T.C.

ANTALYA BILIM UNIVERSITY

INSTITUTE OF POSTGRADUATE EDUCATION

CIVIL ENGINEERING PROGRAM
MASTER'S THESIS

THE ENGINEERING PROPERTIES OF SILICA FUME AND GGBS-BASED GEOPOLYMER MORTARS CURED IN ELEVATED TEMPERATURE.

Asude İrem ÇELİK

FEBRUARY 2024

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This thesis was accepted by the jury (with unanimous vote/majority vote) on the date 08/02/2024 of CIVIL ENGINEERING THESIS PROGRAM in ENGLISH of the DEPARTMENT of CIVIL ENGINEERING.

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Thesis Submission Date: / /2024

DECLARATION

Master Thesis of this study named "**THE ENGINEERING PROPERTIES OF SILICA FUME AND GGBS-BASED GEOPOLYMER MORTARS CURED IN ELEVATED TEMPERATURE.** " which I presented, I declare that scientific moral principles were followed in the preparation of this study, in case of benefiting from the works of others, reference is made following scientific norms, no falsification has been made in the data used, and that any part of this study is not presented as another academic study.

08/02/2024

Asude İrem ÇELİK

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ABSTRACT

THE ENGINEERING PROPERTIES OF SILICA FUME AND GGBS-BASED GEOPOLYMER MORTARS CURED IN ELEVATED TEMPERATURE.

Asude İrem ÇELİK

MSc Thesis in Civil Engineering

Supervisor: Assist. Prof. Fuad ABUTAHA

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Geopolymer, a promising alternative to traditional Portland cement, offers a wide range of sustainable applications in the construction industry. Geopolymer mortar presents a sustainable future by mitigating carbon dioxide emissions associated with cement production. This study aims to investigate three primary objectives: firstly, to investigate the effect of using different minerals admixtures on the engineering properties of geopolymer mortar, secondly to investigate the effect of curing method of GM on the engineering properties of concrete, thirdly to investigate the possibility of incorporating geopolymer concrete to developed construction areas with sustainability features. Five different mixes were prepared, each utilizing various mineral admixtures in different ratios: M20-80 (20% SF and 80% GGBS), M80-20 (80% SF and 20% GGBS), M50-50 (50% SF and 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF).The curing methods for each sample were investigated separately under ambient and oven temperatures (65°C) for 7 and 28 days to determine the final values of compressive and flexural strength. The results revealed that*;* The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 and MSF100 cured in oven temperature show similar compressive strength compared to the ambient temperature curing method.

KEYWORDS: Different Mineral Admixture, Elevated Temperature, Geopolymer Mortar, Sustainability

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ÖZET

YÜKSEK SICAKLIKLARDA KÜRLENEN SİLİS DUMANI VE YÜKSEK FIRIN CÜRUFU ESASLI GEOPOLİMER HARÇLARIN MÜHENDİSLİK ÖZELLİKLERİ.

Asude İrem ÇELİK

Yüksek Lisans Tezi, İnşaat Mühendisliği Anabilim Dalı

Danışman: Dr. Öğr. Üyesi Fuad ABUTAHA

Şubat 2024; 45 sayfa

Geopolimer, geleneksel Portland çimentosuna vaat edici bir alternatif olarak, inşaat sektöründe sürdürülebilir bir dizi uygulama sunmaktadır. Geopolimer harç, çimento üretimi ile ilişkilendirilen karbon dioksit emisyonlarını azaltarak sürdürülebilir bir gelecek sunar. Bu çalışmanın üç temel amacı vardır: ilk olarak, farklı mineral katkı maddelerinin geopolimer harcın mühendislik özellikleri üzerindeki etkisini araştırmak; ikinci olarak, geopolimer harcın mühendislik özellikleri üzerindeki kürleme metodunun etkisini araştırmak; üçüncü olarak, gelişmiş inşaat alanlarına sürdürülebilir özelliklerle geopolimer beton entegrasyonunun olasılığını araştırmak. Amaç doğrultusunda her biri farklı oranlarda çeşitli mineral katkı maddeleri içeren beş farklı karışım hazırlanmıştır: M20-80 (20% SF ve 80% GGBS), M80-20 (80% SF ve 20% GGBS), M50-50 (50% SF ve 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF). Her örnek için iyileştirme metotları, çevresel ve fırın sıcaklıklarında (65°C) 7 ve 28 gün boyunca ayrı ayrı incelendi ve basınç dayanımı ile eğilme dayanımının nihai değerlerini belirlemek için kullanıldı. Sonuçlar gösteriyor ki; çevresel metodun kullanıldığı MS100, M50-50 ve M80-20 karışımlarının basınç dayanım değerleri, aynı karışımların fırın sıcaklığında iyileştirilmiş olanlarına göre önemli ölçüde artış göstermektedir. Çevresel iyileştirme metodunun basınç dayanımındaki artış oranı, sırasıyla MS100, M50-50 ve M80-20 karışımları için %14,4, %25,8 ve %46,4'tür. Özetle, bu sonuçlar farklı mineral katkı maddeleri ve kürleme yöntemlerinin geopolimer harcın mekanik özellikleri üzerindeki önemli etkisini vurgulamaktadır. Özellikle, M20-80 karışımının çeşitli koşullarda üstün performans sergilediği gözlenmektedir.

ANAHTAR KELİMELER: Geopolimer Harç, Sürdürülebilirlik, Farklı Mineral Katkı, Yüksek Sıcaklık

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SYMBOLS AND ABBREVIATIONS

OPC : Ordinary Portland Cement

GPM : Geopolymer Mortar

FA : Fly Ash

GGBS : Ground Granulated Furnace Slag

RM : Red Mud

RHA : Rice Hask Ash

SF : Silica Fume

GP : Geopolymer

IBPs : Industrial By Products

HVFA: High Volume Fly ASH

EN : European Standard

ASTM: American Society for Testing and Materials

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PREFACE

Welcome to my thesis exploring the properties of special mortar mixes by utilization of Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBS), known as geopolymers. These materials have the potential to make construction more sustainable.

I decided to focus on how these geopolymers behave when they're cured at higher temperatures, as these conditions they might face in real-world applications. The goal is to understand how they perform and, in turn, improve the durability and versatility of construction materials. This thesis represents months of research and experiments, bringing together material science and practical engineering. I want to thank my advisor Fuad Abutaha, mentors and my family for their guidance and support throughout this journey. Special thanks also go to those who participated in the experiments—your contributions were crucial to this study.

As you read through this thesis, I hope it provides a clear picture of the potential of Silica Fume and GGBS-based geopolymers in sustainable construction. My aim is that this work sparks further interest and advancements in this field.

1. INTRODUCTION

1.1. Introduction

Geopolymer concrete, initially developed by French Professor Davidovits in 1978, represents a cement-free type of concrete with mechanical and high-temperature resistances (Davidovits, 2002). These alternatives gain prominence for its potential to mitigate environmental harm associated with traditional cement sources, particularly the pollutants found in fly ash and GGBS. The primary source of fly ash, a key component of geopolymer materials, contains alumina, ferric oxide, and silica, which, due to their structural behavior, pose environmental concerns (Khan et al., 2021). Notably, aluminosilicate materials like fly ash and GGBS, when properly harnessed, can serve as sustainable alternatives. The preference for F type fly ash over C type is attributed to its lower contamination and higher alumina oxide content (Fernández-Jiménez, A., Palomo, A., 2003). Utilizing fly ash as a binder in mortar enhances its eco-friendliness, reducing the need for OPC and contributing to a more sustainable construction industry. Considering the alarming one-to-one carbon dioxide emission ratio associated with cement production (Akbar and Liew, 2020), geopolymer mortar, often referred to as "green mortar" (Wang et al., 2019), emerges as a promising solution due to its cement-free composition and reliance on mineral admixtures. Geopolymer mortar is a blend of source materials and alkaline liquids, with Si and Al serving as the main activators. Notably, the absence of additional water during manufacturing eliminates the hydration process, differentiating it from traditional mortar (Al Bakri et al., 2012). The ecological balance benefits from reducing OPC production, making geopolymer mortar a crucial player in promoting sustainability. Approximately 600,000 tons of fly ash are produced, but only a fraction is utilized for concrete production, highlighting the underutilized potential of geopolymer materials (Van Chanh et al., 2008). Geopolymer concrete, utilizing sodium hydroxide and sodium silicate as alkali activators, offers an eco-friendly alternative to OPC. The absence of a hydration process in geopolymer concrete eliminates the need for curing, contributing to its sustainability. Geopolymer mortar's suitability and sustainability lie in the compatibility of silica and alumina content, fostering reactions without the need for additional water (Mucsi et al., 2015). These amorphous alumina silicates, produced through the reaction between silica and alumina silicate, exemplify eco-friendly features (Mucsi et al., 2015). Geopolymers, being amenable to low-tech and high-tech applications, present a viable replacement for conventional materials in the building sector. Their ease of use, energy efficiency, eco friendliness, high durability, and good mechanical qualities position geopolymers as an environmentally conscious choice.

In conclusion, geopolymers have the potential to revolutionize the construction industry by offering an alternative that aligns with sustainability goals and environmental responsibility.

1.2. Problem Statement

Geopolymer stands out as a promising candidate for replacing traditional Portland cement, offering a range of applications in sustainable construction, including concrete materials, fire-retardant coatings, fiber-reinforced composites, and waste-immobilization solutions for chemical and nuclear sectors. Extensive research has pointed out that GP concrete shares comparable properties with OPC concrete, indicating its suitability for civil engineering applications (Singh et al., 2015). Notably, the ceramic-like characteristics inherent in Geopolymer (GP) enable it to withstand high temperatures and fire, adding to its versatility (Kong et al., 2010).

Despite these promising attributes, there is a notable gap in the existing literature, particularly concerning the combined effects of Silica Fume and GGBS under different ambient and oven temperatures. The optimization of results in this context is essential for understanding the intricate correlation between temperature variations and the presence of mineral admixtures. Bridging this gap in knowledge will not only contribute to the comprehensive understanding of geopolymer materials but also offer insights into their optimal performance in diverse environmental conditions.

The focus of this study is to address this research gap, shedding light on the specific interactions and outcomes resulting from the combination of Silica Fume and GGBS at varying temperatures. By doing so, the study aims to provide valuable information for optimizing geopolymer formulations, considering both temperature effects and the presence of mineral admixtures. This optimization is crucial for advancing the practical application of geopolymer materials and fostering their role in sustainable construction practices.

1.3. Aim and Objectives

1) To investigate the effect of using different minerals admixtures on the engineering properties of geopolymer mortar.

2) To investigate the effect of curing method of GM on the engineering properties of concrete.

3) To investigate the possibility of incorporating geopolymer concrete to developed construction areas with sustainability features.

1.4. Significant of This Study

The strength of geopolymer mortar exhibits a noteworthy increase with the passage of time. This phenomenon underscores the long-term durability and performance benefits associated with geopolymer technology.

The practical application of geopolymer technology in real construction projects is gaining considerable traction. Notable examples include the University of Queensland's Global Change Institute and Brisbane Airport, where over 30,000 metric cubic meters of geopolymer concrete have been successfully employed (Pouhet and Cyr, 2016). These real-world applications showcase the adaptability and reliability of geopolymer materials in diverse construction settings.

