strengths, even better. Integrating stronger strands or nanomaterials may be needed to do this.



REFERENCES

- [1.] Yang, K.H., Song, J.K. and Song, K.I., 2013. Assessment of CO₂ reduction of alkali-activated concrete. *Journal of Cleaner Production*, 39, pp.265-272.
- [2.] Shi, C., Jiménez, A.F. and Palomo, A., 2011. New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and concrete research*, 41(7), pp.750-763.
- [3.] Hasanbeigi, A., Menke, C. and Price, L., 2010. The CO₂ abatement cost curve for the Thailand cement industry. *Journal of Cleaner Production*, 18(15), pp.1509-1518.
- [4.] Couvidat, J., Diliberto, C., Meux, E., Cotelle, S., Bojic, C., Izoret, L. and Lecomte, A., 2021. Greening effect of slag cement-based concrete: Environmental and ecotoxicological impact. *Environmental Technology & Innovation*, 22, p.101467.
- [5.] Zhao, Y., Yu, M., Xiang, Y., Kong, F. and Li, L., 2020. A sustainability comparison between green concretes and traditional concrete using an emergy ternary diagram. *Journal of Cleaner Production*, 256, p.120421.
- [6.] Davidovits, J., 1989. Geopolymers and geopolymeric materials. *Journal of thermal analysis*, 35, pp.429-441.
- [7.] Xu, H. and Van Deventer, J.S.J., 2000. The geopolymerisation of aluminosilicate minerals. *International journal of mineral processing*, 59(3), pp.247-266.
- [8.] Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A. and van Deventer, J.S., 2007. Geopolymer technology: the current state of the art. *Journal of materials science*, 42, pp.2917-2933.
- [9.] Van Deventer, J.S.J., Provis, J.L., Duxson, P. and Lukey, G.C., 2007. Reaction mechanisms in the geopolymeric conversion of inorganic waste to useful products. *Journal of hazardous materials*, 139(3), pp.506-513.
- [10.] Djobo, J.Y., Tchadjé, L.N., Tchakoute, H.K., Kenne, B.B.D., Elimbi, A. and Njopwouo, D., 2014. Synthesis of geopolymer composites from a mixture of volcanic scoria and metakaolin. *Journal of Asian Ceramic Societies*, 2(4), pp.387-398.
- [11.] Albitar, M., Ali, M.M., Visintin, P. and Drechsler, M., 2015. Effect of granulated lead smelter slag on strength of fly ash-based geopolymer concrete. *Construction and Building Materials*, 83, pp.128-135.

- [12.] Karakoc, M.B., Türkmen, İ., Maraş, M.M., Kantarci, F. and Demirboğa, R., 2016. Sulfate resistance of ferrochrome slag based geopolymer concrete. *Ceramics International*, 42(1), pp.1254-1260.
- [13.] Laskar, S.M. and Talukdar, S., 2017. Preparation and tests for workability, compressive and bond strength of ultra-fine slag based geopolymer as concrete repairing agent. *Construction and building materials*, 154, pp.176-190.
- [14.] Zhuguo, L.I. and Sha, L.I., 2018. Carbonation resistance of fly ash and blast furnace slag based geopolymer concrete. *Construction and Building Materials*, 163, pp.668-680.
- [15.] Zhu, H., Liang, G., Xu, J., Wu, Q. and Du, J., 2019. Surface-modification of fly ash and its effect on strength and freezing resistance of slag based geopolymer. *Construction and Building Materials*, 199, pp.574-580.
- [16.] Gupta, A., 2021. Investigation of the strength of ground granulated blast furnace slag based geopolymer composite with silica fume. *Materials Today: Proceedings*, 44, pp.23-28.
- [17.] Qu, F., Li, W., Wang, K., Zhang, S. and Sheng, D., 2021. Performance deterioration of fly ash/slag-based geopolymer composites subjected to coupled cyclic preloading and sulfuric acid attack. *Journal of Cleaner Production*, 321, p.128942.
- [18.] Vickers, L., Pan, Z., Tao, Z. and Van Riessen, A., 2016. In situ elevated temperature testing of fly ash based geopolymer composites. *Materials*, 9(6), p.445.
- [19.] Wu, Y., Lu, B., Bai, T., Wang, H., Du, F., Zhang, Y., Cai, L., Jiang, C. and Wang, W., 2019. Geopolymer, green alkali activated cementitious material: Synthesis, applications and challenges. *Construction and Building Materials*, 224, pp.930-949.
- [20.] Djobo, J.N.Y., Elimbi, A., Tchakouté, H.K. and Kumar, S., 2017. Volcanic ash-based geopolymer cements/concretes: the current state of the art and perspectives. *Environmental Science and Pollution Research*, 24, pp.4433-4446.
- [21.] Shaikh, F.U.A., 2013. Review of mechanical properties of short fibre reinforced geopolymer composites. *Construction and building materials*, 43, pp.37-49.
- [22.] Ng, C., Alengaram, U.J., Wong, L.S., Mo, K.H., Jumaat, M.Z. and Ramesh, S., 2018. A review on microstructural study and compressive strength of geopolymer mortar, paste and concrete. *Construction and Building Materials*, 186, pp.550-576.
- [23.] Kanagaraj, B., Anand, N., Andrushia, A.D. and Lubloy, E., 2022. Investigation on engineering properties and micro-structure characteristics of low strength and high strength geopolymer composites subjected to standard temperature exposure. *Case Studies in Construction Materials*, 17, p.e01608.

