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**MECHANICAL PERFORMANCE OF LIGHTWEIGHT
FIBER REINFORCED GEOPOLYMER MORTAR
INCORPORATING EXPANDED CLAY AT ELEVATED
TEMPERATURES**

**M.Sc. THESIS
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**BY
MAYSAM ALI AMOORI ALJANABI**

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Civil Engineering

Gaziantep University

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July 2021



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**MECHANICAL PERFORMANCE OF LIGHTWEIGHT FIBER
REINFORCED GEOPOLYMER MORTAR INCORPORATING EXPANDED
CLAY AT ELEVATED TEMPERATURES**

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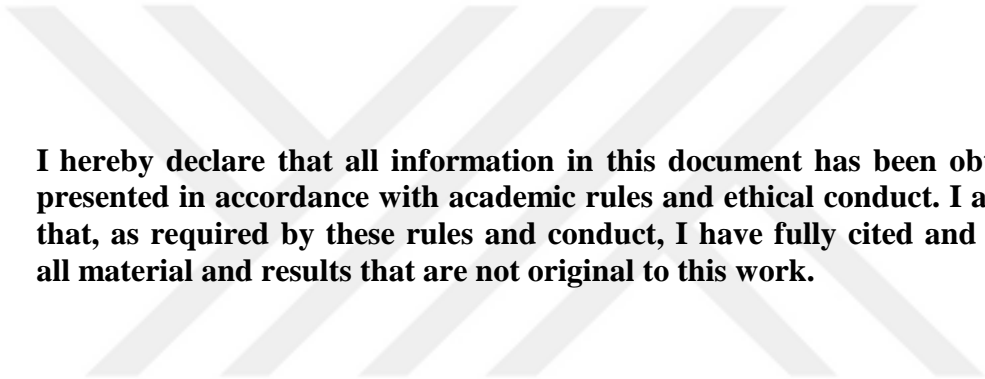
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ABSTRACT

MECHANICAL PERFORMANCE OF LIGHTWEIGHT FIBER REINFORCED GEOPOLYMER MORTAR INCORPORATING EXPANDED CLAY AT ELEVATED TEMPERATURES

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M.Sc. in Civil Engineering

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This study examines the impact of using lightweight expanded clay aggregate (LECA) and polyvinyl alcohol (PVA) fibers on the properties of lightweight geopolymer mortar. The effect of temperature level (room temperature, 250°C, and 500°C) on the mechanical properties of LWGM with and without fibers is also explored. LECA is used as a partial replacement to river sand with 60% and 80%. The base material utilized for LWGM is slag which was activated by a mixture of sodium silicate and sodium hydroxide solutions. Three different mixtures were prepared and cured at ambient temperature. The fresh properties in terms of workability and density were performed. A series of experiments, such as compression, flexural and uniaxial tensile tests were carried out to assess the mechanical properties of LWGM with and without fibers. The study found that increasing the level of LECA replacement leads to a decrease in the density and compressive strength of the LWGM. Furthermore, incorporating a 1% PVA fiber volume fraction improved the flexural, and tensile behavior of LWGM significantly. The experimental results indicated that the mechanical properties of tested samples subjected to the elevated temperatures of 500°C changed noticeably.

Keywords: Lightweight Geopolymer Mortar (LWGM), Lightweight Expanded Clay Aggregate (LECA), PVA Fibers; Elevated Temperatures, Mechanical Properties.

ÖZET

YÜKSEK SICAKLIKLARDA GENİŞLETİLMİŞ KİL İÇEREN HAFİF ELYAF TAKVİYELİ GEOPOLİMER HARCININ MEKANİK PERFORMANSI

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77 sayfa

Bu çalışma, hafif genleşmiş kil agregası (HGKA) ve polivinil alkol (PVA) liflerinin hafif jeopolimer harcın (HJH) özellikleri üzerindeki etkisini incelemektedir. Sıcaklık seviyesinin (oda sıcaklığı, 250°C ve 500°C), lifli ve lifsiz HJH'nin mekanik özellikleri üzerindeki etkisi araştırılmıştır. HGKA, %60 ve %80 oranları ile nehir kumunun kısmi ikamesi için kullanılmıştır. HGKA için kullanılan ana malzeme, sodyum silikat ve sodyum hidroksit çözeltilerinin bir karışımı ile aktive edilen cüruftur. Üç farklı karışım yapılmış ve normal oda koşullarında kürlenmiştir. İşlenebilirlik ve taze haldeki yoğunluk özellikleri ölçülmüştür. HGKA'nın lifli ve lifsiz mekanik özelliklerini değerlendirmek için basınç, eğilme ve tek eksenli çekme testleri gibi bir dizi deney yapılmıştır. Çalışmada, HGKA oranının artırılmasının, HGKA'nın yoğunluğunda ve basınç dayanımında bir azalmaya yol açtığını bulunmuştur. Ayrıca, %1'lik bir PVA fiber oranının, HGKA'nın eğilme ve çekme davranışını önemli ölçüde iyileştirdiği görülmüştür. Deneysel sonuçlar, 500°C'lik yüksek sıcaklıklara maruz kalan numunelerin mekanik özelliklerinin belirgin şekilde değiştiğini göstermiştir.

Anahtar Kelimeler: Hafif Jeopolimer Harcın (HJH), Hafif Genleşmiş Kil Agregası (HGKA), PVA Lifler, Yüksek Sıcaklık, Mekanik Özellikler



To my Father and Mother

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TABLE OF CONTENTS

	Page
ABSTRACT	v
ÖZET	vi
ACKNOWLEDGEMENTS	viii
TABLE OF CONTENTS	ix
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xv
CHAPTER 1	1
INTRODUCTION	1
1.1 General	1
1.2 Research Aim	3
1.3 Research Objectives	3
1.4 Thesis Organization.....	4
CHAPTER 2	5
LITERATURE REVIEW	5
2.1 Introduction	5
2.2 Geopolymer Technology	6
2.2.1 Geopolymer Terminology.....	6
2.2.2 Geopolymer Structure.....	6
2.2.3 Geopolymerization Reaction	7
2.2.4 Constituents of Geopolymer	8
2.2.5 Applications of Geopolymers	10
2.3 Slag.....	10
2.3.1 Production of Slag	10
2.3.2 Geopolymer binder from Slag	11
2.4 Lightweight Aggregate.....	12
2.4.1 Lightweight Expanded Clay Aggregate.....	13

2.4.2 Lightweight Expanded Clay Aggregate Production	14
2.4.3 Lightweight Aggregate Concrete.....	17
2.4.4 Lightweight Geopolymer Concrete	19
2.4.5 Lightweight Geopolymer Mortar.....	21
2.5 Polyvinyl alcohol (PVA) Fiber.....	22
2.5.1 Fiber Reinforced Geopolymer Mortar	22
CHAPTER 3	25
METHODOLOGY.....	25
3.1 Introduction	25
3.2 Materials Used.....	25
3.2.1 Slag	25
3.2.2 Aggregates	26
3.2.3 Alkaline Activator.....	28
3.2.4 Super-plasticizer (SP)	30
3.2.5 Water.....	30
3.2.6 Polyvinyl Alcohol (PVA) Fibers	31
3.3 Preparation Alkaline Activator Solution For Geopolymer.....	31
3.4 Mix Design	32
3.5 Lightweight Geopolymer Mortar Samples Preparation, Casting and Curing	34
3.5.1 Preparation of Lightweight Geopolymer Samples without Fibers	34
3.5.2 Preparation of Lightweight Geopolymer Samples with Fibers	36
3.6 Elevated Temperatures Exposure	38
3.7 Experimental Tests	38
3.7.1 Flow Table Test	38
3.7.2 Density Test	39
3.7.3 Compressive Test.....	40
3.7.4 Flexural Test	42
3.7.5 Tensile Test.....	43
CHAPTER 4	45
TEST RESULTS AND DISCUSSIONS.....	45
4.1 Introduction	45
4.2 Workability.....	45
4.3 Fresh and Dry Densities	46

4.4 Compressive Properties	48
4.4.1 Compressive Strength of Cube Samples.....	48
4.4.2 Stress-Strain Relationship of Cylinder Samples.....	52
4.5 Flexural Behavior	55
4.5.1 Load–Displacement Curves.....	55
4.6 Uniaxial Tensile Performance	60
CHAPTER 5	63
CONCLUSIONS	63
REFERENCES.....	66
CV	77



LIST OF TABLES

	Page
Table 3.1 Chemical composition of slag and LECA used	27
Table 3.2 General characteristics of LECA.....	28
Table 3.3 Chemical composition of sodium silicate	29
Table 3.4 Specification of Super-plasticizer	30
Table 3.5 PVA fiber properties	31
Table 3.6 Lightweight geopolymer mortar mix designs	33
Table 4.1 Fresh and dry density values (kg/m ³)	47

LIST OF FIGURES

	Page
Figure 2.1 Structures of poly (sialates)	7
Figure 2.2 Phases of geopolymerisation process	8
Figure 2.3 Sources of GGBS	11
Figure 2.4 Lightweight aggregates types	13
Figure 2.5 Interconnected holes and airfilled gaps of varying sizes	16
Figure 2.6 Different size of LECA grains	16
Figure 3.1 Slag used in this study	26
Figure 3.2 River sand used in this study	26
Figure 3.3 LECA	27
Figure 3.4 LECA's grain size distribution.....	28
Figure 3.5 Alkaline Activator.....	29
Figure 3.6 Super-plasticizer used in this study	30
Figure 3.7 PVA fibers used in this study	31
Figure 3.8 Preparation of alkaline solution	32
Figure 3.9 Mixing, casting and curing of samples without fibers.....	36
Figure 3.10 Mixing, casting and curing of samples with fibers.....	37
Figure 3.11 Electric oven used in this study	38
Figure 3.12 Flow table test of lightweight geopolymer mortar.....	39
Figure 3.13 Measuring the weight of samples by using a digital balance	40
Figure 3.14 Compression test of a cube specimen	41
Figure 3.15 (a) Compression test of the cylinder specimen; (b) Sulfur capped samples before compression test.....	42
Figure 3.16 Test setup for flexural strength	43
Figure 3.17 (a) Tensile test setup; (b) Dimensions of the dogbone specimens.....	44
Figure 4.1 Measurement of flow diameter of (a) 60%EC ; (b) 80%EC ; (c) 80% EC-1%PVA.....	46
Figure 4.2 Flow table results	46

Figure 4.3 Compressive strength of LWGM at different ages	49
Figure 4.4 Compressive strength results before and after exposure to elevated temperatures	51
Figure 4.5 Failure modes of cube samples after compression test. (a) 80%EC ;(b) 80%EC-1%PVA	51
Figure 4.6 Failure characteristics of samples after subjected to 250°C. (a) 60%EC ; (b) 80%EC ; (c) 80%EC-1%PVA.....	52
Figure 4.7 Stress-strain curves of cylinder samples at different temperatures.....	53
Figure 4.8 Failure patterns of cylinder samples under different temperatures (RT: Room temperature)	54
Figure 4.9 Load-displacement curves of the prism samples under different temperatures	56
Figure 4.10 Flexural failure modes of prism samples at different temperatures (RT: Room temperature)	58
Figure 4.11 Load-displacement curves of the beam samples at different temperatures	59
Figure 4.12 Flexural failure patterns of beam samples: (a) without fibers and (b) with 1% PVA fibers	60
Figure 4.13 Tensile stress-strain curves of dogbone specimens after exposure to different temperatures	62
Figure 4.14 Tensile failure modes of dogbone sample (a) with fibers ; (b) without fibers	62

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
FA	Fly Ash
GGBS	Ground Granulated Blast Slag
LWA	Lightweight Aggregate
LWGM	Lightweight Geopolymer Mortar
LECA	Lightweight Expanded Clay Aggregate
PVA	Polyvinyl Alcohol
LWGC	Lightweight Geopolymer Concrete
OPC	Ordinary Portland Cement
GPC	Geopolymer Concrete
CO₂	Carbon Dioxide
NaOH	Sodium Hydroxide
Na₂SiO₃	Sodium Silicate
Al	Aluminum
Si	Silicon
KOH	Potassium Hydroxide
K₂SO₄	Potassium Silicate
CaO	Calcium Oxide
Na₂O	Sodium Oxide
SiO₂	Silica (Silicon Oxide)
Al₂O₃	Alumina (Aluminum Oxide)
L.O.I	Loss of Ignition
SP	Super-plasticizer
M	Molarity
<i>f_c</i>	Compressive Strength
°C	Degree Celsius
LVDT	Linear Variable Displacement Transducers

CHAPTER 1

INTRODUCTION

1.1 General

Environmental pollution has been seen as the biggest challenge facing humanity today. Pollution of the environment involves the addition of impurities into the atmosphere. This type of pollution adversely affects the ecosystem. There are several factors that contribute to pollution. In the construction sector, the main component for making concrete is cement. Nevertheless, the manufacture cement production consumed large amounts of energy and resources as well as released a lot of greenhouse gas emissions, resulting in environmental pollution. Actually, it has been stated that Ordinary Portland cement (OPC) manufacturing emitted approximately 5-7% of total carbon dioxide (CO₂) emissions into the atmosphere. Thence, a rise in CO₂ emissions leads to global warming, which is an unwelcome critical problem that has considerable influence on the future of human beings (Bidwe and Hamane, 2015).