One of the key advantages of geopolymer technology lies in the production of geopolymer binders using industrial by-products (IBPs). This innovative approach not only addresses sustainability concerns but also significantly reduces the energy requirements and greenhouse gas emissions associated with traditional cement production (Zhang et al., 2018). By utilizing IBPs, geopolymer technology aligns with the broader goals of environmentally friendly construction practices.

As research and real-world applications continue to unfold, the strengthening of geopolymer mortar over time, combined with its sustainable production methods, positions geopolymer technology as a promising and impactful solution in the construction industry.

In terms of by-product utilization, geopolymer mortar signifies sustainability and applicability in construction areas, providing compressive strength ranging from 19 to 70 MPa. This compares in positive way with Ordinary Portland Cement (OPC), which, according to the ACI Standard, has a minimum compressive strength requirement of 17 MPa. Consequently, even at its lowest strength, geopolymer mortar proves suitable for construction in various scenarios. (Standard, A. C. I. 2008)

2. LITERATURE REVIEW

2.1. Introduction

The surge in urbanization, particularly in emerging nations, has intensified the adverse environmental impacts stemming from traditional cement production, contributing to pollution. The release of carbon dioxide during the manufacturing of conventional concrete further compounds environmental concerns, emphasizing the urgency for a new generation of concrete. In response to this environmental imperative, the development of innovative concrete formulations becomes paramount. The exploration of sustainable alternatives not only addresses the ecological consequences but also presents a strategic solution for cost reduction and reduced emissions associated with cement production from natural raw materials. An insightful approach is to consider the utilization of waste materials as a foundation for creating sustainable cement substitutes. This not only mitigates the environmental impact of waste disposal but also offers a pragmatic solution to the escalating costs, limited coverage, and emissions associated with traditional cement manufacturing (J. Mishra, 2020). In essence, the imperative for a new generation of concrete extends beyond its structural properties; it encompasses a conscientious effort to harmonize urbanization with environmental sustainability, fostering a resilient and responsible approach to construction practices.

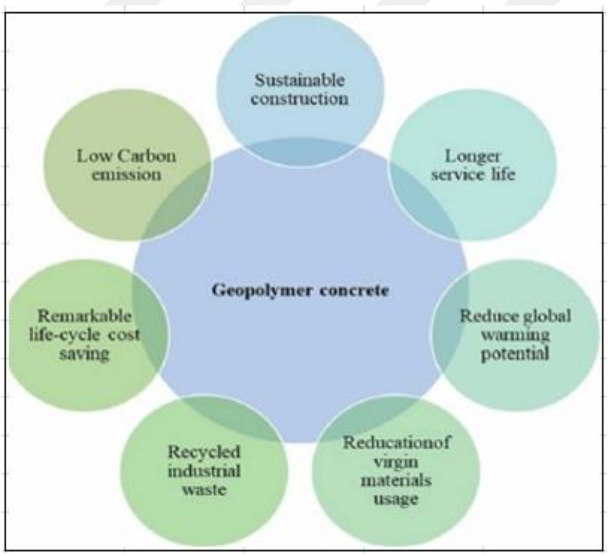

Figure 2.1. Definition of GP

Source: (Singh., et al., 2020)

Figure 2.1 clearly illustrates the positive environmental impact of geopolymer mortar, reinforcing its role in enhancing sustainability (Singh et al., 2020). This visual representation underscores the importance of geopolymer technology as a eco-friendly alternative in construction practices.

A fundamental aspect of geopolymers is the content of aluminosilicates. Notably, water does not react directly with aluminosilicates; however, these materials undergo hydrolysis and condensation processes, resulting in the formation of new inorganic polymers. The key distinguishing factor for these polymers is a high amorphous content, providing them with load-bearing capacity. Consequently, the geopolymerization process hinges on the chemical processes of these precursors, emphasizing their pivotal role in shaping the characteristics and performance of geopolymer materials.

Understanding and optimizing the chemical processes of precursors is a critical step towards harnessing the full potential of geopolymer technology. This knowledge not only contributes to the development of high-performance materials but also aligns with broader objectives of sustainability in the construction industry.

2.2. Mineral Admixtures

Aluminosilicate content materials can be expressed as; fly ash, metakaolin, silica fume, ground granulated blast slag, rice husk ash, red mud (Almutairi, 2021).

For last decade, geopolymer concrete production and utilization is in high demand due to its environmentally friendly feature. Geopolymer generally procure by aluminosilicates; fly ash, silica fume, metakaolin, ground granulated blast slag, red mud, rice husk ash and alkali silicate solutions; sodium hydroxide and sodium silicate (P. Krivenko, 2006).

Figure 2. 2. Mineral Admixtures

Source: (Kanamarlapudi et al., 2020)

For instance, the geopolymer mortar contained high activator levels and required steam curing so that the product had relatively high shaped energy and emissions leading to the conclusion that there was little benefit in terms of carbon footprint compared to ordinary Portland cement concrete (L. Turner and F. Collins, 2013).

The most utilized concrete classes are 32 and 40 MPa, with cylinder strengths measured up to 70 MPa. Other important properties, such as drying shrinkage of geopolymer concrete (GP), have been found to be lower than ordinary Portland cement (OPC) based on experimental tests (Sanjayan JG, 2011).

Fly ash, ground granulated blast slag (GGBS), and rice husk ash are some waste materials utilized in the production of geopolymer concrete, and this is the reason it is referred to as green concrete. The properties of the material, including its low shrinkage, heat, and hydration, as well as its strong tensile strength, may offer technical benefits over traditional concrete, particularly in structural elements exposed to external loads (James Aldred and John Day, 2012).

2.2.1. Fly Ash

Geopolymers can be manufactured from fly ash, a waste material generated by the operation of coal power plants. This fly ash is characterized by a low concentration of calcium, referred to as FA (A. Bilodeau, V.M. Malhotra, 2000). Typically, geopolymer mixes are prepared with two types of potassium activators: sodium hydroxide and sodium silicate, or potassium hydroxide and potassium silicate (A. Albidah, 2021).

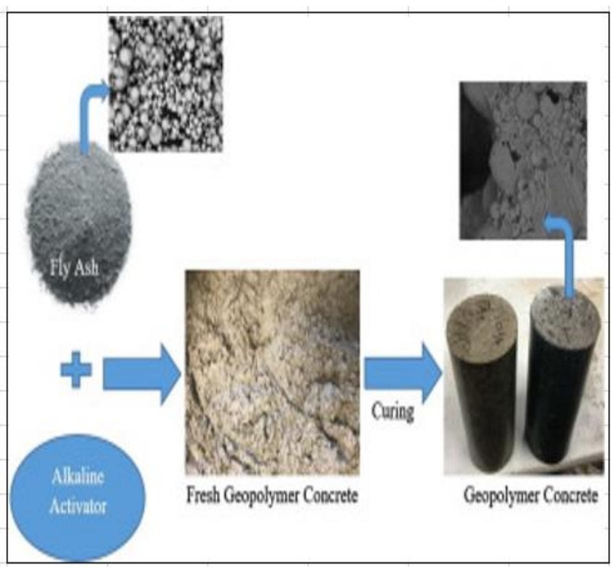

Figure 2. 3. Fly Ash Based Geopolymer Concrete Production Process

Source: (Farhan, et al., 2019)

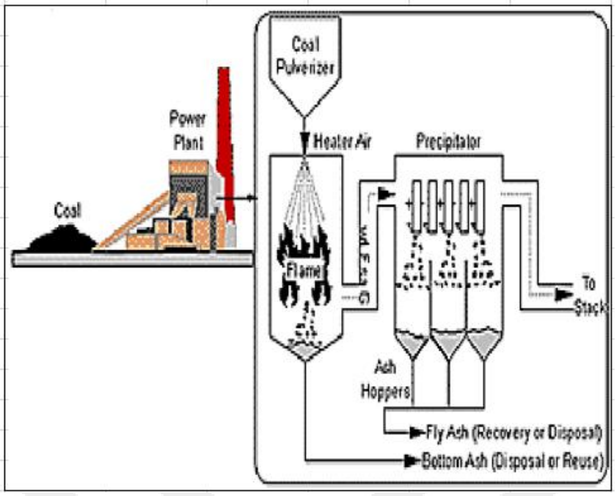

Figure 2. 4. Production of Fly Ash

Source: (Turuallo et al., 2016)

Figure 2.4 illustrates that during the coal burning production process, minerals in the coal, such as clay, feldspars, and shales, fuse together in a suspended state. They exit the combustion chamber with the exhaust gases. The resulting compound material rises to the surface, cools down, and solidifies into small, glassy spheres known as fly ash. Fly ash has been used to partially replace cement in concrete since ancient times (R. Siddique, 2004).

The incorporation of fly ash into geopolymer mortar has the potential to enhance workability, strength, and durability (A. Bilodeau and V.M. Malhotra, 2000).

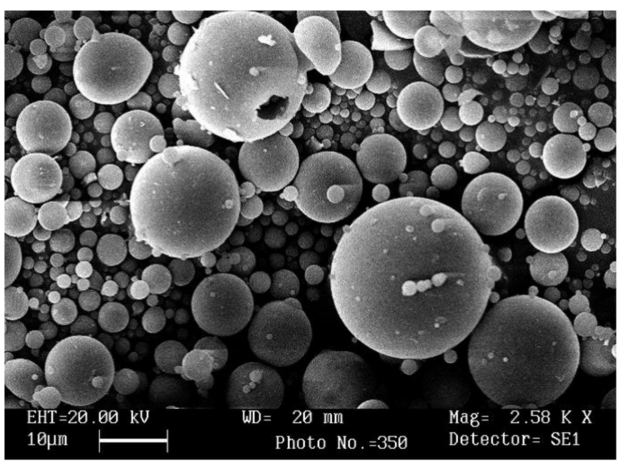

Figure 2. 5. Fly ash particles

Source: (Terzano et al., 2005)

Environmentally friendly construction materials are crucial in addressing carbon dioxide emissions, offering positive effects for future generations. Ordinary Portland cement production alone contributes to 1.35 billion tons of greenhouse gas emissions into the atmosphere (Malhotra, July 2002). Consequently, by-products play a significant role in introducing a new generation of mortar called geopolymer mortar. This innovative mortar requires less energy, utilizes fewer natural resources, and mitigates the greenhouse gas effects on the environment.

Table 2.1: Chemical Composition of FA

Chemical Composition	Fly Ash (%)	Lime (%)
C	23.23	0
CaO	3.1	91.99
SiO2	36.1	3.75
AL2O3	25.03	2.09
FeO	8.66	0.50
MgO	1.24	1.19
Na2O	0	0.43
SO3	0.59	0.05
TiO2	0.91	0
K2O	1.08	0
TOTAL	100	100

Source: (Tudjona et al., 2014)

The accomplishment of developing high-volume fly ash concrete (HVFA) is noteworthy. This concrete variant utilizes only about 40% of ordinary Portland Cement while maintaining excellent mechanical properties and superior durability performance. Test results indicate that high-volume fly ash concrete is stronger than ordinary Portland Cement concrete (Malhotra, July 2002).

Geopolymer concrete, when exposed to low drying shrinkage and a small amount of creep, demonstrates significant resistance against sodium sulfate (Wallah et al., 2003).

2.2.2. Silica Fume

Silica Fume is an additional product of silicon metal or ferrosilicon alloy. A study conducted by Y.H. M. Amin et al. (2020) revealed that silica in Pozzolana reacts with the Portlandite formed during the hydration process of OPC, leading to an increase in its strength (C. Sreenivasulu et al., 2015). Silica fume can be utilized in geopolymers and is particularly suitable for applications where high compressive strength values need to be achieved.