- [24.] Krishna, R.S., Mishra, J., Zribi, M., Adeniyi, F., Saha, S., Baklouti, S., Shaikh, F.U.A. and Gökçe, H.S., 2021. A review on developments of environmentally friendly geopolymer technology. *Materialia*, 20, p.101212.
- [25.] Al-Qutaifi, S., Nazari, A. and Bagheri, A., 2018. Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing. *Construction and Building Materials*, 176, pp.690-699.
- [26.] Sambucci, M., Sibai, A. and Valente, M., 2021. Recent advances in geopolymer technology. A potential eco-friendly solution in the construction materials industry: A review. *Journal of Composites Science*, 5(4), p.109.
- [27.] Di Sia, P., 2020. Nanotechnologies and advanced smart materials: the case of architecture and civil engineering. *The ELSI Handbook of Nanotechnology: Risk, Safety, ELSI and Commercialization*, pp.67-87.
- [28.] Abdullah, M.M.A., Hussin, K., Bnhussain, M., Ismail, K.N. and Ibrahim, W.M.W., 2011. Mechanism and chemical reaction of fly ash geopolymer cement-a review. *Int. J. Pure Appl. Sci. Technol*, 6(1), pp.35-44.
- [29.] Moujoud, Z., Sair, S., Ousaleh, H.A., Ayouch, I., El Bouari, A. and Tanane, O., 2023. Geopolymer composites reinforced with natural Fibers: A review of recent advances in processing and properties. *Construction and Building Materials*, 388, p.131666.
- [30.] McLellan, B.C., Williams, R.P., Lay, J., Van Riessen, A. and Corder, G.D., 2011. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. *Journal of cleaner production*, 19(9-10), pp.1080-1090.
- [31.] Bosoaga, A., Masek, O. and Oakey, J.E., 2009. CO2 capture technologies for cement industry. *Energy procedia*, 1(1), pp.133-140.
- [32.] Shehata, N., Sayed, E.T. and Abdelkareem, M.A., 2021. Recent progress in environmentally friendly geopolymers: A review. *Science of The Total Environment*, 762, p.143166.
- [33.] Jindal, B.B. and Sharma, R., 2020. The effect of nanomaterials on properties of geopolymers derived from industrial by-products: A state-of-the-art review. *Construction and Building Materials*, 252, p.119028.
- [34.] Mohammed, M.A.A., 2021. Production of Geopolymer Materials from Solid Wastes of Drinking Water Treatment Plants and Alum Industry (Doctoral dissertation, Faculty of Science, Port Said University).
- [35.] Alahmari, T.S., Abdalla, T.A. and Rihan, M.A.M., 2023. Review of recent developments regarding the durability performance of eco-friendly geopolymer concrete. *Buildings*, 13(12), p.3033.
- [36.] Kong, D.L. and Sanjayan, J.G., 2008. Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites*, 30(10), pp.986-991.