Therefore, the cement industry has been working to find an alternative to traditional OPC. Furthermore, huge amounts of industrial wastes are created worldwide. Most of these wastes are unused or underused. Owing to the limited landfills capacity and unregulated disposal of these wastes, environmental problems are caused. The proper use of such industrial wastes has many benefits, such as enhancing the protection of natural resources and addressing waste management problems. So, industrial by-product like ash fly ash (FA) and ground granulated blast slag (GGBS), silica fume, etc, were used as a substitution for OPC (Islam, 2014).

Geopolymer concrete, with the utilize of industrial by-product, has been considered perfect alternative material for achieving environmentally sustainable concrete. GPC has good mechanical strength, high resistance to chemicals, and excellent resistance to heat. It has been reported that the use of GPC to substitute to OPC concrete reduces CO₂ emission by 25% to 50% and up to 80% (Zhang, 2015). GPC is formed by the reaction amongst alkali solution and raw materials which are rich in silicon

(Si) and aluminum (Al). Several industrial by-products have been used as raw materials for making geopolymer such as FA, GGBS, and metakaolin. The selection of these raw materials in the manufacture of GPC depends on the availability of these materials, cost, and kind of application.

GGBS and FA are the mostly used raw materials of alumina-silicate binders because they having soluble silica and alumina species. GGBS is a waste material that is plentiful all over the world. The efficient use of GGBS in the production of geopolymers leads to a reduction in the carbon footprint of concrete manufacturing. As well as, It has been found that GGBS manufacturing requires less energy compared to the same amount of ordinary cement manufacturing (Hassan and Shariq, 2019).

Recently, using lightweight aggregate (LWA) in GPC production has been observed. The utilize lightweight aggregate in GPC provides several advantages such as minimizing the structural dead load, saving energy, reducing costs, improving thermal insulation for buildings. So, lightweight aggregate has been considered as an effective way to enhance concrete performance. Many LWGC was produced using either natural aggregates or artificial aggregates. Artificial aggregates could be produced from natural sources such as clay or waste materials such as fly ash (Wongsa et al., 2018).

Expanded clay aggregate (ECA) is a kind of lightweight aggregate that is created artificially. LECA has become more prevalent because clay, which is widely available, is the raw material used for manufacturing. As well, LECA has high strength among lightweight aggregates. LECA is formed by burring clay at temperatures ranging from 1100 to 1300 °C to make lightweight, porous grains with different sizes. LECA has been used in different fields such as construction, water treatment, and agriculture, because of its high technical characteristics and various advantages. LECA is used as an alternative to fine and coarse aggregates or both of them in geopolymer concrete (Vijayalakshmi and Ramanagopal, 2018).

Geopolymer concrete has some drawbacks, such as low tensile strength, low fracture toughness, and large shrinkage that prevent its significant utilization in practice. GPC is well-known to be brittle as well. In order to address these limitations, different approaches have been proposed. One of the best efficient methods is to utilize fibers.

The incorporation of fibers to geopolymer has been altered its brittle behavior to ductile with enhancement in toughness, tensile strength, and flexural strength (Singh and Middendorf, 2020). Nonetheless, fibers can have various impacts on the mechanical characteristics of GPC, and this depends on its kind, length, and content. There are several kinds of fibers. Polyvinyl alcohol (PVA) fibers have gained attention in several studies due to their high tensile strength and elastic modulus. As well as, PVA fiber has good merit which is that it could survive in an alkali environment (Zahid et al., 2020).

In this study, slag was used as source material activated by the combination of NaOH solution and sodium silicate as an alkaline activator. River sand was replaced by LECA at 60% and 80%, by weight. PVA fibers were incorporated at 1%, by volume to strengthen geopolymer mortar containing 80% LECA. Fresh properties including the flow table test and fresh density were performed. A number of experiments were conducted to investigate the mechanical properties of lightweight geopolymer mortar before and after exposure to elevated temperatures of 250 °C and 500 °C.

1.2 Research Aim

The aim of this study is to manufacture lightweight geopolymer mortars utilizing lightweight expanded clay aggregate (LECA) and geopolymer binder made by the activation of slag as the sole source material. Furthermore, this study was conducted to enhance the strength and ductility of lightweight geopolymer mortar samples by the use of Polyvinyl alcohol (PVA) fibers. Also, this study aims to understand the mechanical performance of LWGM with and without fibers after exposure to elevated temperatures.

1.3 Research Objectives

The following objectives have been set to achieve the goal of the project:

1. Conduct a detailed search review on geopolymer and lightweight geopolymer concrete and mortar as well as highlighting the use of PVA fibers.
2. Explore the reasons for the production of lightweight geopolymer mortar and identify the methods followed to improve its performance.
3. Study the impact of using LECA as a fine aggregate in the production of geopolymer mortar by conducting several tests such as flow table test, density, compressive test, flexural test, and tensile test.

4. Investigate the influence of the incorporation of PVA fiber as reinforcement in the geopolymer mortar containing LECA.
5. Conduct a series of experiments to examine the effect of elevated temperatures on the mechanical properties of lightweight geopolymer mortars with and without the presence of fibers.

1.4 Thesis Organization

This thesis includes general, literature reviews, methodology, results, and analysis from laboratory investigations. Five chapters compose this thesis. The contents of each chapter are summarized below:

Chapter 1: It covers briefly general information on geopolymer concrete. The aims and objectives of the study were then presented.

Chapter 2: It includes a literature review about geopolymer in terms of its terminology, structure, constituents, and applications. A comprehensive review of previous studies on lightweight aggregate concrete, lightweight geopolymer concrete, and mortar. A brief review of fiber reinforced geopolymer mortar is also presented.

Chapter 3: The experimental program carried out during this study is included in this chapter. It displays the materials that used in this study, mix proportions, preparation of specimens as well as testing procedures.

Chapter 4: The results of the experimental work are presented and discussed in this chapter. The effect of PVA fibers and elevated temperatures on LWGM is also included.

Chapter 5: The conclusions drawn from the experimental work of the present study are presented in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is one of the most widely utilized construction materials in worldwide. Ordinary Cement has been conventionally utilized as the essential binder for concrete manufacturing and the demand for OPC continues increasing because of continuous urban growth all over the world (Taylor et al., 2006). But, OPC production emits considerable amounts of carbon dioxide (CO₂) into the atmosphere that cause environmental issues such as universal climate change. Around one ton of CO₂ is released into the atmosphere when producing one ton of Portland cement (Lawrence, 1998).

On the contrary, it has been demonstrated that by-product materials such as slag emit up to 80 percent lower greenhouse emissions than OPC manufacture (Roy & Idorn, 1982) and 80 to 90 percent lower greenhouse emissions are emitted in fly ash manufacture (Duxson et al., 2007). So, utilizing slag or FA as a full substitution of Portland cement would notably cut down on CO₂ emissions of concrete manufacture.

In order to develop a new binder as an alternative to traditional cement, numerous researches have been carried out. One of the best substitutes is geopolymers which could be produced by the alkali activation of various by-product materials like slag or FA (Davidovits, 1991). In recent years, the utilize of geopolymer concrete has gained significance in building due to its excellent mechanical strength, good fire resistance, economic benefit, and low CO₂ emissions.

This chapter provides a literature review of geopolymer in terms of terminology, structure, basic components, and common applications, and lightweight concrete and mortar. Also, a literature review on geopolymer mortar incorporating polyvinyl alcohol (PVA) fibers is displayed. Materials utilized in this study like slag, lightweight expanded clay aggregate, and PVA fibers are mentioned.

2.2 Geopolymer Technology

2.2.1 Geopolymer Terminology

Geopolymer is a common term utilized to represent a wide variety of aluminosilicate products manufactured with various formulations at different curing conditions. Geopolymer has been applied in different fields. For instance, concrete infrastructure, agriculture, ceramics, and fire-resistant materials.

Geopolymer is manufactured from a broad range of aluminosilicate materials under various curing regimes. The aluminosilicate sources which are affluent in silica and alumina might be by-product materials such as FA and slag or natural materials such as calcined clay (Shayan, 2016).

Geopolymer technology has been presented in the 1970s by Prof. Joseph Davidovits to describe a large variety of inorganic substances. There are nine geopolymer classes, but classes that are of special interest consist of aluminosilicate materials. It could be utilized as a substitution to cement in diverse infrastructure applications (Davidovits, 2005). These geopolymers are formed by mixing aluminosilicate materials with an alkaline solution in order to produce source silicon and aluminum that polymerizes to form molecular bonds and end up the binder. Such materials are commonly known as alkali activated cements or inorganic polymer cements (Rana et al, 2014).

2.2.2 Geopolymer Structure

In order to describe the chemical designation of geopolymers, Davidovits (1988) introduced the term “poly-(sialate)” where sialate is an abbreviation for Silicon-oxo-Aluminate. The sialate network comprises SiO_4 and AlO_4 tetrahedral connected by sharing oxygen atoms.

Based on Davidovits (2008), the proportion of Si to Al (Si/Al) has a considerable effect on the geopolymer structure. The geopolymer materials widely used in concrete applications usually have a Si to Al ratio of 2 to 3.5. According to the ratio of Si to Al, the structure of the geopolymer can be classified into three fundamental forms, as illustrated in Figure 2.1 (Davidovits et al., 2012).

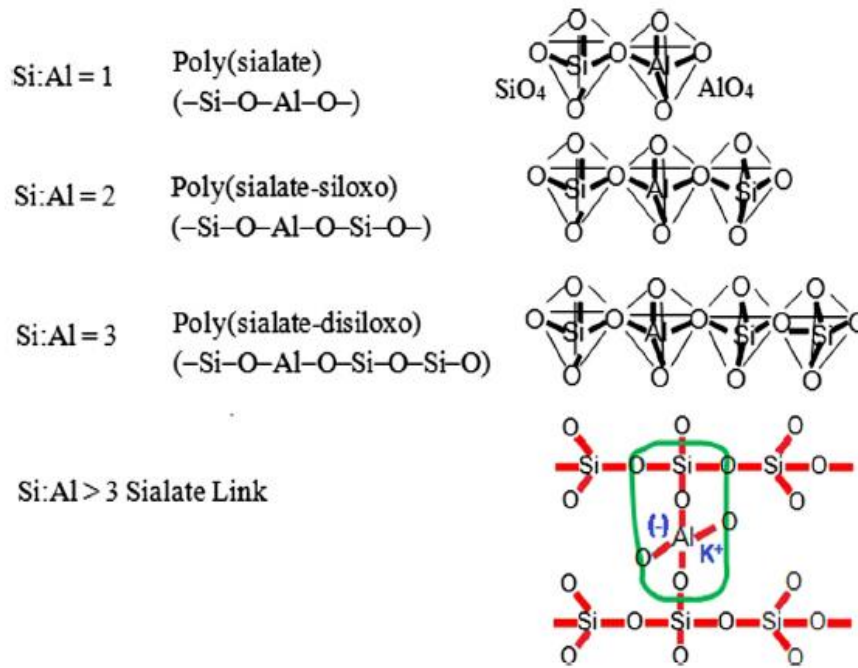


Figure 2.1 Structures of poly (sialates) (Liew et al., 2016)

2.2.3 Geopolymerization Reaction

Geopolymerization is considered an advanced technology able of transforming many alumino-silicate materials into beneficial products known as geopolymers (Dimas et al., 2009). The process of geopolymerization involves a chemical reaction between alkaline solution and raw material rich in Si and Al which can take place at ambient temperature. Geopolymerization is considerably various from the hydration reactions in cement-based materials.

As reported by Davidovits (1999), geopolymerization can generally be partitioned into three fundamental steps:

- Dissolution of alumino-silicate oxides from raw material in alkaline solution.
- The dissolved oxide ions can be transformed into monomers to form a gel.
- Poly-condensation to create a three-dimensional aluminosilicate network.

These three phases may take place simultaneously and can overlap with each other, as stated by Palomo et al. (1999). The process of geopolymerization is shown in Figure 2.2.

There are several elements that play a significant role in geopolymerization process, such as the physical and chemical characteristics of raw materials having aluminosilicate, the ratio of alkaline solution to raw material, and the type of alkaline solution (Diaz et al., 2010).