Figure 2. 6. Appearance of Silica Fume

Source: (Xiamen All Carbon Corporation)

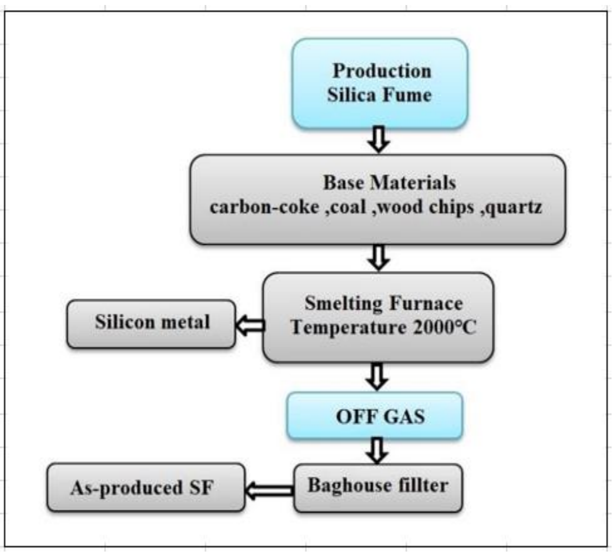

Figure 2. 7. Production of Silica Fume

Source: (Waseem Khairi Mosleh et al., 2020.)

The production of silica fume, as depicted in the above figure, is based on using materials such as carbon-coke, coal, wood chips, and quartz. These base materials undergo smelting in a furnace with a temperature of 2000°C. As a result of this high temperature, off gases and silicon metals are generated. The off gases are then processed through a baghouse filter, ultimately leading to the production of silica fume (Mohamed, Heba A., 2011).

Table 2.2: Chemical Composition of Silica Fume

Consituent	Content (%)
SiO2	97
Fe2O3	0.5
AL2O3	0.2
CaO	0.5
MgO	0.5
Na2O	0.2
SO3	0.15
C1	0.01
H2O	0.5

Source: (Mohamed, Heba A., 2011)

2.2.3. Ground Granulated Blast Slag

GGBS (Ground Granulated Blast Slag) is utilized as a by-product in the production of metal in a blast furnace (M. Ananthayya, 2014). GGBS is also employed to enhance long lasting performance and reduce the heat generated during the hydration process of ordinary Portland Cement (A. Castel, S.J. Foster, 2015).

Figure 2. 8. Appearance of GGBS

Source: (Devi, Ch, et al.,2022)

Table 2.3: Chemical Composition of GGBS

Oxide	Mass Percentage (%)
SiO2	35.47
AL2O3	19.36
Fe2O3	0.8
CaO	33.25
MgO	8.69
Others	3.25

Source: (Sounthararajan et al., 2018)

Ordinary Portland cement shares a chemical composition that is like that of GGBS. The chemical compositions of common Portland cement and GGBS are compared below. Like other raw materials, GGBS also has a high silica and alkaline content.

2.2.4. Rice Husk Ash

Rice husk ash is a 'carbon-neutral green' byproduct (M.T. Junaid et al., 2014) that is occasionally used as boiler fuel. The crystalline silica content of rice husk ash poses potential health and safety threats when inhaled (J.G. Sanjayan et al., 2015). However, due to its alumina and silica content, it can also be utilized as precursors in the manufacturing process of geopolymers.

Figure 2. 9. Rice husk ash GP production process

Source: (Hossain et al., 2021)

Table 2.4: Chemical Composition of Rice husk

Constituent	Percentage (%)
SiO2	91.1
AL2O3	0.4
CaO	0.4
Fe2O3	0.4
MgO	0.1
Na2O	0.1
MgO	0.5
KaO	2.2
Loss on ignition	4.8

Source: (Rama Subbarao et al., 2011)

The importance of sustainable cementitious materials has grown significantly due to the rapid increase in demand, high greenhouse gas (GHG) emissions, and the elevated cost of traditional Portland cement (PC). The cement industry alone contributes 5–7% to global CO2 emissions, generating an equivalent amount of CO2 (Mathew and Joseph, 2018). Polymerization products, such as geopolymer mortar, are created through the synthesis of aluminosilicate and silica binders. These binders can be sourced from cost-effective materials or industrial by-products such as fly ash and rice husk ash, making these polymeric concrete products sustainable. The aluminosilicate-silica network is formed by the reaction of alumina and silica with alkaline-activated solutions, resulting in a three-dimensional network. This network can be further reinforced by increasing the reaction rate at high temperatures (Daniel and Jay, 2010; Hussin et al., 2015).

2.2.5. Red Mud

Red mud is a secondary product produced by the Bayer process for the refining of bauxite into alumina, comprising between 55% and 65% of the targeted bauxite (G. Zhang et al., 2011). It is possible that this material may contain radioactive elements if the initial bauxite contains radioactive constituents (Adeyemi Adesina et al., 2021). With the high alkalinity of red mud, its economical and safe disposal poses a major environmental problem solution (Xiao, Q. Huang, 2013). However, the utilization of red mud in geopolymers presents a sustainable and more economical way to manage these hazardous waste materials.

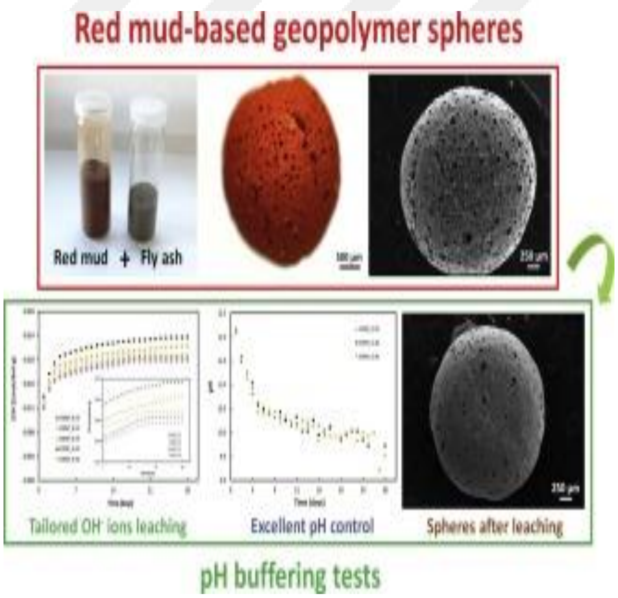

Figure 2. 10. Red mud ph experiments

Source: (Novais et al., 2018)

Geopolymer spheres (RM) based on red mud were synthesized in Fig14, with various porosity values and RM content. The pH regulation of these spheres was then assessed. The sources of this inorganic polymer were entirely waste-derived, composed of a combination of RM materials and fly ash waste (Novais, Rui M., et al., 2018). The chemical composition of red mud is given below in table 2.5, percentage of raw materials are on the right side of the table.

Table 2.5: Chemical Composition of Red Mud

Consituent	Percentage (%)
SiO2	19,2
AL2O3	22,8
Fe2O3	27,4
TiO2	3
MnO	0,2
MgO	0,4
CaO	2,2
Na2O	7,9
K2O	0,8
P2O5	0,4
Loss on ignition	15,5
Total	99,8

Source: (Maria Lúcia Pereira et al.,2014)

For the last decade, geopolymer concrete production and utilization is in high demand due to its environmental features. Geopolymer generally procure by aluminosilicates such as fly ash, silica fume, metakaolin, ground granulated blast slag, red mud, rice husk ash and alkali silicate solutions, such as sodium hydroxide and sodium silicate (P. Krivenko et al., 2003). The geopolymer concrete, for example, had extremely high activator concentrations and necessitated steam curing, resulting in a product with a relatively high shaped volume and carbon footprint compared to ordinary Portland cement concrete (L. Turner and F. Collins, 2013).

2.2.6. Metakaolin

Geopolymerization, also known as geopolymer binding, is the process by which silicon (Si) is combined with aluminum (Al) to form geopolymers in natural source materials metakaolin (MK) or in by-products fly ash using alkali activators (H.Abbas et al., 2021).

Figure 2. 11. Appearance of Metakaolin

Source: (Olawale, Margaret Damilola, 2013)

Table 2.6: Chemical Composition of Metakaolin

Oxide composition	Oxide content (%)
SiO2	51.59
AL2O3	38.11
Fe2O3	1.82
CaO	0.45
MgO	0.23
SO3	0.14
K2O	0.43
Na2O	0.11
Loss on ignition	6.12

Source: (Al-Shathr, et al., 2016)

Geopolymer binders act as calcium silicon hydrates in OPC to bond the aggregate materials. MK is one of the most widely used source materials containing an aluminosilicate in Geopolymer Concrete (GPC). MK is manufactured from natural clay (kaolin) through the process of calcination at a mild temperature. Generally, geopolymer mixes are composed of two alkali activators: sodium hydroxide in combination with sodium silicate, and potassium hydroxide in association with potassium silicate (H.Abbas et al., 2021).

2.3 Alkaline Activators

Geopolymer mortar is a rapidly expanding industrial process that has the potential to promote environmental sustainability in the industrial and construction industries by recycling waste materials, particularly from the factories, with the objective of reducing carbon dioxide emissions. Research into geopolymers has been conducted over the past two decades to demonstrate the potential for alkali-activated concrete to replace ordinary Portland cement (Abbas Mohajeran, et al., 2019). Despite the potential for geopolymers to be adopted, there are a number of obstacles that need to be addressed. A significant portion of the research conducted on geopolymers has focused on the use of sodium silicate solutions as alkali activators (Mohajerani et al.,2019).

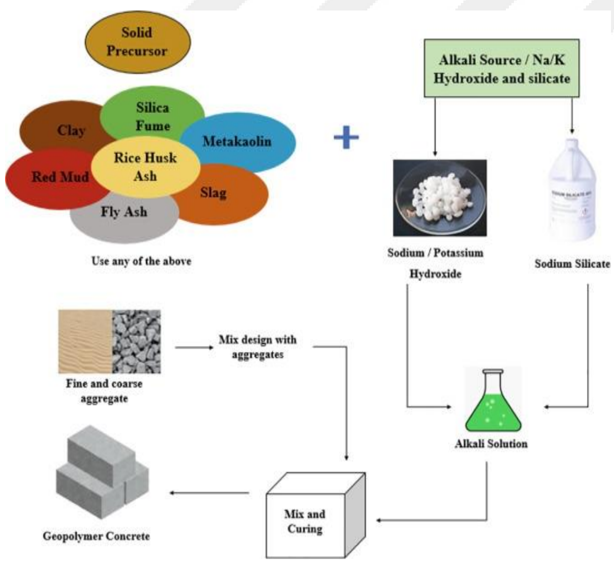

Figure 2.12. General Representation of GPC regrading with Alkaline Solutions

Source: (Blessen Skariah et al.,2022)

Studies have also been conducted in recent years to identify alternatives to binder materials as there has been a significant increase in demand for materials such as fly ash or GGBS. The results of the experiment demonstrated that the optimal amount of waste wood ash is 30% of the overall binder material, at which the maximum compressive and flexural strength are achieved (Arunkumar et al.,2021). A comparable study was conducted on Geopolymer concrete derived from GGBFS and utilizing bio-medical ash as an ash source. (Kumar et al., 2020). The technological revolution in various fields has resulted in the emergence of numerous and diverse solid waste materials that have been generated by commercial, agricultural, mining, and residential activities. According to the "Global Waste Management Outlook" developed by UNEP and ISWA, the annual amount of municipal solid waste leftovers is estimated to be around 2 billion tons. On the other hand, the amount of municipal solid urban waste initiated by industries such as business, residential, and construction, as well as other production units, is estimated to be between seven and ten billion tons per year (Siddika et al., 2019). The projected annual consumption of scrap materials is projected to reach 19 billion tons by 2025, and the demand for land for the disposal of these materials is a major concern for engineers in the civil and environmental fields. (Al Mutairi et al., 2010).