- [37.] Ajay, A., Ramaswamy, K.P. and Thomas, A.V., 2020, June. A critical review on the durability of geopolymer composites in acidic environment. In IOP Conference Series: Earth and Environmental Science (Vol. 491, No. 1, p. 012044). IOP Publishing.
- [38.] Danish, A., Ozbakkaloglu, T., Mosaberpanah, M.A., Salim, M.U., Bayram, M., Yeon, J.H. and Jafar, K., 2022. Sustainability benefits and commercialization challenges and strategies of geopolymer concrete: A review. *Journal of Building Engineering*, p.105005.
- [39.] Shehata, N., Mohamed, O.A., Sayed, E.T., Abdelkareem, M.A. and Olabi, A.G., 2022. Geopolymer concrete as green building materials: Recent applications, sustainable development and circular economy potentials. *Science of the Total Environment*, 836, p.155577.
- [40.] Kanagaraj, B., Anand, N., Andrushia, D. and Kodur, V., 2023. Residual properties of geopolymer concrete for post-fire evaluation of structures. *Materials*, 16(17), p.6065.
- [41.] Figueira, R.B., Sousa, R., Coelho, L., Azenha, M., De Almeida, J.M., Jorge, P.A.S. and Silva, C.J.R., 2019. Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods. *Construction and Building Materials*, 222, pp.903-931.
- [42.] Nath, P. and Sarker, P.K., 2014. Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction and Building materials*, 66, pp.163-171.
- [43.] Poranek, N., Łażniewska-Piekarczyk, B., Czajkowski, A. and Pikoń, K., 2022. MSWIBA Formation and Geopolymerisation to Meet the United Nations Sustainable Development Goals (SDGs) and Climate Mitigation. *Buildings*, 12(8), p.1083.
- [44.] Djobo, J.N.Y., Elimbi, A., Tchakouté, H.K. and Kumar, S., 2016. Mechanical properties and durability of volcanic ash based geopolymer mortars. *Construction and Building Materials*, 124, pp.606-614.
- [45.] Kouamo, H.T., Elimbi, A., Mbey, J.A., Sabouang, C.N. and Njopwouo, D., 2012. The effect of adding alumina-oxide to metakaolin and volcanic ash on geopolymer products: A comparative study. *Construction and Building Materials*, 35, pp.960-969.
- [46.] Kouamo, H.T., Mbey, J.A., Elimbi, A., Dikko, B.K. and Njopwouo, D., 2013. Synthesis of volcanic ash-based geopolymer mortars by fusion method: Effects of adding metakaolin to fused volcanic ash. *Ceramics International*, 39(2), pp.1613-1621.
- [47.] Metekong, J.V.S., Kaze, C.R., Deutou, J.G., Venyite, P., Nana, A., Kamseu, E., Melo, U.C. and Tatietsé, T.T., 2021. Evaluation of performances of volcanic-ash-laterite based blended geopolymer concretes: Mechanical properties and durability. *Journal of Building Engineering*, 34, p.101935.

- [48.] Karolina, R., Sofran, M.A., Handana, M.A.P. and Siregar, R.I., 2020. Geopolymer concrete made from volcanic ash of Mount Sinabung. *International Journal of Integrated Engineering*, 12(1), pp.315-320.
- [49.] Tchakoute, H.K., Elimbi, A., Yanne, E. and Djangang, C.N., 2013. Utilization of volcanic ashes for the production of geopolymers cured at ambient temperature. *Cement and Concrete Composites*, 38, pp.75-81.
- [50.] Churata, R., Almirón, J., Vargas, M., Tupayachy-Quispe, D., Torres-Almirón, J., Ortiz-Valdivia, Y. and Velasco, F., 2022. Study of geopolymer composites based on volcanic ash, fly ash, pozzolan, metakaolin and mining tailing. *Buildings*, 12(8), p.1118.
- [51.] Tchadjié, L.N., Ekolu, S.O., Quainoo, H. and Tematio, P., 2021. Incorporation of activated bauxite to enhance engineering properties and microstructure of volcanic ash geopolymer mortar composites. *Journal of Building Engineering*, 41, p.102384.
- [52.] Tome, S., Etoh, M.A., Etame, J. and Sanjay, K., 2018. Characterization and leachability behaviour of geopolymer cement synthesised from municipal solid waste incinerator fly ash and volcanic ash blends. *Recycling*, 3(4), p.50.
- [53.] Kupwade-Patil, K., De Wolf, C., Chin, S., Ochsendorf, J., Hajiah, A.E., Al-Mumin, A. and Büyüköztürk, O., 2018. Impact of Embodied Energy on materials/buildings with partial replacement of ordinary Portland Cement (OPC) by natural Pozzolanic Volcanic Ash. *Journal of cleaner production*, 177, pp.547-554.
- [54.] Hamada, H.M., Abed, F., Beddu, S., Humada, A.M. and Majdi, A., 2023. Effect of Volcanic Ash and Natural Pozzolana on mechanical properties of sustainable cement concrete: A comprehensive review. *Case Studies in Construction Materials*, p.e02425.
- [55.] Celik, K., Hay, R., Hargis, C.W. and Moon, J., 2019. Effect of volcanic ash pozzolan or limestone replacement on hydration of Portland cement. *Construction and Building Materials*, 197, pp.803-812.
- [56.] Wilson, T.M., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G. and Barnard, S.T., 2012. Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth, Parts a/b/c*, 45, pp.5-23.
- [57.] Siddique, R., 2012. Properties of concrete made with volcanic ash. *Resources, Conservation and Recycling*, 66, pp.40-44.
- [58.] Hossain, K.M.A. and Lachemi, M., 2006. Performance of volcanic ash and pumice based blended cement concrete in mixed sulfate environment. *Cement and concrete research*, 36(6), pp.1123-1133.
- [59.] Papa, E., Medri, V., Amari, S., Manaud, J., Benito, P., Vaccari, A. and Landi, E., 2018. Zeolite-geopolymer composite materials: Production and characterization. *Journal of cleaner production*, 171, pp.76-84.