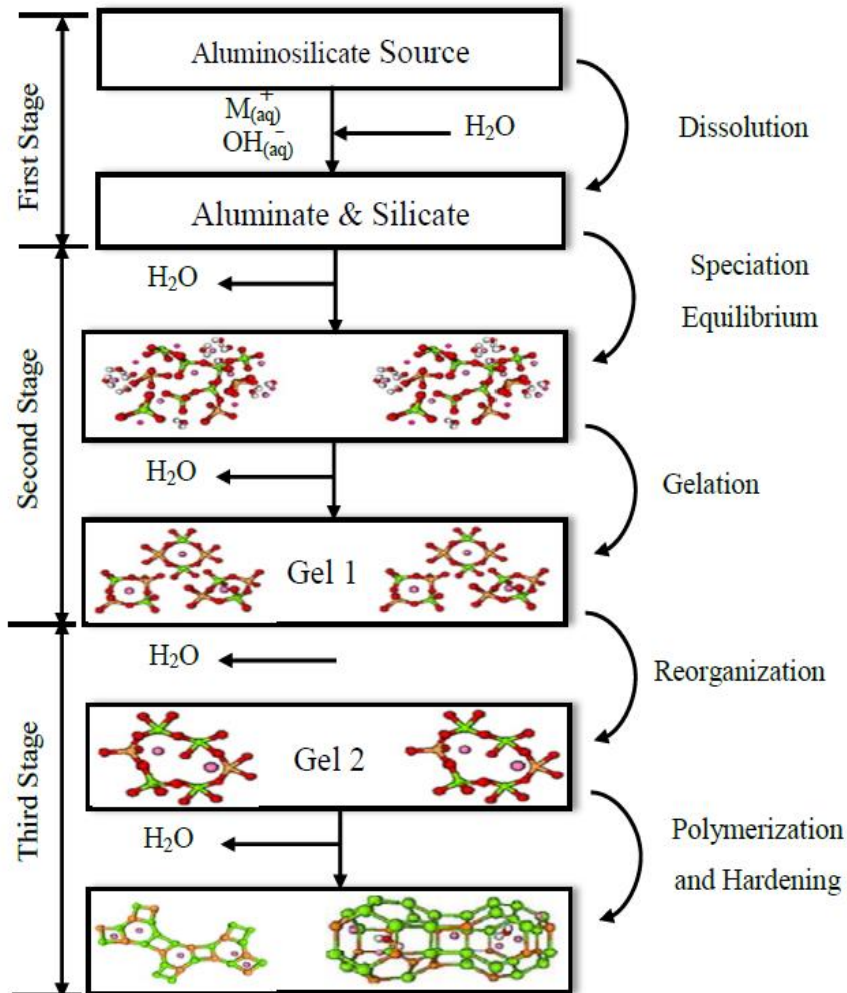


Figure 2.2 Phases of geopolymerisation process (Duxson et al., 2007)

2.2.4 Constituents of Geopolymer

2.2.4.1 Source Materials

In general, any material containing silica (SiO_2) and alumina (Al_2O_3) can be utilized as raw material for producing geopolymer. The source materials can be referred to as precursors or raw materials. There are numerous materials that have been used in past to make geopolymer. These may be natural materials like kaolinite and clays or by-product materials like fly ash (FA), red mud, and slag. Recent studies focus more

on using by-products material as raw material and FA and slay are the most common materials used in geopolymer. In this research, slag has been used as source material. The source materials can be used as a single material or a combination of different materials. The selection of source materials for synthesizing the geopolymer primarily relied on a variety of factors such as availability, cost, application nature, and particular end-user request (Rangan, 2008).

Based on the source materials used in geopolymer manufacturing, geopolymers show a variety of characteristics and properties which lead them to be appropriate for different applications (Van Jaarsveld et al., 2003). The source materials have been reported to play a significant role in the geopolymerization process, the chemical composition control, and the microstructure of the resulting geopolymers. The difference between the materials in terms of their amorphous phases, ability to dissolve in an alkaline solution, and the Si to Al ratio resulted in variability in mechanical characteristics and curing period of geopolymers (Photisan et al., 2018).

2.2.4.2 Alkaline Activators

Any strong alkaline solution can be utilized as an alkaline activator to make a geopolymer. A single type of alkaline activator or a combination of various alkalis may be utilized. However, the most generic alkali activators that have been used to activate aluminosilicate materials is a mixture of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate solution (Na_2SiO_3) or potassium silicate solution (K_2SiO_4) (Davidovits, 1999) Because of its improvement in the reaction amongst the raw material and the solution, NaOH blended with Na_2SiO_3 solution is the most effective alkaline activator. There are some factors that affect the selection of the alkaline activator such as the cost and reactivity of the alkaline activator.

Several studies have been reported that the type of alkali liquid plays a significant role in geopolymerisation reaction. For example, Fernández-Jiménez and Palomo (2005) examined the impact of three forms of alkali solutions which are NaOH, Na_2CO_3 , and Na_2SiO_3 in geopolymerisation. It has been found that the strength of GP produced using NaOH is greater than that of geopolymer produced using Na_2SiO_3 or Na_2CO_3 . They demonstrated in their research that the quantity of sodium

oxide (Na_2O) in the mix had an important impact on geopolymer's strength. They concluded that geopolymer with higher Na_2O showed higher compressive strength.

2.2.5 Applications of Geopolymers

Geopolymers have many excellent properties including long-term durability, high early strength, low energy consumption, and low CO_2 emissions. All of these properties allow the widespread use of geopolymer in many applications as an alternative to OPC.

Geopolymer concrete (GPC) can be used in the precast industries to produce railroad sleepers, sewer piping, and other elements of pre-stressed construction. This is mostly because of the early strength advantage provided by GPC (Cheema et al., 2009).

Owing to the high resistance of geopolymer concrete to chemical attacks, it is ideally suited for use in aggressive environments such as sewage systems.

In addition, geopolymers can immobilize hazardous waste or radioactive waste, as toxic chemical waste can be consumed and solidified. This is mainly because geopolymer has a molecular structure similar to zeolitic materials (Desbats et al., 2011).

Geopolymer materials applications can be classified depending on the atomic ratio of silica to alumina (Si: Al) in the poly-sialate. A low Si to Al ratio (1,2 or 3) initiates a very rigid 3D-Network, while a Si to Al ratio greater than 15 creates the geopolymeric material with a polymeric character. A low Si to Al ratio is appropriate for several applications in the fields of civil engineering (Davidovits, 1999).

2.3 Slag

2.3.1 Production of Slag

Ground granulated blast slag (GGBS) or usually called slag is a waste material resulting from the iron industry. This material is produced in the furnace when iron ore, coke, and limestone are melted with each other at a high temperature of about 1600°C (Figure 2.3). The molten slag that floats on the top of the pig iron is chilled quickly after it leaves the blast furnace in large amounts of water. Granulated slag is the resulting material that is desiccated and ground into a fine powder is called as ground granulated blast slag. (Suresh and Nagaraju, 2015).

Slag or GGBS is a glassy granular material primarily composed of SiO_2 , CaO , and Al_2O_3 . Slag is a useful by-product that could be utilized in the production of both aggregate and concrete (Kumar et al., 2010).

GGBS has been categorized into three various grades, as stated in ASTM C989-99. The three grades are 80, 100, and 120. This classification is made based on the slag activity index (SAI).

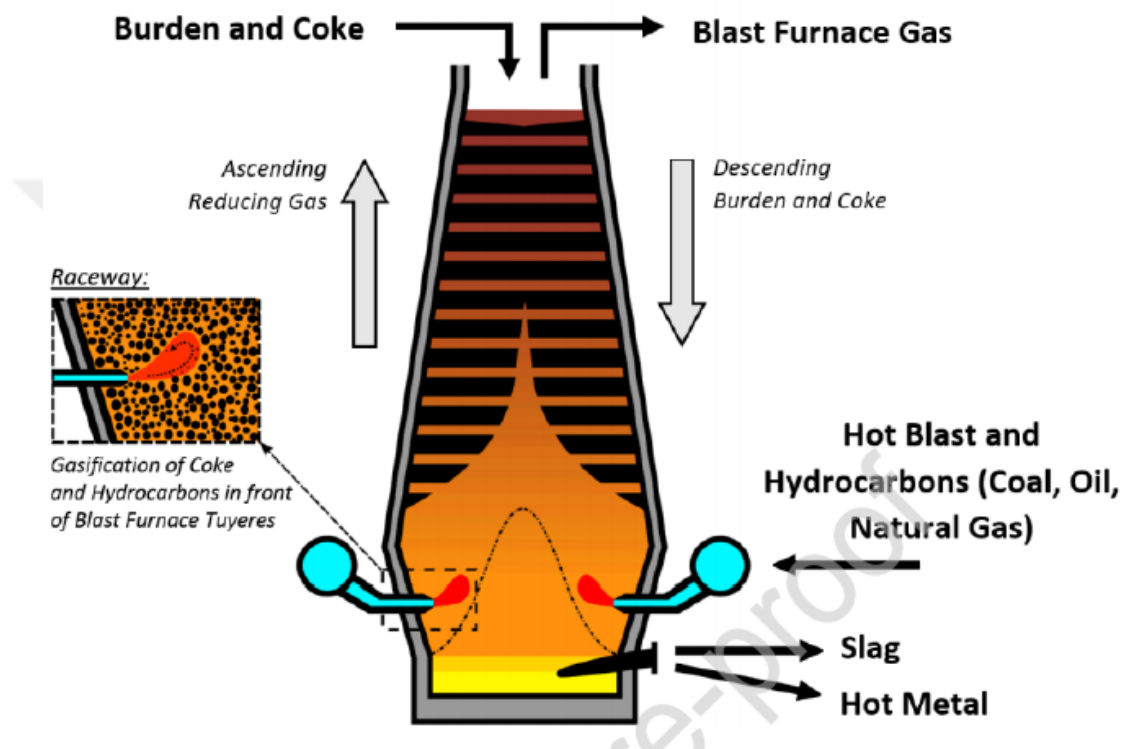


Figure 2.3 Sources of GGBS (Amran et al., 2020)

2.3.2 Geopolymer binder from Slag

Slag is an aluminosilicate material. The components of slag are alumina, silica, and calcium oxide which are the same oxides that form ordinary cement. So, slag has can be used as an alternative material for OPC. In general, the use of slag leads to low cost, energy-saving, and low environmental effects.

Slag has been successfully used as source material to synthesize geopolymer. In the manufacture of geopolymer concrete, the aluminum and silicon that exists in the slag are activated by the alkaline solution to make the geopolymer paste which connects the aggregates (Islam et al., 2014).

From the past research, it was found that slag-based geopolymer concrete performance is better at both elevated and ambient temperature curing. Geopolymer concrete made with slag at ambient temperature curing exhibits excellent mechanical strength even at an early age and good chemical attack resistance (Arioz et al., 2020). In addition, there are various studies have included slag as a precursor for producing geopolymer mortars with high compressive strength. For example, Omer et al. (2015) introduced slag-based geopolymer mortar (sand/slag ratio = 2.75) that had a strength of 47 MPa at 7 days utilizing Na_2SO_3 and NaOH as the alkaline activator.

Oh et al (2010) investigated the comparison between slag and fly ash (FA). They reported that calcium (Ca) in slag is more reactive than calcium in fly ash class F because the ability of the Ca in slag to dissolve in the alkaline activator is easier than the Ca in such a kind of FA. Moreover, slag requires a much lower concentration of alkaline activator than fly ash, as reported by Rakhimova and Rakhimov (2015). This is one of the benefits of using slag since alkaline activator is costly.

2.4 Lightweight Aggregate

Aggregate is the main ingredient of the concrete system since it occupies a high volume of it. So, aggregate has an important impact on its properties. Fresh and hardened properties of concrete are significantly affected by the type of aggregate.

In general, aggregates can be divided into two types depending on the aggregate source: natural or artificial aggregates. However, in terms of their unit weights, aggregates also are classified as normal-weight, heavyweight, and lightweight aggregates (Aşık, 2006).

Lightweight aggregate (LWA) is classified as a building material with a lower bulk density than the normal building aggregate. One of the common ways of producing lightweight construction materials is the use of lightweight aggregate. Utilizing lightweight aggregate (LWA) has been considered to be an efficient method for developing concrete's functional performance. Lightweight aggregate concrete (LWAC) has several advantages that overstanding normal weight concrete such as decreasing the structure's self-weight, improving sound and thermal insulation, and reducing transport costs. Owing to these advantages, Lightweight aggregate concrete has been widely utilized in the construction of pavement, concrete precast units,

bricks, and blocks. As well, LWAC is favored used in the construction of buildings in seismic zones because of its low weight (Mouli and Khelafi, 2008).

Lightweight aggregates (LWA) are categorized as natural and artificial aggregates. Natural aggregate can beget from the volcanic rock like pumice aggregate. Artificial aggregate can be manufacture from a natural source such as clay and slate or could be obtained from byproduct materials such as fly ash, water glass, etc. (Kumar and Arunakanthi, 2018). Figure 2.4 briefly illustrates kinds of lightweight aggregates. Using artificial aggregates leads to minimize the consumption of natural aggregates and may contribute to the protection of the ecosystem. It has been noted that the type of lightweight aggregate has a major effect on the density, and therefore on the concrete's mechanical properties. Natural and artificial aggregated which used in the concrete must comply with ASTM C330. Lightweight expanded clay aggregate is the dominant lightweight aggregate commonly used in the manufacture of lightweight concrete.