There are several benefits to effectively reusing some of the by-products, such as enhanced strength and durability, reduced construction costs by reducing the use of cement and virgin aggregate, habitat benefits such as reducing carbon dioxide emissions, and easy disposal of the contaminated waste. (Xie et al., 2019). Concrete is one of the most unsustainable composite materials out there, partly because it uses a lot of virgin aggregate. It's important for the economy of the world, and the amount of concrete handled each year is around 30 billion tons. With that, it's expected that the demand for virgin aggregate will only increase over the next two or three decades. The concrete industry is using up a lot of virgin supplies, which means it's causing a lot of environmental, energy and economic damage, since it's using up 50% of primary matter and 40% of the net energy, and it's also bringing in around 50% of aggregate waste (Oikonomou, N. D. 2005).

Sodium silicate solutions are known to be really corrosive, so they can be seen as a user-hostile system. But alternative alkali activators like potassium silicate solutions are more user-friendly, so they're more likely to be accepted by the industry. Future research should focus on mix designs that use waste materials that are locally available and don't need to be processed too much. A lot of research has been done on heat treated geopolymers, but this means you're increasing the embodied material but decreasing the environmental benefits, which is a problem for in-situ applications. Research needs to be done on ambient temperature curing, to figure out compressive strength, strength development rate, and curing time. (Ahmari S, Zhang L, 2012).

Durability needs to be addressed, with studies showing that compressive strength decreases after relatively short time immersion in water, as well as potential problems related to chloride induced corrosion in reinforcing steel. Standardized leachate analysis should be developed for geopolymers that contain recycled waste materials. The purpose of this review is to provide an overview of the research that has been done on waste-incorporated geopolymers and to identify the barriers to industry acceptance with the aim of indicating the next steps for future research.

2.3.1. Sodium Silicate

Geopolymer concrete doesn't need to be heated to get to its early compressive strength. When you use 5-15% Portland cement replacement, you can reduce your CO2 emissions by 20% compared to OPC concrete. Plus, you can use waste materials, like fly ash and slag cement, as well as silica fume. These materials can be dangerous to the environment and to people, so geopolymer concrete mixes are one of the few sustainable options (Assi et al., 2020).

Figure 2. 13. Representation of GP

Source: (Hassan et al., 2019)

A study in 1991 by Douglas et al. tested five different combinations of GPC that were activated with sodium silicate. The results showed that GPC has good workability and strong properties. There were a lot of things that affected the mechanical strength of GPC. The most important ones were the type of alkali that was used, the amount of alkali in the activator, and the curing temperature (Hassan et al., 2019).

Table 2.7: Mixture proposition of GP with Alkaline Activators

Material	Mass (kg(m^3)
Coarse and fine aggregates	1830
Fly Ash	404
Sodium Hydroxide solution (14M)	41
Sodium silicate solution	102
Superplasticizer	6

Source: (Sumajouw et al.,2005)

Geopolymer concrete has superior properties compared to OPC, such as high compressive strength, durability, resistance to high elevated heat, acid attack resistance, salt scaling resistance, and salt scaling resistance compared to OPC samples. Geopolymer concrete can achieve up to 85% of the final compressive strength in less than 48 hours, resulting in operational efficiency during production. The most common type of geopolymer used in studies is the liquid-activated geopolymer, which is composed of either sodium hydroxide or a combination of sodium silicate, water, and an activating solution. Some disadvantages of this concrete may prevent it from being commercially available, including high pH and molarity variations resulting in performance inconsistency (Assi et al., 2020).

2.3.2 Sodium Hydroxide

The alkaline liquid was selected to be composed of a mixture of sodium silicate and NaOH solution. The NaOH solution was obtained by dissolving either flakes or pellets in water, with the mass of the NaOH solids varying depending on the concentration expressed in molar terms. (Joseph Davidovit, 2002).

Table 2.8: The composition of GP mix designs

Materials	Mix 1	Mix 2
Coarse Aggregate	1200	1142.7
Dia. 4,5 - 9,5 mm	540	547.1
Dia. 9,5 - 19,5 mm	660	685.6
Fine Aggregate	600	521.8
Fly Ash	450	410
NaOH Solutions	80	110
Na2SiO3 Solutions	120	120
Superplasticizer	9	8.2
Added Water		2.3

Source: (Pane et al., 2018)

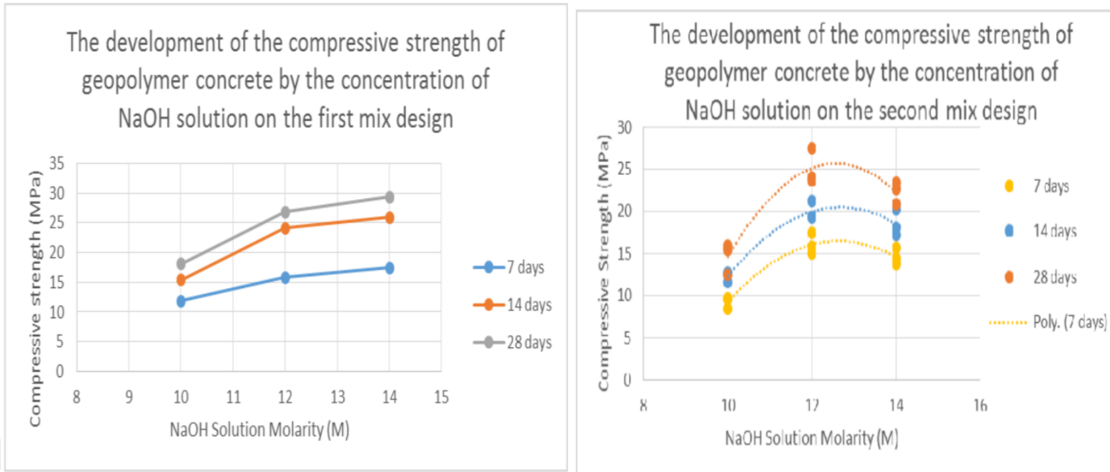

Figure 2. 14. Compression Strength relation in different molarities of Sodium Hydroxide for mix design

Source: (Pane et al., 2018.)

Different molarities of Sodium Hydroxide above Figure 2.14. demonstrates that the changes in compressive strength (Yin et al., 2023). Geopolymer concrete increases compressive strength by increasing the NaOH solution concentration for both mix designs.

Geopolymer concrete achieves its peak compressive strength of 30 MPa at 28 days old, particularly at a 14 M sodium hydroxide concentration (Pane et al., 2018). However, the sample's porous nature may contribute to less consistent behaviors. The relationship between compressive strength at 28 days and NaOH molarity at 7 days is illustrated in the graph below. Notably, the trend for increases in strength at molarities 12M and 14M is not as pronounced.

Balaraman R. (2016) explored the influence of sodium hydroxide molarity on the strength of geopolymer concrete, concluding that an increase in molarity enhances workability. Positi, P. (2013) examined the mechanical characteristics of geopolymer concrete containing reused lightweight aggregate, noting a decrease in compressive strength with an increase in reused lightweight aggregate. Geopolymer concrete's potential applications include construction and maintenance of roads, sidewalks, and air terminals, particularly in developing countries due to its heat resistance and reduced vulnerability to chloride-induced damage in winter conditions. The study results show that increasing sand content in mortar enhances its density due to the high quartz percentage in sand. It's essential to consider that geopolymer concrete strength depends on materials used and curing time. Al Bakri (2011) emphasized the significance of curing, highlighting a slight increase in compressive strength at a curing temperature of 120°C for 18 hours. Jamdade (2017) and Krishnan (2018) also conducted studies on curing temperatures and ratios of fly ash to GGBS, respectively.

GGBS with low calcium has been found to influence the setting time and initial strength enhancement of geopolymer concrete under room temperature (Krishnan, 2018). The role of alkaline activators, such as sodium hydroxide, in strength development and surface cracking prevention at elevated temperatures (600°C) is acknowledged.

Concrete, widely used in construction, doesn't require maintenance during its lifetime. The properties of GGBS- and SF-based geopolymer products depend on various factors, including alkaline solution concentration, activators, and curing conditions. Changes in Si/Al ratios and alkali solutions can result in different forms, affecting the final structure. Geopolymers with a compact and dense structure exhibit high mechanical strength and resistance to chloride, sulfate, and acid solutions (Okoye et al., 2011).

3. METHODOLOGY

The properties of geopolymer mortar exhibit a correct correlation with material properties. Each property plays a vital role in strength tests. Figure 3.1 below illustrates some of the factors influencing geopolymer mortar, emphasizing their significance in determining strength.

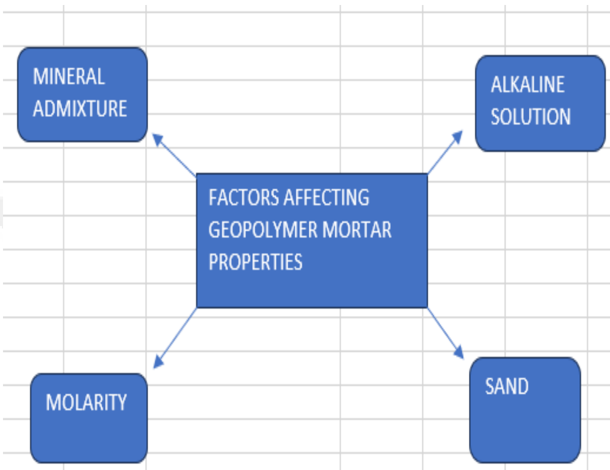

Figure 3.1: Factors of geopolymer mortar

Geopolymer is a type of aluminosilicate binder material formed through the activation of solid aluminosilicate-based materials, such as silica fume, ground granulated blast slag, and alkaline solutions like sodium hydroxide and silicate solution.

Geopolymers are produced by blending mineral admixtures with an alkaline activator solution, resulting in a substance referred to as geopolymer paste. This mixture typically forms a homogeneous slurry with a dark green color. Both geopolymer paste and mortar mix exhibit cohesive properties in their fresh state during the initial stages.

In the preparation of geopolymer mixes, this study demonstrates specific synthesizing parameters to highlight the influence of mineral admixtures. The inclusion of mineral admixtures significantly impacts the compressive strength and flexural strength of geopolymer mortar.

3.1. Experimental Procedure

Due to a lack of studies on the combination of silica fume and GGBS at both ambient and oven temperatures, this research was conducted to investigate their engineering properties. The structure of geopolymer mortar has been examined independently under the categories of mineral admixtures and alkaline activators.