- [60.] Lazorenko, G., Kasprzhitskii, A. and Mischinenko, V., 2021. Rubberized geopolymer composites: Effect of filler surface treatment. *Journal of Environmental Chemical Engineering*, 9(4), p.105601.
- [61.] Kohout, J. and Koutník, P., 2020. Effect of filler type on the thermo-mechanical properties of metakaolinite-based geopolymer composites. *Materials*, 13(10), p.2395.
- [62.] Sahin, F., Uysal, M., Canpolat, O., Cosgun, T. and Dehghanpour, H., 2021. The effect of polyvinyl fibers on metakaolin-based geopolymer mortars with different aggregate filling. *Construction and Building Materials*, 300, p.124257.
- [63.] Kovářík, T., Rieger, D., Kadlec, J., Křenek, T., Kullová, L., Pola, M., Bělský, P., Franče, P. and Říha, J., 2017. Thermomechanical properties of particle-reinforced geopolymer composite with various aggregate gradation of fine ceramic filler. *Construction and Building Materials*, 143, pp.599-606.
- [64.] Zhang, X., Li, J., Pang, S., Zhu, K., Su, L., Liu, J. and Zhang, X., 2023. Mechanical properties and interface microscopic characterisation of fibre-reinforced slag-fly ash geopolymer agglutinated iron tailings filling materials. *Materials Today Communications*, 36, p.106650.
- [65.] Yangthong, H., Pichaiyut, S., Jumrat, S., Wisunthorn, S. and Nakason, C., 2018. Novel natural rubber composites with geopolymer filler. *Advances in Polymer Technology*, 37(7), pp.2651-2662.
- [66.] Uysal, M., Kuranlı, Ö.F., Aygörmez, Y., Canpolat, O. and Çoşgun, T., 2023. The effect of various fibers on the red mud additive sustainable geopolymer composites. *Construction and Building Materials*, 363, p.129864.
- [67.] Ferdous, W., Manalo, A., Khennane, A. and Kayali, O., 2015. Geopolymer concrete-filled pultruded composite beams—concrete mix design and application. *Cement and concrete composites*, 58, pp.1-13.
- [68.] Felaous, K., Aziz, A., Achab, M., Fernández-Raga, M. and Benzaouak, A., 2023. Optimizing Alkaline Activation of Natural Volcanic Pozzolan for Eco-Friendly Materials Production: An Investigation of NaOH Molarity and Na₂SiO₃-to-NaOH Ratio. *Sustainability*, 15(5), p.4453.
- [69.] Pundienė, I., Pranckevičienė, J., Zhu, C. and Kligys, M., 2021. The role of temperature and activator solution molarity on the viscosity and hard structure formation of geopolymer pastes. *Construction and Building Materials*, 272, p.121661.
- [70.] Ibrahim, M., Johari, M.A.M., Rahman, M.K. and Maslehuddin, M., 2017. Effect of alkaline activators and binder content on the properties of natural pozzolan-based alkali activated concrete. *Construction and Building Materials*, 147, pp.648-660.
- [71.] Ghafoor, M.T., Khan, Q.S., Qazi, A.U., Sheikh, M.N. and Hadi, M.N.S., 2021. Influence of alkaline activators on the mechanical properties of fly ash