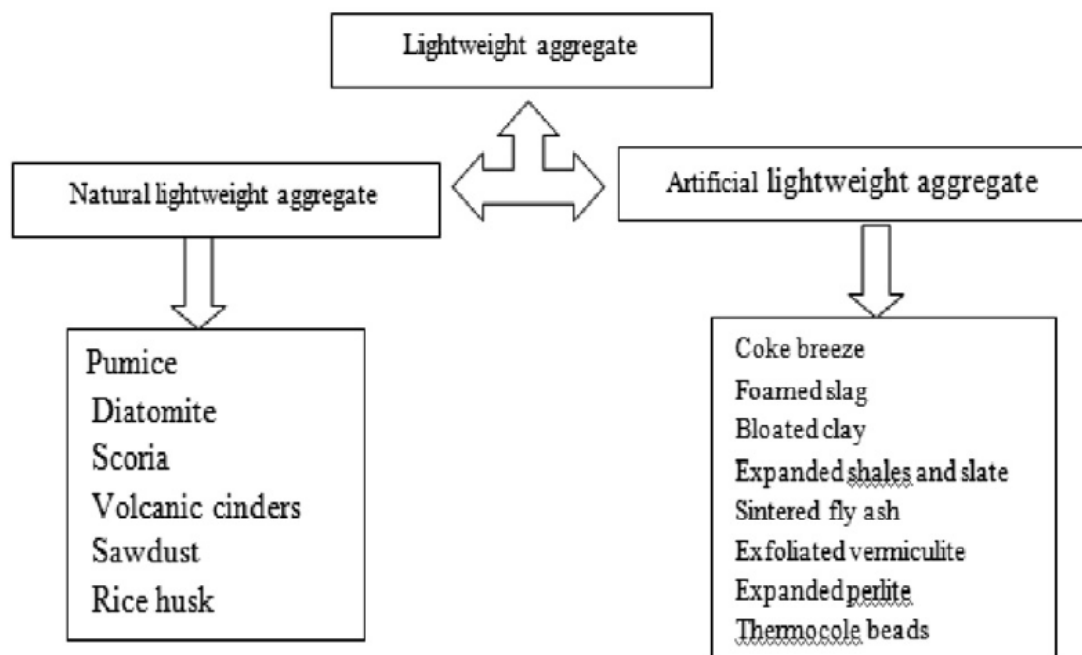


Figure 2.4 Lightweight aggregates types (Priyanka et al., 2020)

2.4.1 Lightweight Expanded Clay Aggregate

Lightweight expanded clay aggregate is a type of artificial lightweight aggregates obtained from natural clay. As the abbreviation for lightweight expanded clay aggregate, LECA was used. Unlike other industrial raw materials, LECA has been

used in several various industries because of its technical characteristics and various merits. LECA is one of the materials with the highest compressive strength when compared to other lightweight aggregates. Therefore, LECA has a substantial role in the building industry. Buildings having lightweight expanded clay aggregate may save 20% of steel reinforcement and can save up to 50 percent of heating and cooling costs. In order to improve the concrete properties, expanded clay was used in the mixture due to its desirable insulation properties (Vijayalakshmi and Ramanagopal, 2018).

LECA is a lightness material that has no harmful materials. Lightweight ECA exhibits several advantages such as excellent fire resistance, outstanding characteristics of thermal and sound insulation, resistant against crushing, high chemical and humidity resistance, non-biodegradable and , non-water-damage. Besides that, it has a natural pH value of almost 7 (Rashad, 2018).

LECA is an excellent versatility substance which can be used in many applications. For instance, LECA has been commonly used as a raw material in the production of lightweight bricks, concrete, and precast in the building industry. In the field of water treatment, it can be utilized for the liquidation and purging of potable water by removing fluoranthene and phenanthrene from water (Nkansah et al., 2012). Also, LECA has been used in the agricultural sector for the treatment of agricultural wastewater where it has shown an excellent ability to extract various pollutants, including polyphenols pharmaceuticals, and pesticides from agriculture waste water (Dordio and Carvalho, 2013). Furthermore, LECA can drain underground water and surface water in order to control the underground water pressure.

2.4.2 Lightweight Expanded Clay Aggregate Production

Lightweight expanded clay aggregate has been manufactured in more than twenty countries with different product names. Relying on the producing countries, LECA also has other distinct patented names such as “kermazite”, “Liapor ” and “Argex” (Othman et al, 2020).

The manufacturing of LECA began in 1917 in Kansas City in the united states. LECA was made of clay with particular characteristics without or with low lime content. In rotary kilns with temperatures ranging from 1100 to 1300 degrees centigrade, clay is desiccated, heated, and firing. Gas is emitted within the pellets

during heating and trapped in them during cooling. However, organic compounds in the clay burned off cause the pellets to expand creating ceramic pellets which are porous, lightest and have a neutral pH value, and are not biodegradable. LECA particles could be expanded to 5-6 times the volume (Ozguven and Gunduz, 2012). The circular movement of the kiln leads to LECA having spherical shapes. There are holes of various sizes within LECA grains that are often interconnected, as illustrated in Figure 2.5.

Each type of LECA has various structures and geometry. This depends mainly on the manufacturing method of LECA. The increase in temperature during sintering contributed to an increase in the total porosity and creating continuous pores. Furthermore, A more increase in temperature above the range of pyro-plasticity causes decreasing porosity and the size of the pore (Ayati et al., 2018). LECA is composed of spherical pellets showing a vesicular texture when broken open. Generally, LECA could be dark brown or reddish, or brown-red colors. However, there are also yellow or black available. It has been found that these variations in LECA colors may be related to LECA chemical composition varieties and their manufacturing process.

The size of the manufactured LECA varies from 0 to 25 mm and can be used as fine aggregate or coarse aggregate or both (Figure 2.6). The existence of multi-separated air spaces within and between the aggregates has been contributed to the lightness of LECA. It has been reported that, depending on its size, the bulk density range for LECA is 160-850 kg/m³ (Vijayalakshmi and Ramanagopal, 2018). One advantage of using LECA is that has different densities. This is because it makes it appropriate for structural and non-structural lightweight concretes.

The chemical composition of LECA has been shown to consist primarily of silicon dioxide, aluminum oxide, ferric oxide, calcium oxide, and some alkalis, like sodium oxide and potassium oxide. It has been found that LECA has a variety of significant physical characteristics. LECA has been stated to have thermal conductivity ranging from 0.097 to 0.123 W/m K (Rashad, 2018).

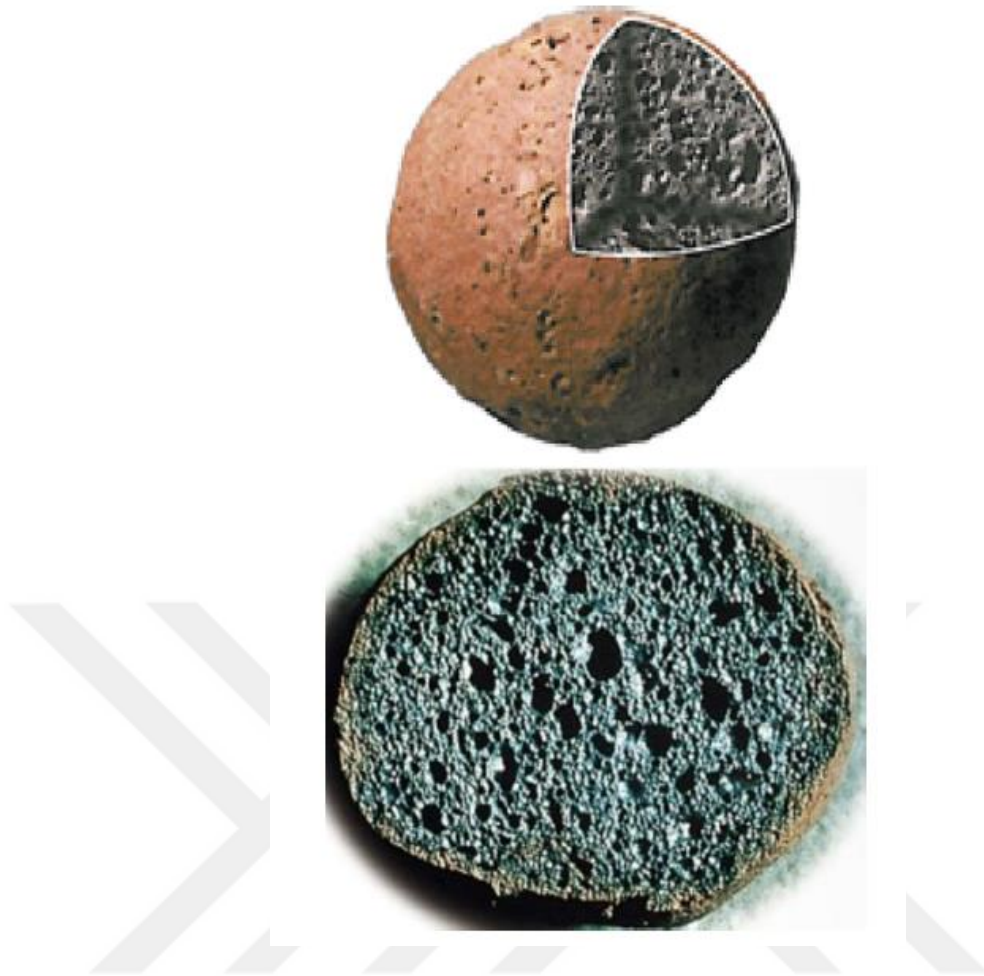


Figure 2.5 Interconnected holes and airfilled gaps of varying sizes (Rashad, 2018)



Figure 2.6 Different size of LECA grains (Rashad, 2018).

2.4.3 Lightweight Aggregate Concrete

In general, conventional concrete has a density ranging from 2200 kg/m³ to 2600 kg/m³. Low strength-to-weight ratio is considered as one of the demerits of concrete. Taking the self-weight of the structure into account is significant. One of several ways to overcome this issue in structural applications is by using lightweight concrete (LWC). Utilizing LWC allows resilience in the design, lessen the dead load and less cost as well as low reinforcing steel (Azizul, 2014).

According to ACI committee 231, lightweight concrete can be classified into three different types of division according to strength and density. These are : Low-density concrete (0.7-7) MPa and density between (300-800) kg/m³, Moderate-strength concrete (7-14) MPa and density between (800-1350) kg/m³, and Structure concrete (17-63) MPa and density between (1350-1920) kg/m³.

There are three distinct methods that have been adopted to produce lightweight concrete which are foam concrete, lightweight aggregate concrete, and no-fine concrete (Priyanka et al, 2020).

However, lightweight aggregate has been considered the commonly method utilized to produce LWC. Utilizing LWA led to a reduction in the unit weight of concrete and an improvement in its thermal and sound insulation. Lightweight aggregate concrete (LWAC) has been produced by using natural lightweight aggregate or artificial manufactured lightweight aggregate using natural sources or byproducts (Ahmad and Chen, 2019). LWAC is manufactured by completely or partially replacing normal aggregates with lightweight aggregate in a concrete mixture.

Lightweight expanded clay aggregate is one of the artificial aggregates produced from natural clay. LECA has been used in many applications in the construction sector due to its properties. Among lightweight aggregates, expanded clay is considered to be ideal for use in structural elements because of its Lightweight and reasonable strength.

There are a variety of publications relating to the use of expanded clay as building material. The aim of these publications was to replace normal weight aggregates with expanded clay aggregate fully or partially in concretes.

Wegian (2012) studied the effect of utilizing LECA as fine and coarse on the workability of concrete. Different LECA grades of 2-4, 4-8, and 8-20 mm were used. It was found that mixtures having LECA was more workable compared to those having normal aggregate, sand as fine aggregate, and gravel or dolomite as coarse aggregate. The slump of LECA mixtures ranged from 112 to 114mm, while it ranged from 58 to 78 mm in those having normal aggregates.

Adrakani and Yazdain (2014) conducted a study on concrete containing various sizes of expanded clay ranging from 4 to 14 mm. They showed that smaller LECA contributes to a higher density where the density was ranging from 480 to 1100 kg/m³. The density relies on the particle size of LECA. In addition, the results illustrated that the relationship between the density of LECA and the modulus of elasticity is linear. LECA density increased as the modulus of elasticity increased.

The study carried out by Rajprakash and Krishnamoorthi (2017) has been investigated the impact of partial substitution of coarse aggregate by LECA in concrete. Natural aggregates have been partially replaced by 20%, 40 %, 60%, 80%, and 100% utilizing LECA. They found the highest compressive strength was 29.89 N/mm² at 20% LECA substitution at 28-day.