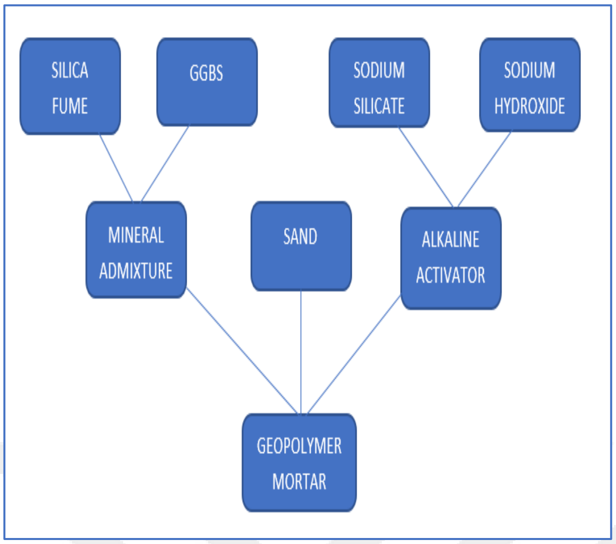

Figure 3.2. GM Mixture demonstration

3.1.1. Used Materials

Silica fume is a micro-sized material that can be utilized in concrete as a mineral additive due to its high Si and Al content and pozzolanic features. It improves granulometry by filling the spaces between cement grains.

Ground Granulated Blast Slag is a by-product of iron production in blast furnaces in iron and steel plants. The GGBS is granulated through abrupt cooling and subsequently ground.

The study also examines the impact of different additives, such as silica fume and GGBS on geopolymer mortar. Each sample exhibits distinct properties based on the materials used. These properties are a result of the mineral admixture content utilized in geopolymer mortar.

3.1.2. Alkaline Solutions

In this study, sodium silicate was used as the alkaline solution and the ratio of sodium hydroxide to sodium silicate was maintained throughout the entire study.

Alkaline solution ratios for each sample are constant due to measuring the properties of mineral admixtures in geopolymer mortar.

3.1.2.1. Sodium Hydroxide

Sodium Hydroxide (NaOH) is commonly available in the market in pellet or flake form, and the cost of the product is dependent on the purity of its ingredients. In this research, Sodium Hydroxide (NaOH) solution with a molarity of 8M was prepared by dissolving it in pure water. The choice of 8M molarity was consistent for each specimen to measure the properties of the mineral admixture in geopolymer mortar samples.

The concentration of 8M denotes that the amount of Sodium Hydroxide (NaOH) in one liter of water is 8 × 40 = 320 g, where 40 is the molecular weight of NaOH. Dissolved Sodium Hydroxide (NaOH) pellets were used to achieve this concentration. The NaOH solutions were prepared at the planned concentrations and allowed to stand at room temperature for 24 hours. It should be rested for a day, covered with nylon to prevent heat dissipation.

Figure 3. 3. Preparation of 8M Sodium Hydroxide solution

3.1.2.2. Sodium Silicate

Sodium silicate (Na_2SiO_3), also known as waterglass, is available in the market in both gel and solid forms. The ratio of silicon dioxide (SiO_2) to sodium oxide (Na_2O) in sodium silicate gel is a crucial factor distinguishing between the two forms.

3.2 Preparation of Geopolymer Mortars

The fundamental step involves preparing materials properly to obtain the most effective final test results. A programmable mortar mixer is used with properties designed to meet standard requirements for mixing mortars and cement pastes. The mixing paddle employs a planetary motion and is driven by a motor with a microprocessor-based speed. The mixer features preset programs complying with EN and ASTM standards, custom-designed programs, or manual mode. The mode button allows for quick selection or different program options.

The machine includes an automated sand dispenser for automatic sand discharge. It allows lowering the bowl without disrupting the application of a mix where the motor speed is set to zero. The user can monitor the mixed time on the display, and a lamp signals critical time period.

The alkaline solution was prepared by converting milliliters into grams using density. Sodium silicate has a density of 1.38 kg/m3, and sodium hydroxide has a density of 1.28 kg/m3. The conversion results in 91 grams of sodium silicate and 171 grams of sodium hydroxide. These liquid components were added to the mixed aggregate, and mixing continued for an additional 5 minutes, ensuring the binding paste covered all sands, achieving homogeneity and a uniform color.

In subsequent steps, standard sand was mixed with silica fume/Ground Granulated Blast Slag (GGBS) and alkaline solutions (sodium hydroxide and sodium silicate) in an automatic programmable cement mixer for 5 minutes.

After mixing, the fresh geopolymer mortar was filled into molds in three layers with required compaction, following standard methods for geopolymer cement mortar. The specimens were placed on a vibrating table to minimize the number of voids in the fresh mortar, a significant factor for achieving high durability properties

Figure 3. 4. Prism Mold Demonstration

The mortars were shaped using the vibration method in metal molds, forming prisms with dimensions of 40 mm x 40 mm x 160 mm. To prepare geopolymer specimens, silica fume, ground granulated blast slag, and sand were mixed for 5 minutes. Afterward, the activating solution was added and mixed sequentially. The mortar was cast into prismatic molds measuring 40 mm × 40 mm × 160 mm. Vibrating for 1 minute removed entrained air, and the molds were sealed with a film to prevent moisture loss from the surface.

Both seven (7) and twenty-eight (28) days' mortars were used in all tests applied to the geopolymer mortar samples, representing early and final strength, respectively. Subsequently, the samples were placed in a laboratory in prisms for further testing.

The materials and mixing ratios used in the preparation of the geopolymer mortar samples are detailed in Table 3.1.

Table 3.1: Mixture Proportion of geopolymer mortar

Mixture Proportions	Code Name	Silica Fume (g)		GGBS (g)		Sodium Silicate (ml)	Sodium Hydroxide Solution (ml)		Sand (g)	Liquid/ Powder Ratio
1th Mixture	M20-80	20%	90	80%	360					
2 nd Mixture	M80-20	80%	360	20%	90					
3rd Mixture	M50-50	50%	225	50%	225	66	8M	134	1350	0.44
4th Mixture	MS100	none		100%	450					
5th Mixture	MSF100	100%	450	none						

Mechanical tests were conducted using an automatic controlled laboratory cement press. For mortars, physical tests, and flexural strength tests, the average values of three samples were taken from each sample group. The results were determined by taking the average of three samples in both the compressive and flexural strength tests.

Geopolymer mortar samples were cast in molds and compacted using a vibrating machine to remove entrapped air. After proper casting, the specimens were left at ambient temperature for 24 hours and demolded the next day. Demolded specimens were then kept in ambient curing and oven curing until the day of testing.

This methodology, employing 5 different ratios of raw materials with the same alkaline activator and sand content, elucidates the impact on compressive and flexural strength. It also highlights the fundamental role of mineral admixtures in the geopolymer mortar structure.

3.2.1. Experimental Test Part

3.2.1.1. Compressive Strength Test

The mechanical test measures the maximum compressive load a material can withstand before fracture. Typically, a prism-shaped test specimen is compressed between the plates of a compression-testing machine, applying a gradually increasing load until fracture occurs.

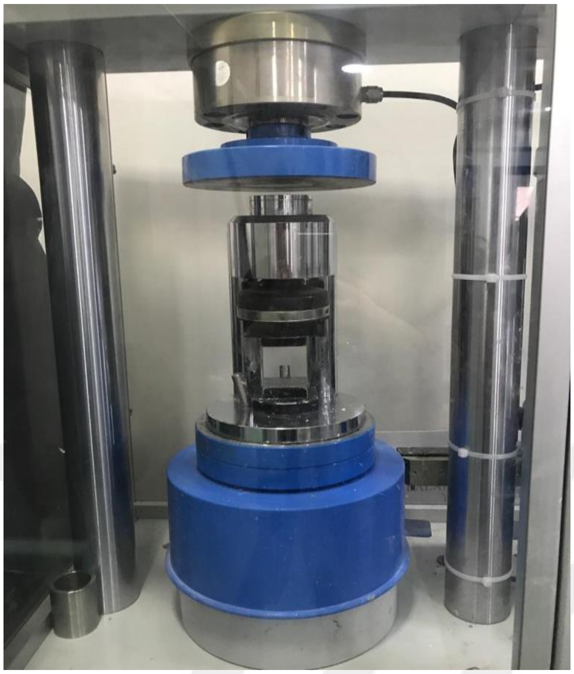

Figure 3.5. Compressive Strength Test Machine

Each test requires three samples, and the average of these three samples determines the compressive strength and flexural strength.

3.2.1.2. Flexural Strength Test

The flexural test measures the force presupposed to bend a beam under three-point loading conditions. The data is generally utilized to distinguish the materials for parts that will support loads without flexing. Flexural modulus is used as an indication of a material's stiffness when flexed. In this study, flexural strength identifies the amount of stress and force of prepared geopolymer mortars an withstand such that it resists any bending failures. After compressive strength test, there are two specimens existing due to fracture and in flexural strength test, this samples should be utilized for flexural strength test results.

Table 3.2: Age of testing with the number of samples

Age in days	Compressive Strength/Flexural Strength				
	M20-80	M80-20	M50-50	MS100	MSF100
Seven days ambient temp.	3	3	3	3	3
Seven days oven temp.	3	3	3	3	3
Twenty-eight days ambient temp.	3	3	3	3	3
Twenty-eight days oven temp.	3	3	3	3	3

Table 3.2 shows the testing age along with the corresponding number of samples. A total of 60 samples were utilized in the experimental phase, enabling a comprehensive comparison of results across various mineral admixtures and elevated temperatures.

Figure 3.6. Tensile Strength Test Machine

Each geopolymer mortar undergoes compressive strength testing at 7 days and flexural strength testing at 28 days. These results will illustrate the impact of mineral admixture content in the mortar. Both compressive and flexural strength tests were conducted on the formulated geopolymer mortar.

In the flexural testing, samples were positioned in the testing machines with one side facing the supporting rollers, and the longitudinal axis parallel to the supports. Vertical loads were applied by the loading rollers on the opposite side of the prism/sample's face, with uniform load increase. Half of the prism/sample used for compressive strength testing was laterally centered on the machine's platen. The maximum force applied was recorded, along with the specimen's dimensions, and the compressive strength was calculated. The final compressive strength result represents the arithmetic average of ten individual test samples.

For early strength, each specimen underwent separate testing. The final strength at 28 days was obtained for this testing phase. Additionally, the impact of heat was observed separately for 7 days and 28 days.

4. RESULTS AND DISCUSSION

4.1 Introduction

This section presents and discusses the experimental results, specifically focusing on the strength development of geopolymer mortar under ambient and oven curing methods. The factors determined in the previous methodology section are considered.

For all specimens, the liquid/powder ratio remained constant at 0.44, with only the percentages of mineral admixtures varying. Results for each test are presented separately based on their mineral admixture content and curing method.