- based geopolymer concrete cured at ambient temperature. *Construction and Building Materials*, 273, p.121752.
- [72.] Ibrahim, M., Johari, M.A.M., Maslehuddin, M., Rahman, M.K., Salami, B.A. and Mohamed, H.D., 2019. Influence of composition and concentration of alkaline activator on the properties of natural-pozzolan based green concrete. *Construction and Building Materials*, 201, pp.186-195.
- [73.] Adewumi, A.A., Mohd Ariffin, M.A., Maslehuddin, M., Yusuf, M.O., Ismail, M. and Al-Sodani, K.A.A., 2021. Influence of silica modulus and curing temperature on the strength of alkali-activated volcanic ash and limestone powder mortar. *Materials*, 14(18), p.5204.
- [74.] Reddy, V.S., Krishna, K.V., Rao, M.S. and Shrihari, S., 2021. Effect of molarity of sodium hydroxide and molar ratio of alkaline activator solution on the strength development of geopolymer concrete. In *E3S Web of Conferences* (Vol. 309, p. 01058). EDP Sciences.
- [75.] Huseien, G.F., Ismail, M., Khalid, N.H.A., Hussin, M.W. and Mirza, J., 2018. Compressive strength and microstructure of assorted wastes incorporated geopolymer mortars: Effect of solution molarity. *Alexandria engineering journal*, 57(4), pp.3375-3386.
- [76.] Kumar, M., Kumar, A., Solanki, D. and Mungule, M., 2023. Low molarity geopolymer concrete: Effects on compressive strength, elastic modulus, sorptivity and chloride migration. *Construction and Building Materials*, 409, p.134065.
- [77.] Mo, B.H., Zhu, H., Cui, X.M., He, Y. and Gong, S.Y., 2014. Effect of curing temperature on geopolymerization of metakaolin-based geopolymers. *Applied clay science*, 99, pp.144-148.
- [78.] Rovnaník, P., 2010. Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer. *Construction and building materials*, 24(7), pp.1176-1183.
- [79.] Aredes, F.G.M., Campos, T.M.B., Machado, J.P.B., Sakane, K.K., Thim, G.P. and Brunelli, D.D., 2015. Effect of cure temperature on the formation of metakaolinite-based geopolymer. *Ceramics International*, 41(6), pp.7302-7311.
- [80.] Sajan, P., Jiang, T., Lau, C., Tan, G. and Ng, K., 2021. Combined effect of curing temperature, curing period and alkaline concentration on the mechanical properties of fly ash-based geopolymer. *Cleaner Materials*, 1, p.100002.
- [81.] Nagral, M.R., Ostwal, T. and Chitawadagi, M.V., 2014. Effect of curing temperature and curing hours on the properties of geo-polymer concrete. *Int. J. Comput. Eng. Res*, 4(9), pp.1-11.
- [82.] Zribi, M., Samet, B. and Baklouti, S., 2019. Effect of curing temperature on the synthesis, structure and mechanical properties of phosphate-based geopolymers. *Journal of Non-Crystalline Solids*, 511, pp.62-67.