Chetan (2018) manufactured lightweight concrete containing LECA to examine its fresh and hardened characteristics. In this study, the coarse aggregate was partially replaced with LECA at 25% and 50%. The size of the LECA particles was between 12 to 15 mm. The findings stated that the strength of lightweight concrete decreases as the proportion of LECA substitution increases.

Another study was also conducted to examine the effect of partial replacement of coarse aggregate by LECA on concrete performance, evaluated by Patel et al (2019). In this study, the coarse aggregate was replaced by LECA at various proportion from 0-100%, with 25% increments in order to investigate the impact the compressive strength, flexural strength, and split strength. After the experiments were conducted, the findings illustrated that compressive strength decreased with an increase of the LECA content. After 28-day, They noted that at 100 % substitution, a weight decrease of about 28%, reflecting a reduction in compressive resistance of about 17 percent, split strength of about 17.20 percent, and flexural strength of about 13.29 percent. The optimum percentage of replacement was 25% where was a negligible

loss of strength was observed. In order to change the mechanical characteristics of concrete having expanded clay, materials such as slag, FA, polypropylene fiber, steel fiber could be utilized to improve its strength.

Lightweight aggregate concrete has good fire resistance, as noted above. So, many studies have been performed. One of them, the study performed by Abdeen and Hodhod (2010). They manufactured lightweight concrete by substituting fine and coarse aggregates with LECA. LECA particles have a maximum size of 25mm and contain a ratio ranged from 40% to 50% size of 2.4-4.76 mm. Normal concretes and lightweight concretes containing LEAC have been exposed to 400 C for 1 hour and then tested in order to obtain residual compressive strength. The findings showed that concrete containing LECA can sustain a residual strength of 80%, whereas concrete containing normal weight aggregate can preserve only 50% of its original strength.

Many studies have showed that lightweight concrete has a strong resistance to chemicals. Motamednia et al (2013) examined the durability of standard concrete and lightweight concrete made from LECA (sizes 2-4mm and 4-12mm) against chemical attacks. Lightweight concrete and standard concrete were subjected to three acids: 15% Hydrochloric and 5% Lactic for three months and 5% Sulfuric for six weeks. According to the findings, LECA-containing concretes were more resistant to hydrochloric and lactic acid than standard concretes. In different ways, lightweight concretes demonstrated low resistance to sulfuric acid compared to normal concretes.

In addition, several studies have been conducted to enhance some of the characteristics of LECA matrices by incorporating materials such as fibers. For example, Hassanpoue et al (2014) investigated the effect of adding steel fibers to lightweight concrete containing LECA (maximum size 12.5 mm) as coarse aggregate on its mechanical properties. Their results showed that adding steel fiber (0.25 - 1%, by volume) improved compressive strength, splitting strength, and flexural strength by 14 to 32%, 21 to 77%, and 6 to 69% respectively.

2.4.4 Lightweight Geopolymer Concrete

Geopolymer has become an acceptable alternative to OPC concrete, due to its advantages. Using lightweight aggregate rather than natural aggregate in geopolymer contributes to a lower concrete density. Lightweight geopolymer concrete is an advanced material that combines the merits of lightweight aggregate with the merits

of geopolymer. Several studies were performed to investigate the fresh and hardened characteristics of lightweight geopolymers manufactured using various raw materials and different types of lightweight aggregate.

In a study conducted by Wu and Sun (2007), cenosphere lightweight aggregate was used to produce lightweight geopolymer concrete based on activation of fly ash and metakaolin with a liquid of sodium silicate and NaOH. They found that after 24 hours at 60 °C, the 28 days of compressive strength reached up to 22.5 MPa. Furthermore, Wu and Sun (2007) have been also used expanded polystyrene (EPS) to produce lightweight geopolymer concrete. The dry density of concrete was found to be 1000 Kg/m³ and the compressive strength was 12.4 MPa at 28 days.

In other studies, Lightweight expanded clay aggregate (LECA) has been used in GPC. The impact of LECA on the efficiency of GGBS-based concrete was investigated by Yang et al (2010). The specimens were cured at room temperatures. Compressive strength obtained for 28 days ranged from 3.3-19.1 MPa with a density of 775-1615 kg/m³.

Paul and Babu (2014) investigated the mechanical characteristics of lightweight geopolymer concrete which was formed by the activation of GGBS/FA via an alkali activator consisting of sodium silicate and NaOH solution. This study involves the substitution of coarse aggregate with LECA at 40%,60%, 80% as well as 100%. The grain size used for the LECA was 4-10 mm. They reported that the mechanical characteristics declined with the rise of the substitution level of LECA. After 28 days of curing, compressive strength, flexural strength, and splitting strength declined from 44 MPa, 5.6, and 2.4 MPa for concrete with 40% LECA to 8 MPa, 0.72 MP, and 0.54 MPa for concrete with 100% LECA, respectively. As well as, the results showed that the 28- day density was reduced from 2350 kg/m³ for concrete having 40% LECA to 1450 kg/m³ for concrete having 100% LECA.

Abdulkareem et al (2014) investigated the impact of temperatures on the mechanical characteristics of LWGC. They manufactured lightweight geopolymer concrete with fly ash as raw material and LECA as coarse aggregate and normal sand as fine aggregate. The samples were subjected to high temperatures in range of 100 to 800 degrees centigrade for one hour with a phase of 100 degrees centigrade. They noticed that, after LWAGC exposed to high temperatures up to 300 degrees centigrade, it

gained strength. After that, when subjected to high temperatures of 400-800 degrees centigrade, the strength of its started to decrease. The variation in the thermal expansion between aggregate and paste may be related to this decrease.

Additionally, Priyanka et al (2020) activated FA by a solution of sodium silicate and NaOH to produced geopolymer concrete. LECA has been used as a partial replacement of coarse aggregates. Fresh and hardened properties were investigated. Based on the results, it was found that as the proportion of LECA increased, LWAGC provides more workability because of the shape of LECA. The density and strength of LWGC decreased as the replacement level of LECA increased.

2.4.5 Lightweight Geopolymer Mortar

Using lightweight aggregate in geopolymer mortar manufacturing can be decreased the unit weight. Some research has been shown that increasing the amount of lightweight aggregate in mortar led to a reduction in its unit weight. The mortar with a unit weight of less than 1920 kg/m³ can be considered lightweight. Lightweight mortar can minimize the dead load, increase the strength to weight ratio, improve fire resistance. In addition, lightweight mortar can be used instead of normal mortar to build anti-earthquake structures since it reduces the structure's self-weight and then reduces the superimposed loads that work during the earthquake on the structure (Mermerdaş et al., 2020).

There are a few studies on the use of lightweight aggregates in geopolymer mortars. Mermerdaş et al (2017) utilized pumice as a fine aggregate to produce lightweight geopolymer mortar (LWGM) with FA and GGBS. In this study, the influence of binder content, curing temperature, and curing period was examined in terms of the compressive strength of LWGM. Their findings showed that as the binder content increased, the strength of lightweight geopolymer mortar increased. As well as, the strength increased with increased curing temperature and curing time.

In other research, Wonges et al (2018) used crumb rubber as fine aggregate in FA-based mortar. The mechanical and thermal characteristics of lightweight geopolymer mortar have been examined. Based on the results, the use of crumb rubber has been found to have contributed to a significant decrease in compressive strength. However, as opposed to the normal mortar, it has been noted that thermal conductivity and density decreased by 79% and 42% respectively.

Two kinds of lightweight aggregates, namely, pumice and lightweight expanded clay aggregate were used by Ameri et al (2020) in producing two LWGM. Various precursors, including GGBS, metakaolin, waste clay brick powder, and waste ceramic powder have been used to produce geopolymer mortars. The results showed that the density of mortar with LECA was around 10-15% lower than the mortar with pumice aggregate, indicating that LECA is more suitable for lightweight applications than pumice aggregate. Because of the higher density of pumice and its strong bonding with paste, mortar with pumice exhibited lower workability and greater strength than those with LECA.

2.5 Polyvinyl alcohol (PVA) Fiber

PVA is chemically known as polyvinyl alcohol. In 1924, Herrmann and Haehnel first synthetically prepared PVA. In the construction sector, PVA has been used widely as an adhesive, catalytic agent, and fiber reinforcement (Xu et al.,2018). PVA fiber is a short discontinuous fiber made of organic material. PVA fiber includes a group of hydroxyl (OH) with the ability to form hydrogen bonds amongst molecules. This unique feature of PVA fiber allows to form of a strong bond with the cementitious matrix (Noushini et al., 2013). The PVA fiber has a higher tensile strength of between 800-2500 MPa and a high modulus of elasticity of between 20-40 GPa (Ranjbar and Zhang, 2020). As well as, PVA fiber has excellent resistance against alkali and acid. Its specific gravity is about 1.3 (Rashad, 2019).

2.5.1 Fiber Reinforced Geopolymer Mortar

Geopolymer has good compressive strength, resistance to heat and flames and excellent durability. In spite of these features, geopolymer has poor tensile strength and low resistance to creaking and fracture. Geopolymer suffers from brittle failure due to these characteristics. In order to improve its ductility, toughness, and tensile strength, fibers can be incorporated into geopolymer (Singh, 2018).

Actually, the use of fibers in concrete began in the early 1960s. The kind and shape of fibers utilized in the construction sector have been significantly developed in recent years (Rashad, 2019). Several types of fibers have been used in cementitious materials like steel fiber, polypropylene (PP), Polyvinyl alcohol (PVA) , carbon fiber, etc. PVA fibers are considered to be one of the most appropriate fibers used due to their good characteristics like tensile strength and elastic modulus.

Several studies have been performed to examine the effect of PVA fiber on geopolymer mortar mechanical characteristics. Ahmed and Lu (2013) stated that the addition of 2% of PVA (length 8 mm), by volume, to FA- based geopolymer mortar led to a rise in the modulus of rupture. In a similar study, Ohno and Li (2014) included 2% PVA fibers (diameter 39 μm length 12 mm) by volume, into fly ash-based geopolymer mortar. The compressive and tensile strength was tested. The results showed that PVA fiber incorporation increased the strength of geopolymer mortar.

Al-Majidi (2017) carried out a study on the impact of the incorporation of PVA on the mechanical performance of GP mortar. FA, GGBS, and silica fume were used to produce a geopolymer matrix activated by potassium silicate. The PVA (diameter 0.015 mm and length 12mm) was incorporated in the mortar at 1% and 2%, by volume. The results illustrated that 28-day compressive strength decreased with the inclusion of 1% fibers whilst the strength was similar to the control with the inclusion of 2% fibers. As the incorporation of fiber increased, the flexural strength improved. With the increase of fibers, the toughness was considerably enhanced. As the inclusion of the PVA fiber increased, so did the toughness.

Nematollahi et al (2017) conducted a study on PVA fiber reinforced geopolymer mortar. In their study, different types of raw materials such as ash fly ash class F and slag were used. The PVA fibers of 2% by volume were utilized. Their findings illustrated that samples with PVA fibers displayed high ultimate tensile strength compared to those with polyethylene (PE) fibers. Additionally, the compressive strength was lightly higher for samples having PVA fibers than that having PE fibers. This may be due to the low aspect ratio of PVA fiber comparison to PE fiber.

The effect of PVA fiber on FA-based geopolymer mortar containing 6% nano-silica was studied by Xu et al (2018). At 3%,5%, and 7%, the PVA fibers (diameter 39 and length 8 mm) have been included in a mortar. Their findings illustrated that the 28-day density was increased by 2.4%, 4.33%, and 6.65% with the inclusion of 3%,5%, and 7% PVA, respectively. In this way, the addition of 3%,5%, and 7% PVA improved the flexural strength of 28 days by 19.1%, 94.1 %, and 52.25%, respectively, whilst increased the 28- day splitting strength by 48%, 131.37%, and 116.67%, respectively.

On the other hand, the addition of PVA fibers to lightweight geopolymer mixture also enhanced the mechanical characteristics of lightweight geopolymer concrete. A study by Mastali et al (2018) incorporated 2% PVA fibers by volume, into slag-based geopolymer concrete having lightweight aggregate manufactured by granulation of Petrit -T. They examined the impact of PVA fiber on the compressive strength and flexural strength of lightweight geopolymer concrete. The findings illustrated that the addition of PVA strengthened both compressive and flexural strengths.



CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the materials and methods utilized to conduct a number of tests. The properties of all materials that have been used in this study are included. In this research, an experimental program was performed in the laboratory of the University of Gaziantep. Slag was utilized as the main precursor in geopolymer mortar production. Three mixes were prepared in this study. In order to produce lightweight geopolymer mortar, river sand was partially substituted by lightweight expanded clay aggregate (LECA) at replacement ratios of 60 % and 80% by weight. PVA fiber was used to strengthen lightweight geopolymer mortar containing 80% LECA. All the samples prepared in this study have been cured at ambient temperature.