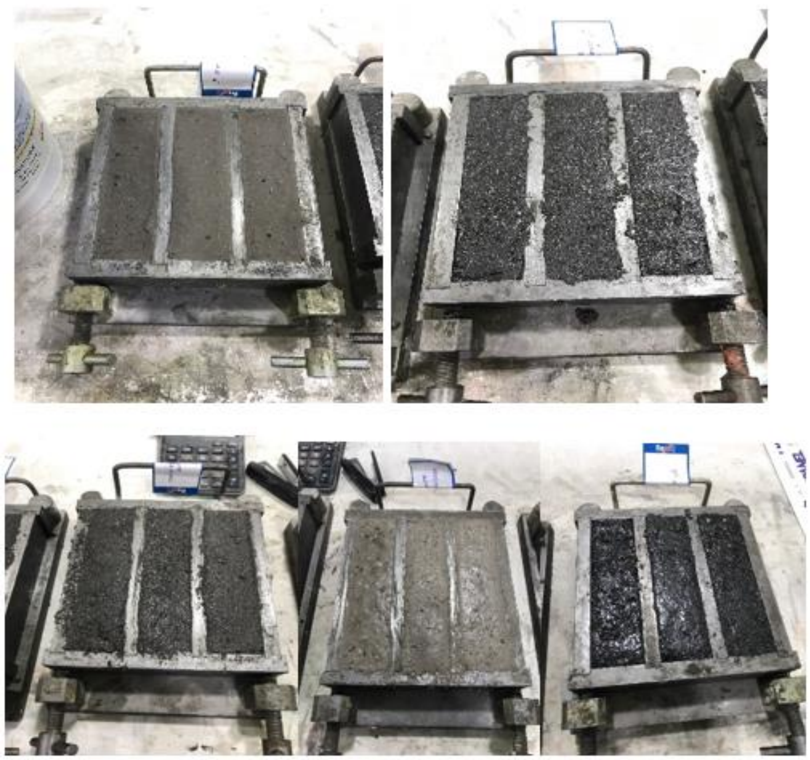

Figure 4. 1. Seven (7) days ambient temperature samples

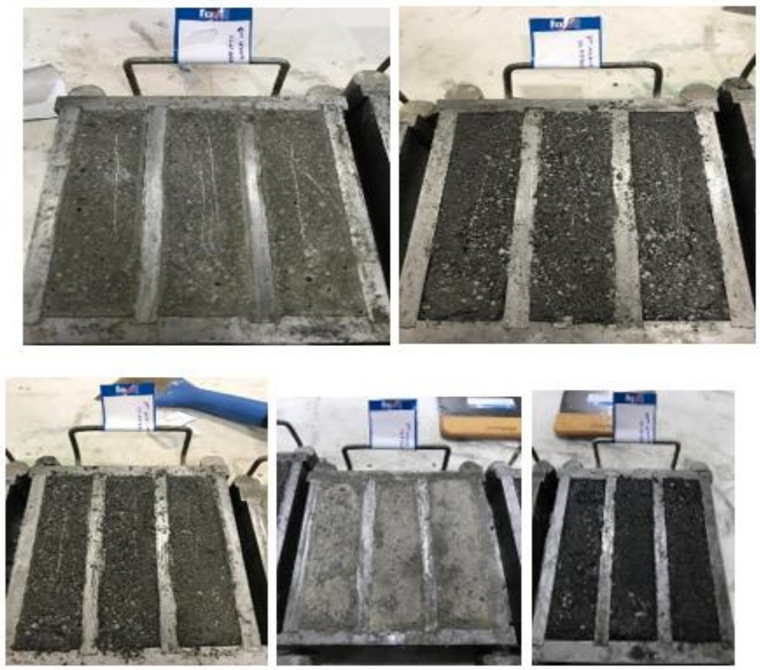

Figure 4. 2. Twenty-eight (28) days ambient temperature samples

Figure 4. 3. Seven (7) days Samples in 65°C oven temperature

Figure 4. 4. Twenty-Eight (28) days Samples in 65°C oven temperature

4.2. Compressive Strength Results

Mixtures were made to study the effect of various parameters on the compressive strength. Some mixtures were prepared to study the influence of curing temperature on the compressive strength of Geopolymer mortar. Each mixture is separately discussed below.

Table 4.1 shows the compressive strength of 7 days for ambient and oven temperatures. Figure 4.5 shows the 7-day compressive strength results of the samples were cured in ambient temperature. The compressive strength values ranged between 14.67 to 58.79 MPa. The maximum strength was for the mix of MS100, and the minimum compressive strength values was for the mix of MSF100.

For the 7-day ambient temperature curing method, the maximum compressive strength values were recorded for the mix of MS100. The compressive strength of MS100 was 4.7%, 40.3%, 41.5% and 75% higher than M20-80, M80-20, M50-50 and MSF100, respectively.

Figure 4.6 shows the 7-day compressive strength results of the samples were cured in oven temperature. The compressive values of the mixes were in the range between 18.4 -70.8 MPa. The results revealed that the maximum compressive strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100.

For the seven-day oven temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 66.6%, 65.2%, 41.6% and 73.9% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.7 shows the comparison between the Seven-day compressive strength results of oven and ambient curing methods. The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 29.6%, 28.2% and 32.5% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 cured in oven temperature show higher compressive strength compared to the ambient temperature curing method. The compressive strength of the oven temperature was 26.4% higher than the ambient temperature curing method.

Table 4.1: Seven days Compressive strength

Age in days 7-day	**Compressive Strength N/mm^2**				
	M20-80	**M80-20**	**M50-50**	**MS100**	**MSF100**
Ambient temperature	52,85	30,01	31,22	58,02	17,36
	63,89	39,98	37,75	29,08	11,18
	51,82	31,05	37,01	57,68	17,98
	61,28	40,02	30,15	59,02	11,28
	50,05	29,87	31,98	58,88	18,05
	59,98	39,5	37,98	59,35	12,22
Average	**56**	**35,07**	**34,34**	**58,79**	**14,67**
Oven temperature 65°C	62.95	18,12	23,83	42,73	17,06
	65,86	23,28	25,51	42,31	18,93
	74,88	22,45	25,31	39,75	18,76
	75,89	24,59	24,89	40,09	19,34
	71,45	29,95	23,88	39,98	17,98
	69,67	23,56	24,5	43,21	18,55
Average	**70,815**	**23,65**	**24,65**	**41,34**	**18,43**

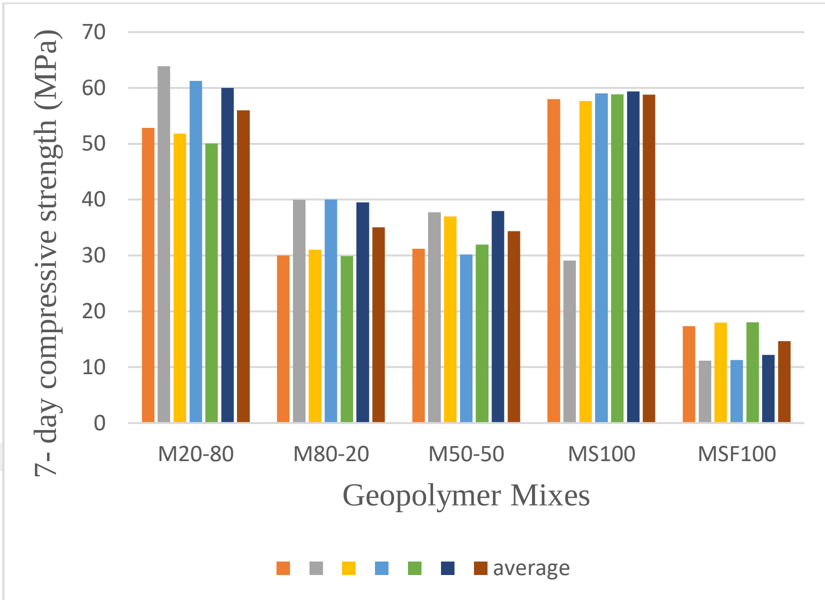

Figure 4.5. Seven days ambient temperature compressive strength

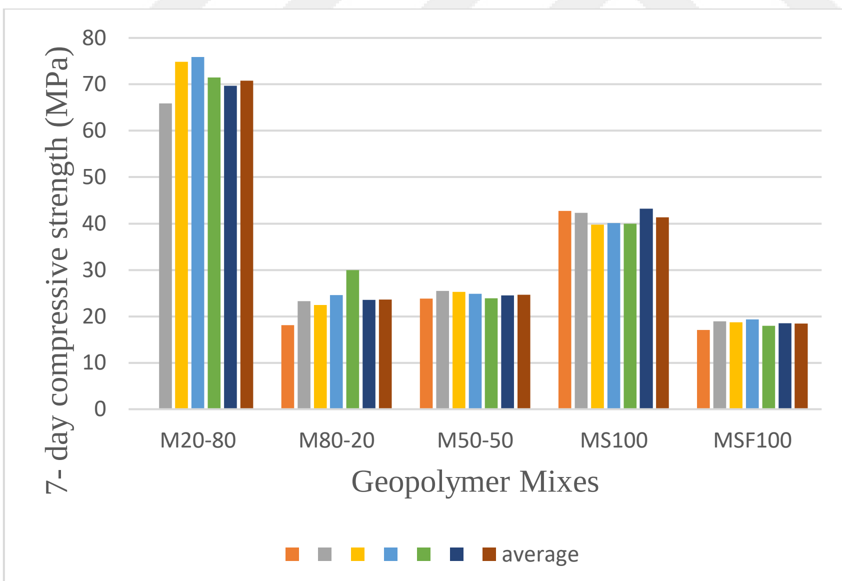

Figure 4.6: Seven-day oven temperature compressive strength

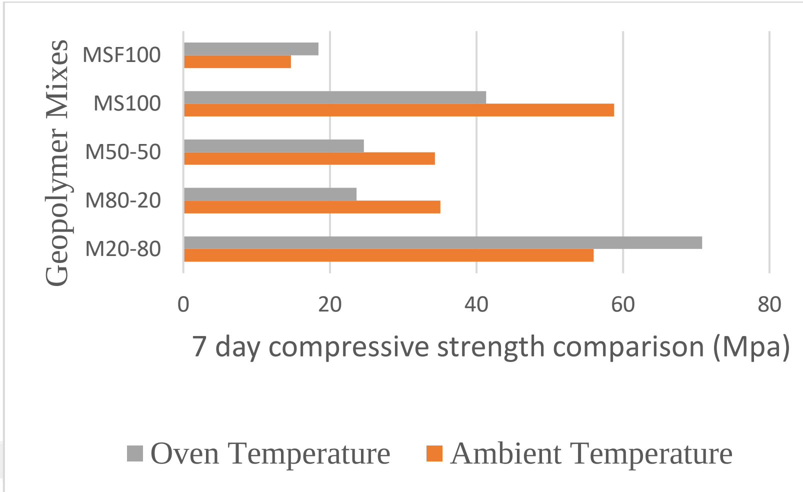

Figure 4.7 Comparison between the Seven-day compressive strength results of oven and ambient curing methods.

Table 4.2 shows the 28 day compressive strength for ambient and oven temperatures. Figure 4.8 shows the 28-day compressive strength results of the samples were cured in ambient temperature. The compressive strength values ranged between 19.2 to 70.7 MPa. The results revealed that the maximum strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100. For the twenty-eight-day ambient temperature curing method, the maximum compressive strength values was recorded for the mix of M20-80. The compressive strength of M20-80 was 27.9%, 26.5%, 14.5% and 72.8% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.9 shows the 28-day compressive strength results of the samples were cured in oven temperature. The compressive strength values of the mixes were in the range between 21.1 -70.6 MPa. The maximum compressive strength was for the mix of M20-80 and the minimum compressive strength value was for the mix of MSF100. For the twenty-eight-day oven temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 61.3%, 44.3%, 26.75% and 70.2% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.10 shows the comparison between the 28-day compressive strength results of oven and ambient curing methods. The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 and MSF100 cured in oven temperature show similar compressive strength compared to the ambient temperature curing method. There is no significant change was observed in compressive strength values of the oven temperature and the ambient temperature curing method.