- [83.] Alraddadi, S. and Assaedi, H., 2020. Characterization and potential applications of different powder volcanic ash. *Journal of King Saud University-Science*, 32(7), pp.2969-2975.
- [84.] Karri, S.K., Rao, G.R. and Raju, P.M., 2015. Strength and durability studies on GGBS concrete. *SSRG International Journal of Civil Engineering (SSRG-IJCE)*, 2(10), pp.34-41.
- [85.] Babu, K.G. and Kumar, V.S.R., 2000. Efficiency of GGBS in concrete. *Cement and concrete Research*, 30(7), pp.1031-1036.
- [86.] ASTM E4-02, Standard Practices for Force Verification of Testing Machines, ASTM International, West Conshohocken, PA, 2002, www.astm.org.
- [87.] ASTM C109 / C109M-16a, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens), ASTM International, West Conshohocken, PA, 2016, www.astm.org.
- [88.] ASTM C348-14, Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars, ASTM International, West Conshohocken, PA, 2014, www.astm.org.
- [89.] Omer, S.A., Demirboga, R. and Khushefati, W.H., 2015. Relationship between compressive strength and UPV of GGBFS based geopolymer mortars exposed to elevated temperatures. *Construction and Building Materials*, 94, pp.189-195.
- [90.] Ganesan, N., Abraham, R. and Raj, S.D., 2015. Durability characteristics of steel fibre reinforced geopolymer concrete. *Construction and Building Materials*, 93, pp.471-476.
- [91.] Deb, P.S., Sarker, P.K. and Barbhuiya, S., 2016. Sorptivity and acid resistance of ambient-cured geopolymer mortars containing nano-silica. *Cement and Concrete Composites*, 72, pp.235-245.
- [92.] Mehta, A. and Siddique, R., 2017. Sulfuric acid resistance of fly ash based geopolymer concrete. *Construction and Building Materials*, 146, pp.136-143.
- [93.] Kwasny, J., Soutsos, M., McIntosh, J.A. and Cleland, D.J., 2016, July. banahCEM-comparison of properties of a laterite-based geopolymer with conventional concrete. In *Proc. of 9th International Concrete Conference* (pp. 383-394).
- [94.] Metekong, J.V.S., Kaze, C.R., Deutou, J.G., Venyite, P., Nana, A., Kamseu, E., Melo, U.C. and Tatietsé, T.T., 2021. Evaluation of performances of volcanic-ash-laterite based blended geopolymer concretes: Mechanical properties and durability. *Journal of Building Engineering*, 34, p.101935.
- [95.] Tayeh, B.A., Zeyad, A.M., Agwa, I.S. and Amin, M., 2021. Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete. *Case Studies in Construction Materials*, 15, p.e00673.
- [96.] Yong-Sing, N., Yun-Ming, L., Cheng-Yong, H., Abdullah, M.M.A.B., Pakawanit, P., Chan, L.W.L., Hui-Teng, N., Shee-Ween, O., Wan-En, O. and

- Yong-Jie, H., 2022. Thin fly ash/ladle furnace slag geopolymer: Effect of elevated temperature exposure on flexural properties and morphological characteristics. *Ceramics International*, 48(12), pp.16562-16575.
- [97.] Omer, S.A., Demirboga, R. and Khushefati, W.H., 2015. Relationship between compressive strength and UPV of GGBFS based geopolymer mortars exposed to elevated temperatures. *Construction and Building Materials*, 94, pp.189-195.
- [98.] Aygörmez, Y., 2022. Elevated temperature effects on fly ash-based geopolymer composites produced with waste granite dust. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 46(6), pp.4205-4217.
- [99.] Hussin, M.W., Bhutta, M.A.R., Azreen, M., Ramadhansyah, P.J. and Mirza, J., 2015. Performance of blended ash geopolymer concrete at elevated temperatures. *Materials and Structures*, 48, pp.709-720.
- [100.] Lemougna, P.N., Melo, U.C., Delplancke, M.P. and Rahier, H., 2013. Influence of the activating solution composition on the stability and thermo-mechanical properties of inorganic polymers (geopolymers) from volcanic ash. *Construction and Building Materials*, 48, pp.278-286.
- [101.] Zheng, Y., Rao, F., Yang, L. and Zhong, S., 2023. Comparison of ternary and dual combined waste-derived alkali activators on the durability of volcanic ash-based geopolymers. *Cement and Concrete Composites*, 136, p.104886.
- [102.] Zhang, M., Zhao, N., Wang, S., Quan, X., Liu, K., Xu, J., Wang, Z., Ying, H. and Liu, B., 2023. Mechanical and durability performance of polyvinyl alcohol fiber hybrid geopolymer-portland cement concrete under freeze–thaw cycles. *Boletín de la Sociedad Española de Cerámica y Vidrio*.
- [103.] Özdal, M., Karakoç, M.B. and Özcan, A., 2021. Investigation of the properties of two different slag-based geopolymer concretes exposed to freeze–thaw cycles. *Structural Concrete*, 22, pp.E332-E340.
- [104.] Al-Mashhadani, M.M., Canpolat, O., Aygörmez, Y., Uysal, M. and Erdem, S., 2018. Mechanical and microstructural characterization of fiber reinforced fly ash based geopolymer composites. *Construction and building materials*, 167, pp.505-513.

RESUME

Marwah Saad Hussein AL-SAEDI

Place Of Birth : Baghdad

Foreign Languages: English, Turkish, Arabic (mother tongue)

EDUCATION:

- Undergraduate Highway & Transportation Engineering Al-Mustansiriyah Univ. 2015
- High School Khawla Bint Al-Azwar 2011 Preparatory School