In this study, the flow table test was performed for each mixture in order to evaluate the workability. Fresh and dry density was also determined. The compressive test, flexural test, and tensile test were carried out to investigate the mechanical characteristics of lightweight geopolymer mortar with and without fibers.

3.2 Materials Used

3.2.1 Slag

Slag or GGBS is a solid waste material that was used as the primary source material for geopolymer mortar production in this study. Slag compliant to ASTM C 989 was utilized. In this research, slag was provided from a local supplier with a specific gravity of 2.79 and a specific surface area of 418 m²/kg. Slag is an off-white color, as illustrated in Figure 3.1. The chemical properties of slag are given in Table 3.1.

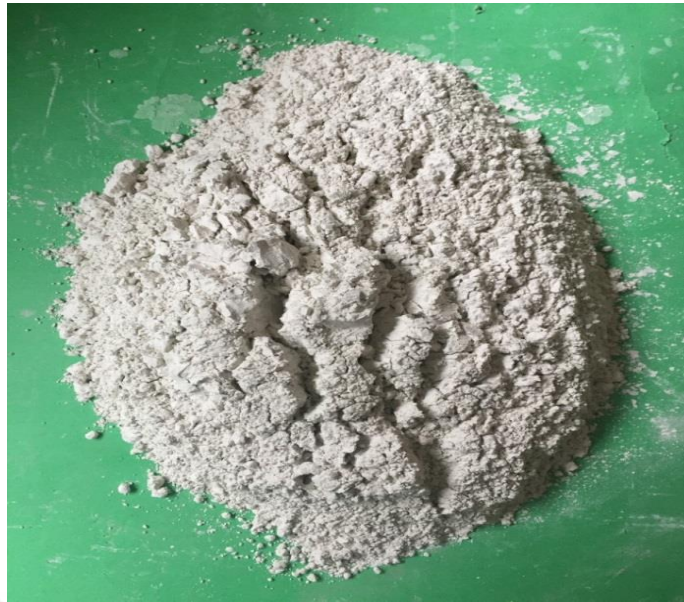


Figure 3.1 Slag used in this study

3.2.2 Aggregates

3.2.2.1 River Sand

The locally available river sand is utilized. River sand was used as fine aggregate in geopolymer mortar and has been partially replaced by LECA in this study. River sand has a specific gravity of 2.68, fineness modulus of 2.86, and water absorption of 0.58% was utilized in all geopolymer mixes. Figure 3.2 shows the river sand used in this study.



Figure 3.2 River sand used in this study

3.2.2.2 Lightweight Expanded Clay Aggregate (LECA)

In this study, LECA was supplied by Light Expanded Clay Aggregate Turkey company, located in Söğüt/Bilecik. LECA with a normal size of 0-3 mm was utilized, as illustrated in Figure 3.3. The LECA shape is round with a rough surface. According to the chemical composition, LECA contains Si and Al oxides with small quantities of CaO and MgO, as shown in Table 3.1. Furthermore, the general characteristics of LECA and the distribution of its grain size are shown in Table 3.2 and Figure 3.4, respectively.



Figure 3.3 LECA

Table 3.1 Chemical composition of slag and LECA used

Compounds	Slag (%)	LECA (%)
CaO	34.12	2.12
SiO ₂	36.4	66.84
Al ₂ O ₃	10.39	18.46
Fe ₂ O ₃	0.69	7.06
MgO	10.3	1.16
SO ₃	0.49	-
K ₂ O	0.97	2.31
Na ₂ O	0.35	1.11
TiO ₂	-	1.40
L.O.I	1.64	0.22

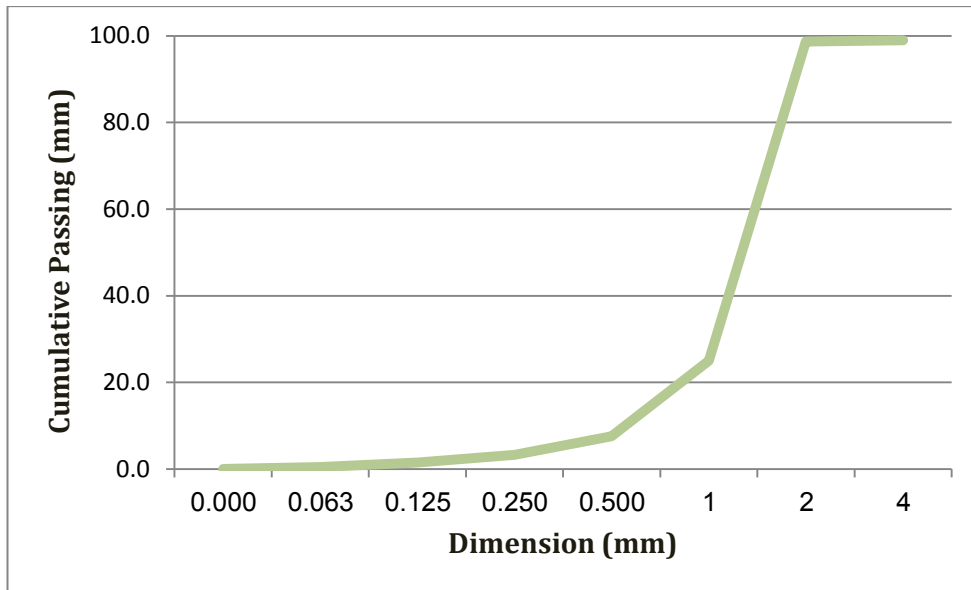


Figure 3.4 LECA's grain size distribution

Table 3.2 General characteristics of LECA

Property	Range
Bulk Density Dry Loose	721 - 928kg/m ³
Oven-Dried Particle Density	1240 -1343 kg/m ³
Air Filled Porosity	>10%
Maximum Water Retention Capacity (24h)	25-40%
Water Permeability	>0.001 cm/s
Particle size	0-3 mm
Particle Shape	Round

3.2.3 Alkaline Activator

The alkaline activator type has a significant role in process of geopolymerisation. In general, previous studies have shown that mortar activated with a sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) has demonstrated excellent performance irrespective of the kind of source material utilized (Huseien et al., 2017; Zhang et al., 2018). Thus, a combination of Na_2SiO_3 and NaOH was used in this study as an alkaline activator solution for slag-based geopolymer mortar production.

The NaOH commercially available in a white pellet shape has 98 % purity, as illustrated in Figure 3.5(a). The Na_2SiO_3 in solution form as illustrated in Figure 3.5(b), has been used for the preparation of alkaline activator. Table 3.3 shows the chemical composition of utilized sodium silicate.



(a) Sodium Hydroxide

(b) Sodium Silicate

Figure 3.5 Alkaline Activator

Table 3.3 Chemical composition of sodium silicate

Grade	NA46
% NaOH (w/w)	14.7
% Na_2O (w/w)	13.7
% SiO_2 (w/w)	29.4
The ratio of SiO_2 to Na_2O	2.14
Specific Gravity (gm./ml @ 20°C)	1.458
Appearance	Viscous clear to light yellow liquid
PH	12.8
Solubility (water)	Soluble
% Volatiles	>60% (water)

3.2.4 Super-plasticizer (SP)

Super-plasticizer has been used in order to attain the workability of fresh lightweight geopolymer mortar. A Polycarboxylic ether type superplasticizer obtained from Master Builders company under the name MasterGlenium RMC 303 was utilized in this study. This type of Super-plasticizer is available in the kind of a light green liquid, as shown in Figure 3.6. As reported by the manufacturer, the specification of the super-plasticizer is presented in Table 3.4.



Figure 3.6 Super-plasticizer used in this study

Table 3.4 Specification of Super-plasticizer

Structure of material	Polycarboxylic Ether Based
Name	MasterGlenium RMC 303
Color	Light Green
Density	1.023-1.063 kg/lt
Alkali content (%)	< 3.00
Chloride content (%)	< 0.10

3.2.5 Water

The potable tap water which is available in the laboratory of Gaziantep University was used in the making of NaOH solution and additional water was also used in order to attain workability.

3.2.6 Polyvinyl Alcohol (PVA) Fibers

PVA fibers have been used to manufacture fiber-reinforced geopolymer mortar having lightweight expanded clay aggregate. PVA fibers have excellent characterizes to enhance LWGM strength. PVA fibers available in the laboratory were used in the present study. PVA with a fraction of 1% was used. PVA fibers used in this study are shown in Figure 3.7 .The diameter and length of PVA fiber that has been used 39 μm and 12 mm, respectively as shown in Table 3.5.



Figure 3.7 PVA fibers used in this study

Table 3.5 PVA fiber properties

Fiber	Diameter (μm)	Length (mm)	Young's modulus (GPa)	Elongation (%)	Nominal strength (MPa)	Density (g/cm^3)	I/d ratio
PVA	39	12	41	6	1600	1.3	308

3.3 Preparation Alkaline Activator Solution For Geopolymer

The NaOH solution was made by dissolving NaOH beads in water. The sodium hydroxide solid weight in a solution change relying on the solution concentration which is commonly specified in terms of molarity (M). In this research, the NaOH concentration utilized was 12M. To make an alkaline solution, first, 495 gm of NaOH solid dissolved in 505 gm water per liter. The solution was then kept at ambient temperature to cool. After that, NaOH solution was mixed with Na_2SiO_3 solution and left for at least 24 hours in order to get the final alkaline solution for

geopolymer mortar production. In this study, the mass ratio of Na_2SiO_3 to NaOH solution used was 2.5. Alkaline solution preparation is shown in Figure 3.8.



Figure 3.8 Preparation of alkaline solution

3.4 Mix Design

To obtain the required strength, workable and lightweight geopolymer mortar, it is important to develop a suitable and logical mix design. There are various parameters that influence mix design such as the concentration of NaOH solution, Na_2SiO_3 to NaOH ratio, curing time and temperature, and aggregate content. Based on previous studies a mixture of sodium silicate and sodium hydroxide has been used as an alkaline solution at a mass ratio of 2.5 ($\text{Na}_2\text{SiO}_3/\text{NaOH} = 2.5$). It was found that the

$\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 2.5 contributes to better mechanical and durability characteristics (Abdullah et al.,2011; Mustafa et al.,2012). All through the study, the concentration of NaOH was kept constant at 12M. The ratio of alkaline solution to the binder used was 0.8 which achieved desirable strength. The proportion of binder to fine aggregate ratio was 1:3.

In this study, three mixtures have been designed and their mix designs are shown in Table 3.6. It shows that river sand was partially replaced with lightweight expanded clay aggregated (LECA) at replacement ratios of 60% and 80% by weight in order to obtain lightweight geopolymer mortar (LWGM). Also, the inclusion of 1% PVA fibers by volume, into geopolymer mortar containing 80% EC. The designation of geopolymer mixtures proposed was based on the parameters investigated (i.e. LECA substitution level and PVA volume fraction). For instance, 80%EC-1%PVA references that the replacement level of LECA is 80% and 1% volume fraction of PVA fiber.

Table 3.6 Lightweight geopolymer mortar mix designs

Description	60% EC	80%EC	80%EC-1%PVA
Slag (kg/m ³)	500	500	500
River sand (kg/m ³)	600	300	300
LECA (kg/m ³)	900	1200	1200
Alkaline solution (kg/m ³)	400	400	400
Extra water (kg/m ³)	50	31.7	31.7
SP (kg/m ³)	15	25	70
PVA Fibers (% Volume)	-	-	1.0
$\text{Na}_2\text{SiO}_3/\text{NaOH}$	2.5	2.5	2.5
Alkaline solution/Slag	0.8	0.8	0.8
Molarity of NaOH solution	12	12	12

3.5 Lightweight Geopolymer Mortar Samples Preparation, Casting and Curing

3.5.1 Preparation of Lightweight Geopolymer Samples without Fibers

A Spiral Mixer with a capacity of 62.5 liters was used to prepare all the mixtures. In order to prepare LWGM, slag, river sand, and LECA were first dry mixed for around 3 minutes. After that, the alkaline liquid was poured slowly, and the mixture was remixed for 4-minute. Then, add the water into the mixture and mix for 2 minutes. Finally, a super-plasticizer was added in order to achieve workable LWGM. The manufacturing process was continued for 3-minute in order to obtain a homogeneous mixture. The workability of LWGM was assessed using a flow table test. Afterward, the mixture was located into pre-oiled molds in three layers, then compacted by using a vibrating table for 1 min to eliminate the air voids. The specimens were cast into three sizes. Cube specimens ($70 \times 70 \times 70$ mm) mm, cylinder samples (100 mm diameter and 200 mm height), and prismatic specimens ($160 \times 40 \times 40$ mm) had been prepared. Next, the samples were wrapped with a nylon sheet in order to prevent moisture loss. Then, samples were left for 24 hours at room temperature in the molds. The following day, the samples were extruded from the molds and left in a laboratory at room temperature till testing day. All the details are shown in Figure 3.9.