Table 4.2: Twenty-eight days Compressive strength

Age in days 28-day	Compressive Strength N/mm2				
	M20-80	**M80-20**	**M50-50**	**MS100**	**MSF100**
Ambient temperature	70,94	52,85	45,8	62,44	19,52
	68,55	51,41	51,09	56,78	18,77
	68,6	5,96	52,57	57,98	18,56
	72,77	51,95	68,75	63,35	18,98
	73,85	49,85	46,85	60,43	19,56
	69,97	48,79	46,89	61,85	20,02
Average	**70,78**	**50,97**	**51,99**	**60,47**	**19,23**
Oven temperature 65°C	69,92	26,85	38,48	55,56	23,44
	72,85	26,98	37,65	53,45	18,75
	69,55	27,78	39,79	52,12	19,87
	71,95	27,21	39,92	50,43	22,45
	68,44	25,95	38,44	49,65	21,77
	70,98	28,99	39,65	49,12	20,19
Average	**70,61**	**27,29**	**39,32**	**51,72**	**21,07**

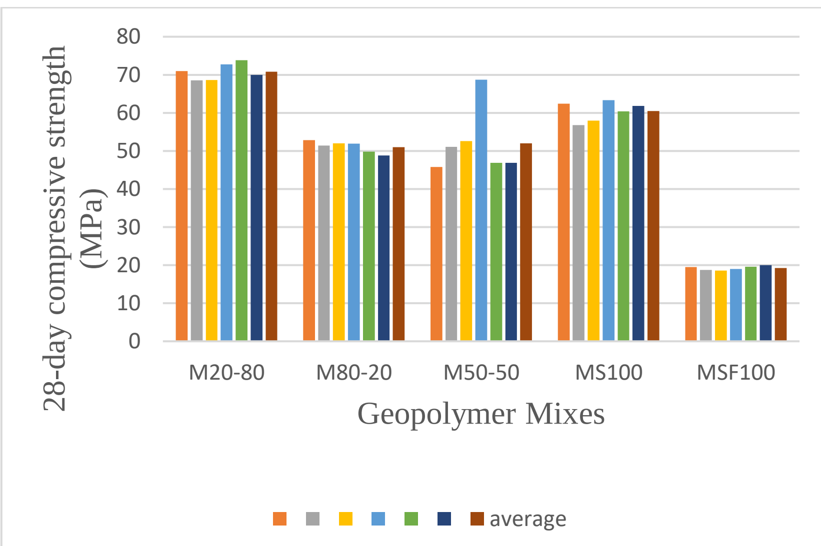

Figure 4.8 Twenty-eight (28) days ambient temperature compressive strength

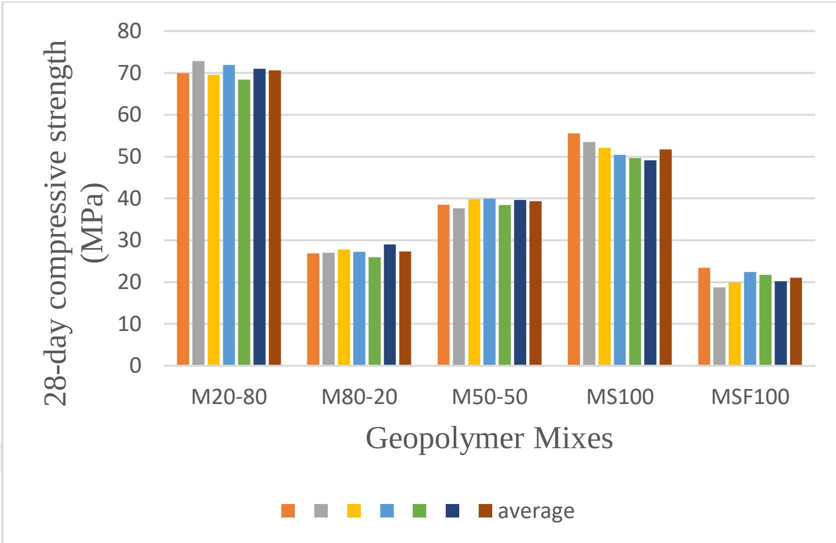

Figure 4.9. Twenty-eight (28) days oven temperature compressive strength

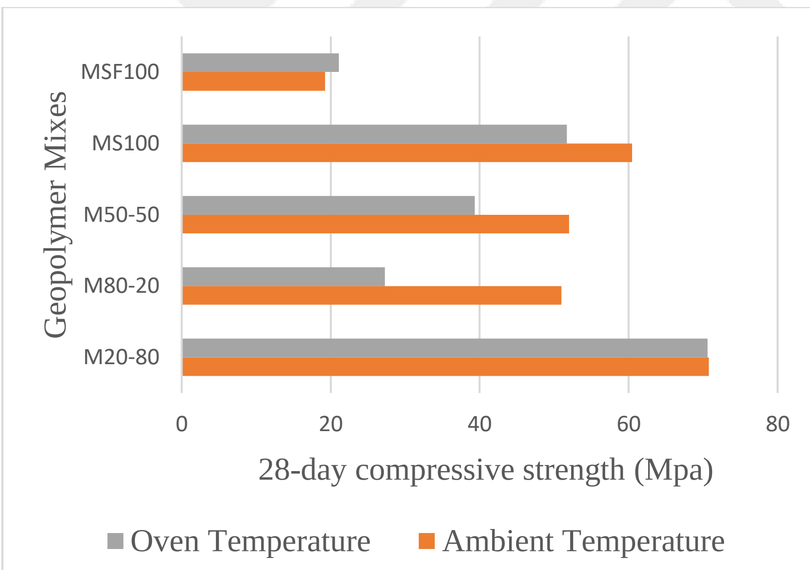

Figure 4.10 Twenty-eight-day Compressive strength

According to the study by Nor Hasanah Abdul Shukor in 2018, geopolymer mortar samples were immediately placed in an oven at 90°C after casting, with the compressive strength decreasing as the heat curing duration increased. Rapid strength increase occurred up to 24 hours, but after that, the strength became moderate or weak. For 24 hours of heat curing, compressive strength was 31.46 megapascals (MPa), slightly increasing to 32.1 MPa for 48 hours. Prolonged heat curing may weaken the mineral structure, and it is suggested not to exceed 24 hours in practical applications.

The general assumption is that GGBS content is more effective, while SF results in lower workability and lower strength values. Compaction of samples significantly influences results. The study indicates that oven and room temperatures do not directly correlate with results. GGBS content penetrates alkaline solutions more than SF, providing durability to geopolymer mortar.

Referring to the study by Narayan & Shanmugasundaram in 2017, geopolymer mortar develops sufficient strength even under ambient temperature conditions without conventional curing. Industrial by-products like GGBS and Silica Fume can be advantageously used in producing ambient-cured geopolymer composites. In general, the strength of ambient-cured geopolymer mortar increases with the rise in GGBS content. Parameters such as alkaline activator molarity, liquid/powder ratio, and binder/aggregate ratio influence the strength development of ambient-cured geopolymer mortar. Geopolymer mortar holds promise as an eco-friendly and sustainable construction material for the production of new-generation mortar or concrete.

4.3. Flexural Strength Results

According to silica fume and GGBS content in 8M of NaOH, the compressive strength results of 7, and 28 days the regression equation was proposed in table and graphs below.

Table 4.3 shows the 7-day flexural strength for ambient and oven temperatures. Figure 4.11 shows the 7-day flexural strength results of the samples were cured in ambient temperature. The flexural strength values ranged between 1.7 to 5.8 MPa. It can be seen that the maximum strength was for the mix of MS100, and the minimum flexural strength values was for the mix of MSF100. For the seven-day ambient temperature curing method, the maximum flexural strength values were recorded for the mix of MS100. The compressive strength of MS100 was 12.7%, 60.5%, 37.9% and 70.2% higher than M20-80, M80-20, M50-50 and MSF100, respectively.

Figure 4.12 shows the 7-day flexural strength results of the samples were cured in oven temperature. The flexural values of the mixes were in the range between 1.8 - 6.8 MPa. It can be seen that the maximum flexural strength was for the mix of M20-80 and the minimum flexural strength value was for the mix of MSF100. For the seven-day oven temperature curing method, the maximum flexural strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 70%, 47.8%, 35.7% and 72.5% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.13 shows the comparison between the 7-day flexural strength results of oven and ambient curing methods. The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 25.6%, 2.7% and 12% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the flexural strength value of the mix of M20-80 and MSF100 cured in oven temperature show increment compared to the ambient temperature curing method. The increment in flexural strength of the oven curing method was 32.5% and 6.8% higher for the mixes of M20-80 and MSF100, compared to the oved curing method, respectively.

Table 4.4 shows the 28-day flexural strength for ambient and oven temperatures. Figure 4.14 shows the 28-day flexural strength results of the samples were cured in ambient temperature. The flexural strength values ranged between 1.78 to 6.63 MPa. It can be seen that the maximum strength was for the mix of M20-80 and the minimum flexural strength values was for the mix of MSF100. For the twenty-eight-day ambient temperature curing method, the maximum flexural strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 49.2%, 33.4%, 8.14% and 73.15% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.15 shows the 28-day flexural strength results of the samples were cured in oven temperature. The flexural values of the mixes were in the range between 2.14 – 6.85 MPa. It can be seen that the maximum flexural strength was for the mix of M20-80 and the minimum flexural strength value was for the mix of MSF100. For the twenty-eight-day oven temperature curing method, the maximum flexural strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 68.3%, 38.2%, 18.4% and 68.7% higher than M80-20, M50-50, MS100 and MSF100, respectively.

Figure 4.16 shows the comparison between the 28-day flexural strength results of oven and ambient curing methods. The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment in the flexural strength compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 8.2%, 4% and 35.6% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the flexural strength value of the mix of M20-80 and MSF100 cured in oven temperature show increment compared to the ambient temperature curing method. The increment in flexural strength of the oven curing method was 3.3% and 20.2% higher for the mixes of M20-80 and MSF100, compared to the oved curing method, respectively.

Table 4.3 Seven days Flexural Strength results

Age in days	Flexural Strength N/mm²				
7-day	M20-80	M80-20	M50-50	MS100	MSF100
Ambient Temperature	5,13	2,32	3,65	5,88	1,73
	5,18	2,3	3,67	5,85	1,75
	5,1	2,35	3,64	5,89	1,77
Average	**5,13**	**2,32**	**3,65**	**5,88**	**1,75**
Oven Temperature 65°C	6,78	2,08	3,5	4,33	1,82
	6,82	2,1	3,5	4,38	1,93
	6,79	1,95	3,59	4,41	1,88
Average	**6,8**	**2,04**	**3,55**	**4,37**	**1,87**

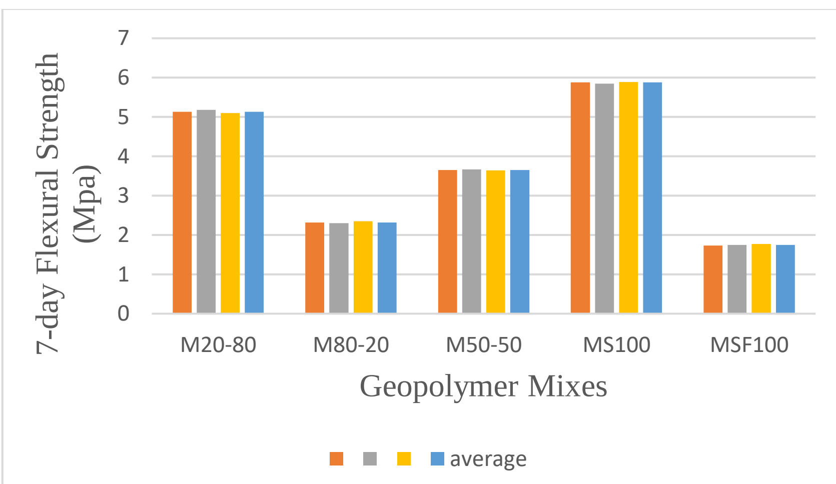

Figure 4.11 Seven (7) days ambient temperature flexural strength

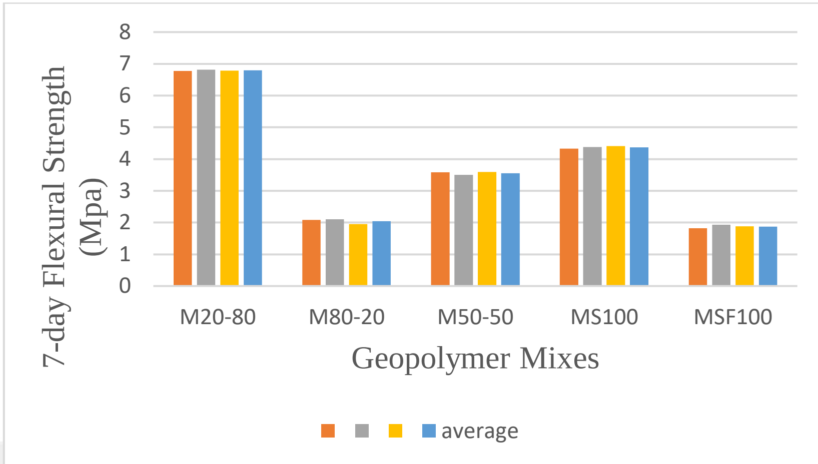

Figure 4.12. Seven (7) days oven temperature flexural strength

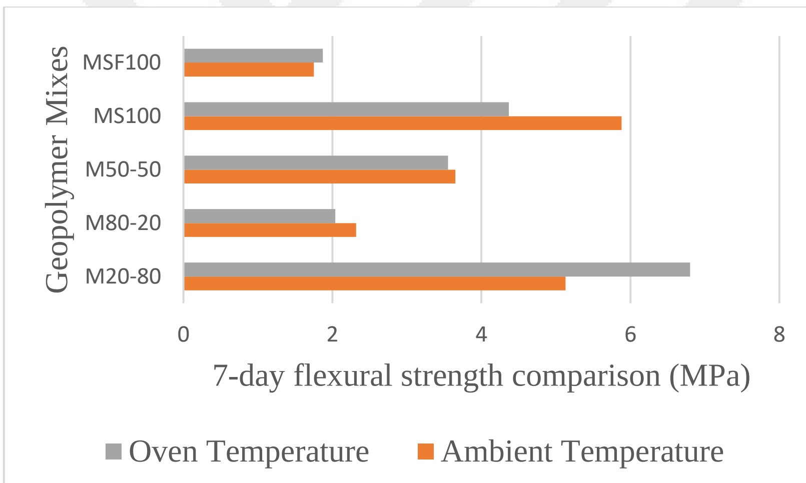

Figure 4.13. Flexural strength for 7 days comparison

Table 4.4: Flexural strength for 28 days

Age in days 28-day	Flexural Strength N/mm^2				
	M20-80	**M80-20**	**M50-50**	**MS100**	**MSF100**
Ambient temperature	6,65	3,37	4,39	6,05	1,78
	6,62	3,4	4,41	6,12	1,82
	6,64	3,36	4,43	6,1	1,79
Average	**6,63**	**3,37**	**4,41**	**6,09**	**1,78**
Oven temperature 65°C	6,85	2,15	4,23	5,62	2,1
	6,87	2,18	4,18	5,58	2,18
	6,83	2,2	4,2	5,57	2,15
Average	**6,85**	**2,17**	**4,23**	**5,59**	**2,14**

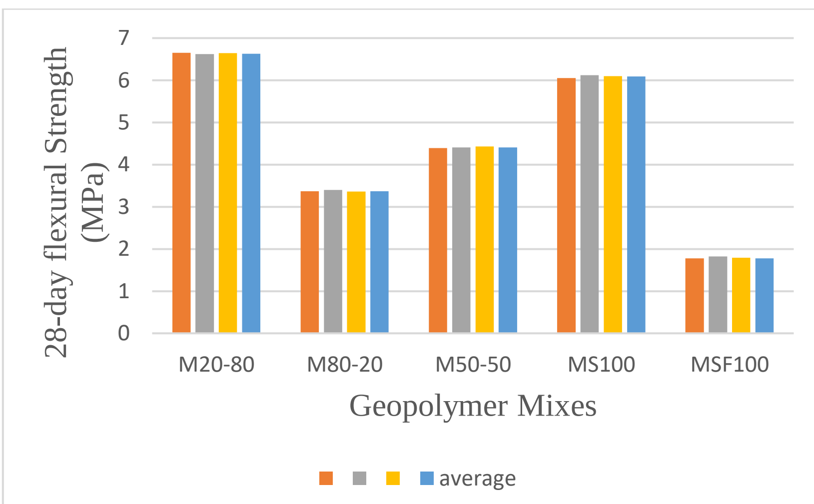

Figure 4.14. Twenty-eight (28) days ambient temperature

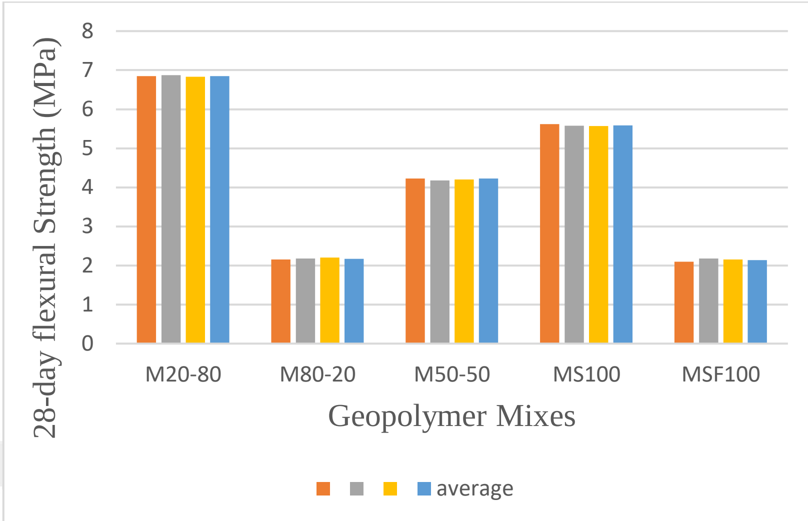

Figure 4.15: Flexural strength for 28 days oven temperature

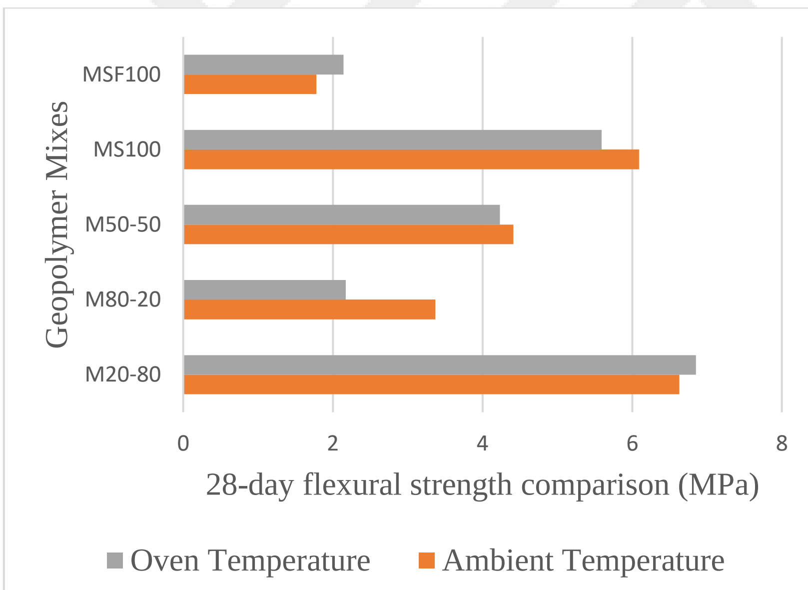

Figure 4.16. Flexural strength for 28 days comparison

5. CONCLUSION

Geopolymer, a promising alternative to traditional Portland cement, offers a wide range of sustainable applications in the construction industry, including concrete materials, fire-retardant coatings, fiber-reinforced composites, and waste-immobilization solutions for chemical and nuclear sectors. Previous research suggests that geopolymer (GP) concrete possesses properties comparable to ordinary Portland cement (OPC), indicating its suitability for civil engineering applications. Geopolymer mortar presents a sustainable future by mitigating carbon dioxide emissions associated with cement production. Despite this, there is limited research on the combined effects of Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBS) under varying ambient and oven temperatures.

This study aims to investigate three primary objectives: firstly, to investigate the effect of using different minerals admixtures on the engineering properties of geopolymer mortar, secondly to investigate the effect of curing method of GM on the engineering properties of concrete, thirdly to investigate the possibility of incorporating geopolymer concrete to developed construction areas with sustainability features.

Five different mixes were prepared, each utilizing various mineral admixtures in different ratios: M20-80 (20% SF and 80% GGBS), M80-20 (80% SF and 20% GGBS), M50-50 (50% SF and 50% GGBS), MS100 (100% GGBS), MSF100 (100% SF).The curing methods for each sample were investigated separately under ambient and oven temperatures (65°C) for 7 and 28 day to determine the final values of compressive and flexural strength.

The results show that; For the 28-day ambient temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 27.9%, 26.5%, 14.5% and 72.8% higher than M80-20, M50-50, MS100 and MSF100, respectively. For the 28-day oven temperature curing method, the maximum compressive strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 61.3%, 44.3%, 26.75% and 70.2% higher than M80-20, M50-50, MS100 and MSF100, respectively. For the 28-day ambient temperature curing method, the maximum flexural strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 49.2%, 33.4%, 8.14% and 73.15% higher than M80-20, M50-50, MS100 and MSF100, respectively. For the twenty-eight-day oven temperature curing method, the maximum flexural strength values were recorded for the mix of M20-80. The compressive strength of M20-80 was 68.3%, 38.2%, 18.4% and 68.7% higher than M80-20, M50-50, MS100 and MSF100, respectively.

The results revealed that*;* The compressive strength values of the mixes of MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment compared to the same mixes cured in oven temperature. The increment in compressive strength of the ambient curing method was 14.4%, 25.8% and 46.4% for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the compressive strength value of the mix of M20-80 and MSF100 cured in oven temperature show similar compressive strength compared to the ambient temperature curing method. There is no significant change was observed in compressive strength values of the oven temperature and the ambient temperature curing method. The flexural strength values of the mixes MS100, M50-50 and M80-20 in which the curing of ambient method is used show significant increment in the flexural strength compared to the same mixes cured in oven temperature. The increment in flexural strength of the ambient curing method was 8.2%, 4% and 35.6% higher for the mixes of MS100, M50-50 and M80-20, compared to the oved curing method, respectively. However, the flexural strength value of the mix of M20-80 and MSF100 cured in oven temperature show increment compared to the ambient temperature curing method. The increment in flexural strength of the oven curing method was 3.3% and 20.2% higher for the mixes of M20-80 and MSF100, compared to the oved curing method, respectively. In summary, these results highlight the significant impact of different mineral admixtures and curing methods on the mechanical properties of geopolymer mortar, with mix M20-80 demonstrating superior performance across various condition.

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