(1)



(2)



(3)



(4)



(5)



(6)



(7)



(8)



(9)



(10)



(11)



(12)



Figure 3.9 Mixing, casting and curing of samples without fibers

3.5.2 Preparation of Lightweight Geopolymer Samples with Fibers

The same procedure as described above has been followed for the production of fiber-reinforced geopolymer mortar. PVA fiber (1% volume fraction) was gradually added at the end stage into the mixture and blended for 3 minutes at rapid speed till the fibers were adequately distributed. After that, the mixtures were cast into three layers. Cubes, cylinders, prisms, beams, and dog bones shape molds were prepared for casting of mortar specimens and compacted for 2 minutes. Samples demolded after 24 hours and left at laboratory temperature till the age of 28-day. Figure 3.10 illustrates all the details.



(1)



(2)



(3)



(4)



(5)



(6)



(7)



(8)



(9)



(10)



(11)



(12)

Figure 3.10 Mixing, casting and curing of samples with fibers

3.6 Elevated Temperatures Exposure

After 28 days of curing, specimens prepared in this study were exposed to temperatures of 250 °C and 500 °C. An electric oven was used for this purpose, as shown in Figure 3.11. The samples were put in the oven and heated at a fixed heating rate of 25 °C/minute in order to reach the target temperature. Instantly after reaching their required temperature, the samples were held for 30 minutes in the oven at each temperature. Subsequently, the samples are left inside the oven in order to completely cool and achieve ambient temperature. Then, the samples were removed from the oven and the mechanical properties were examined to assess the influence of elevated temperatures on the samples.



Figure 3.11 Electric oven used in this study

3.7 Experimental Tests

3.7.1 Flow Table Test

To determine the workability of fresh lightweight geopolymer mortar, a flow table test has been performed according to ASTM C 1437. Flow table test was conducted prior to molding stage. Flow table test was applied using a conical mold with a top diameter of 70 mm, a bottom diameter of 100 mm, and a height of 50 mm. The fresh mixture was poured into the mold cone, which is positioned at the center of the flow

table instrument, with two layers. After the top surface of the mold is leveled, the mold is immediately raised vertically, then the flow table is lowered 25 times to disperse the mixture on the table. The average of two opposite perpendicular diameters of the distributed fresh mixture was stated as flow value. Figure 3.12 shows the test instrument and flow diameter calculation.



Figure 3.12 Flow table test of lightweight geopolymer mortar

3.7.2 Density Test

Fresh and dry densities were determined in this study. The fresh density of lightweight geopolymer mortar has been conducted after mixing. The unit weight test for fresh LWGM was performed utilizing a cubic mold, as shown in Figure 3.13 (a). The cubic mold is filled with fresh LWGM. The weight of mold without and with

LWGM was independently determined. The unit weight is calculated utilizing the formula below:

$$\text{Unit weight} = \frac{M_f - M_e}{v} \quad (3.1)$$

where:

M_f : the weight of mold with fresh LWGM (kg)

M_e : the empty mold weight (kg)

v : the mold volume (m^3)

Furthermore, dry density was also determined for each mixture. The weight of the cube samples has been reported prior subjected to the compressive test, as shown in Figure 3.13 (b). Dry density was computed by dividing the sample's weight by volume.

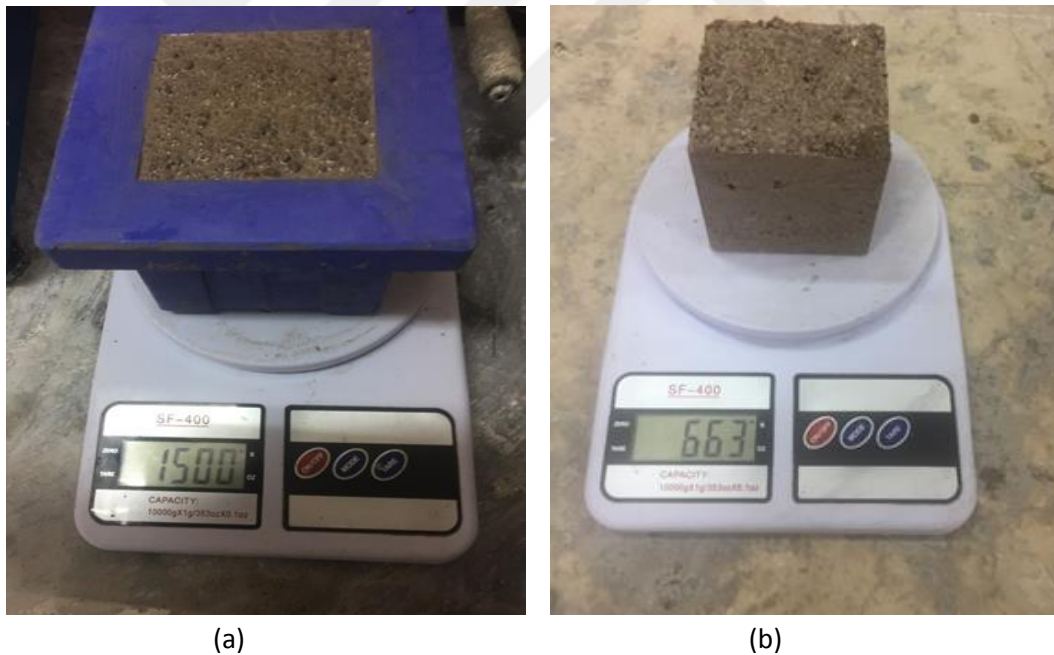


Figure 3.13 Measuring the weight of samples by using a digital balance

3.7.3 Compressive Test

Compressive strength was considered to be the most common test of all concrete hardness tests. In this study, to evaluate compressive strength, cubic samples of $70 \times 70 \times 70$ mm of each mixture were subjected to compressive load utilizing a

digital compressive strength test machine with a load capacity of 2000 kN, as illustrated in Figure 3.14. The test was performed on three cube specimens from each mix. The compressive strength value was reported as the average of three tested samples. All specimens were tested at a constant load rate of 5 kN/s on the non-casting sides of the cube. The specimen's compressive strength was determined by using the following equation:

$$f_c = \frac{P}{A} \quad (3.2)$$

where

f_c : compressive strength (MPa)

P : maximum applied load (kN)

A : cross-sectional area (mm²)



Figure 3.14 Compression test of a cube specimen

Besides, the compressive test was also performed in the present study on cylindrical samples having a diameter of 100 mm and a length of 200. The test machine with a load capacity of 500 kN had been utilized for this purpose, as presented in Figure 3.15(a). The test was carried out under displacement-controlled loading with a rate of 0.5 mm/min. Prior to testing, the sulfur capping process was applied. The purpose of

this process is to gain a flat smooth surface for the samples of the cylinder in order to attain an equal distribution of stress. The sulfur-capped cylinder samples are shown in Figure 3.15 (b).

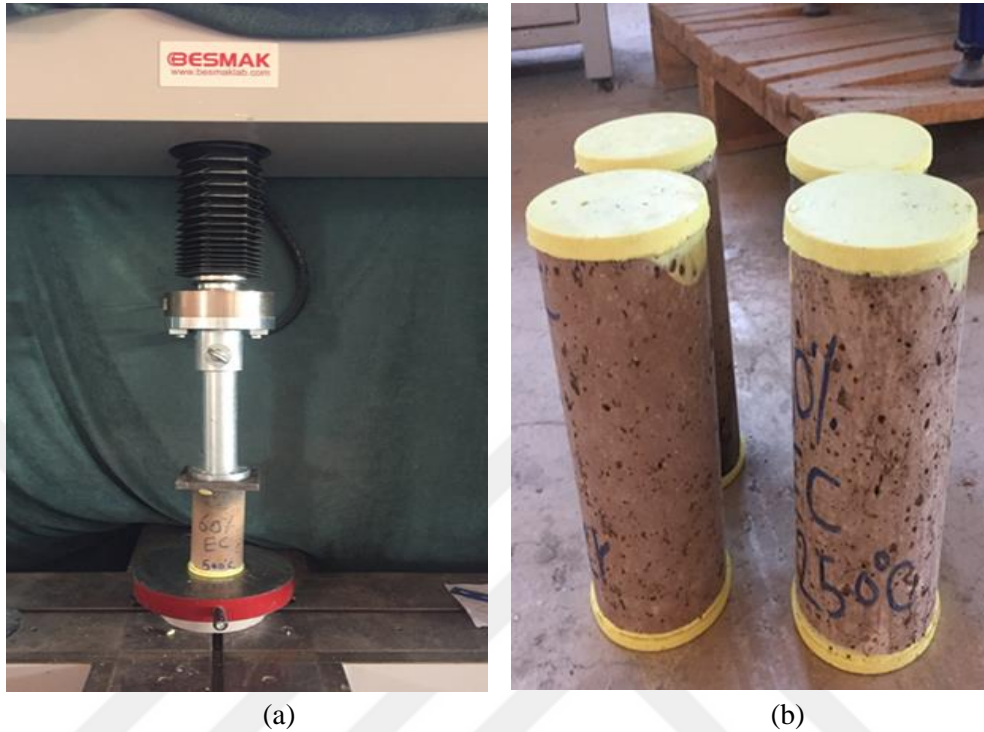


Figure 3.15 (a) Compression test of the cylinder specimen; (b) Sulfur capped samples before compression test

3.7.4 Flexural Test

A flexural test was performed to assess the flexural behavior of the samples prepared in this study. The same test machine utilized for compressive test of cylinder samples was utilized in this test. The displacement of the sample was evaluated by utilizing a linear variable displacement transducer (LVDT) at mid-span. Flexural strength was determined using prism and beam samples. Prisms with the dimensions of $160 \times 40 \times 40$ mm and beams with the dimensions of $350 \times 75 \times 45$ mm have been prepared. A flexural test utilizing a three-point bend test setup was conducted, as illustrated in Figure 3.16. The test has been carried out after 28 days. All the specimens were tested under displacement control with a fixed rate of 0.3 mm per minute. Throughout the testing, loading force and displacement have been recorded and load versus displacement curves were plotted.

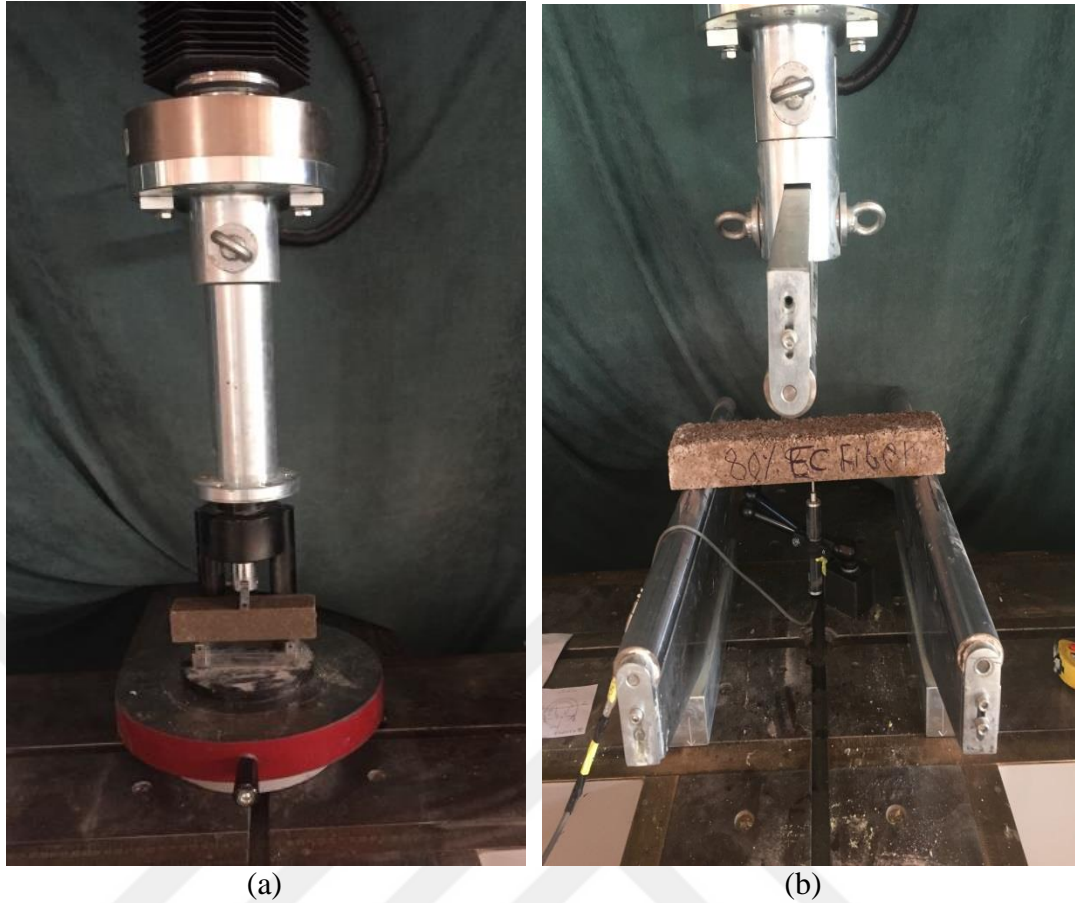
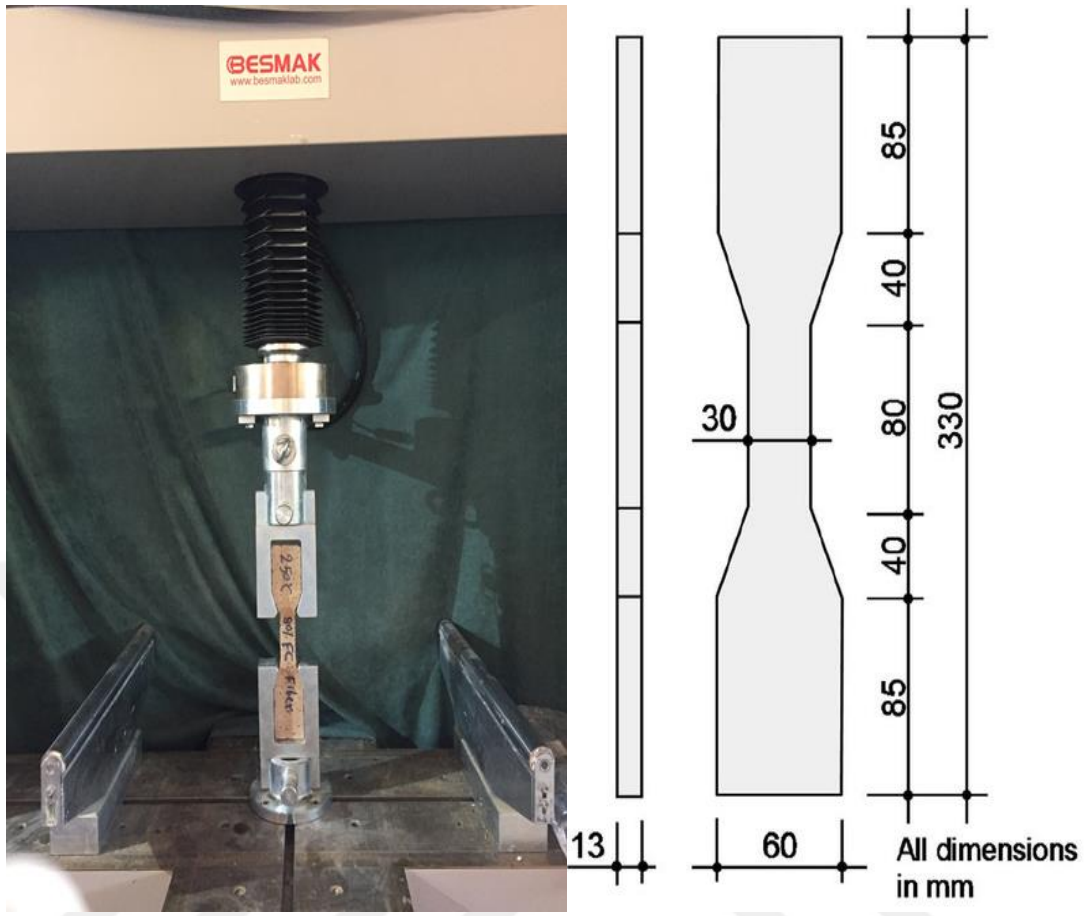


Figure 3.16 Test setup for flexural strength

3.7.5 Tensile Test

A uniaxial tensile test was conducted on dogbone shape specimens that have been prepared in this study. The dimensions of the dogbone specimens are illustrated in Figure 3.17(b). The shape of the dogbone specimens enables the majority of cracks to occur inside a narrow section of 80 mm section in the center. The dogbone samples were 13 mm thick. Dogbone specimens were tested after 28 days of curing. In this test, the same instrument utilized for the flexural test was utilized, as shown in Figure 3.17(a). Throughout the test, dogbone specimens have been subjected to quasi-static uniaxial tension load at a displacement rate of 0.1 mm per minute. The loading force and displacement have been recorded during the test.



(a) (b)
Figure 3.17 (a) Tensile test setup; (b) Dimensions of the dogbone specimens
(Pourfalah, 2018)

CHAPTER 4

TEST RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter lists and discusses the results of all tests carried out in this study. The results include workability, fresh and dry densities, compressive strength, flexural behavior, and uniaxial tensile performance of lightweight geopolymer mortar. The effect of using LECA as a partial replacement for river sand at two different ratios (60% and 80%) is discussed. The impact of PVA fibers on LWGM behavior is also investigated. As well, this chapter aims to understand the effect of elevated temperatures on the mechanical properties of LWGM with and without fibers.

4.2 Workability

The workability of fresh geopolymer mortar is an essential property that can have an effect on the placement as well as on long-term performance. Flow table test is one method to determine the workability of fresh mortar. The measurement of flow diameter of lightweight geopolymer mortar without and with PVA fiber is shown in Figure 4.1. As shown from the figure, aggregate particles showed regular and uniform distribution such that no segregation or bleeding in all mortar mixes was noticed. The results of the workability test of lightweight geopolymer mortars with and without fibers are shown in Figure 4.2. It was clear that the workability decreased as the replacement level of the lightweight expanded clay aggregate (LECA) increased. LECA particles have a high water absorption capacity, which has contributed to a reduction in workability (Ayati et al., 2018).

In terms of the impact of PVA fiber, in general, adding any form of fiber to concrete decreased its workability. The addition of PVA fibers into lightweight geopolymer mortar has increased the cohesion of the mortar. Due to their large surface area, PVA fibers resulted in adherence to aggregates (Bhogayata and Arora, 2019). Based on the results presented in Figure 4.2, it can be seen that the workability of lightweight

geopolymer mortar decreased with the incorporation of PVA fiber. LWGM having PVA fiber had lower workability than LWGM without fiber.

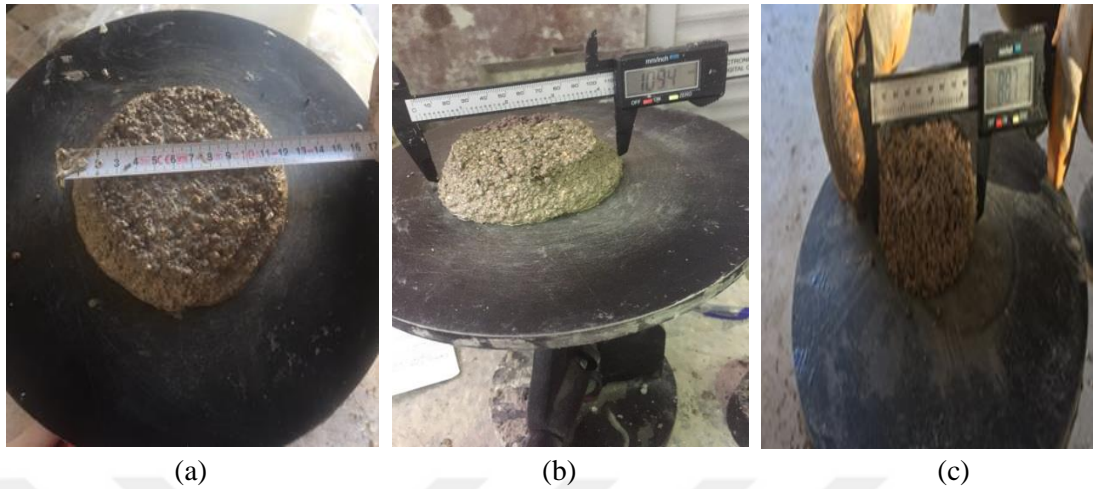


Figure 4.1 Measurement of flow diameter of (a) 60%EC ; (b) 80%EC ; (c) 80%EC-1%PVA

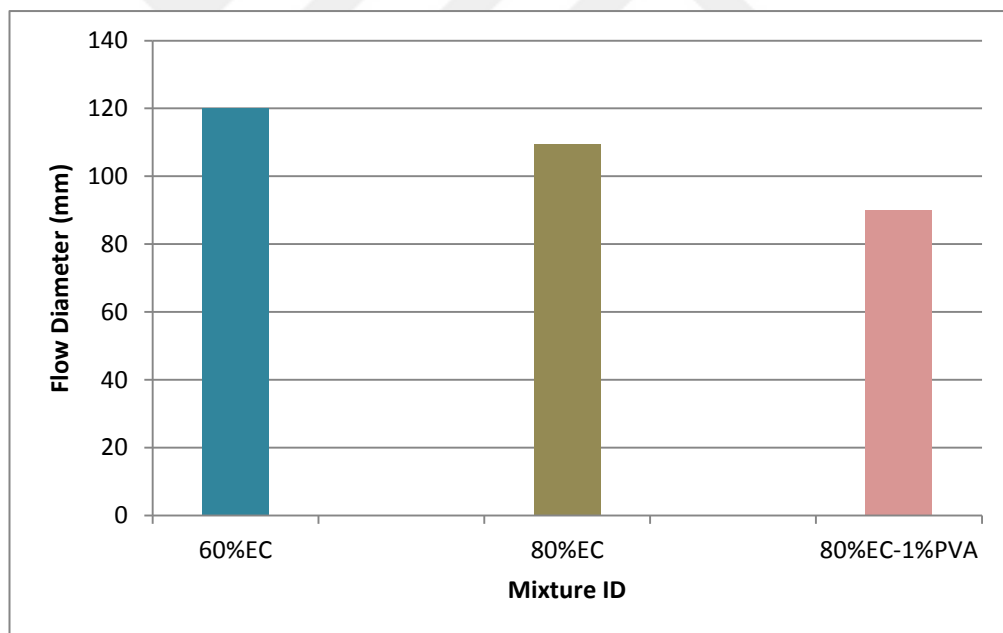


Figure 4.2 Flow table results

4.3 Fresh and Dry Densities

Fresh and dry densities values of each mixture at ages of 1, 7, and 28 days have been presented in Table 4.1. Fresh density was determined immediately after mixing. It was observed from the table that the fresh and dry density of lightweight geopolymer

mortars decreases as the LECA content increases. The fresh density of the 80% EC specimen was 7% lower than the density of the 60% EC specimen. The pores in the structure of aggregate (i.e. LECA) are the primary cause of a decrease in the density of geopolymer mortar (Madadi et al., 2019). Besides, from the table, a marginal decrease in dry density values can be seen by increasing the age of the LWGM from 1 to 28 days. For the 80%EC sample, at 28 days there was about a 3.7% reduction in its dry density compared with that at 1 day. This reduction may be attributed to water evaporation. From the results, it can be concluded that the use of LECA in the manufacture of the geopolymer mortar notably decreased both fresh and dry density. The effect of fiber on fresh and dry density is also presented in Table 4.1. It can be observed that there was a slight decrease in both densities of fiber samples compared to the non-fiber samples. This could be attributed to a fiber-induced damage effect, because of more than adequate amount of fibers are present in the matrix resulting in increased porosity (Xu et al., 2018).

Based on ACI committee 213R (2003), the upper limit of density is 1950 kg/m³ for air dried mortar. Thus, it can be seen from the table that all the geopolymer mortars in this study are less than 1950 kg/m³ and therefore are considered to be lightweight.

Table 4.1 Fresh and dry density values (kg/m³)

Mixture ID	Fresh	Dry		
		1-day	7-day	28-day
60%EC	1950	1945	1932	1896
80%EC	1813	1805	1775	1738
80%EC-1%PVA	1800	-	-	1727

4.4 Compressive Properties

4.4.1 Compressive Strength of Cube Samples

Figure 4.3 shows the effect of lightweight aggregate on compressive strength. Three specimens were tested to take an average for each value of the results. The compressive strength was performed on cubes at 1, 7, and 28 days of curing. It is apparent from Figure 4.3 that the compressive strength of samples increased with the age regardless of the LECA content in the mixture. However, there was a gradual reduction in compressive strength with an increase in the LECA replacement level. The 28-day compressive strength of the geopolymer mortar containing 60% of LECA was 25.35 MPa, while that of 80% of LECA was as low as 21 MPa, reflecting a reduction in strength of about 17%. LECA is porous material compared with the standard aggregate due to the interconnected holes with various sizes in the LECA grains. This implies that a geopolymer mortar with more LECA would be porous compared with a regular one, causing a reduction in compressive strength (Othman et al., 2020). This finding is also supported by the previous findings of Sonia and Subashini (2016) that the compressive strength decreased with an increase in LECA content.

Based on the literature review, the compressive strength depends greatly on the density (Subaşı, 2009; Yang et al., 2010). As the density increases, the compressive strength increases. The findings of this study are also in agreement with this.

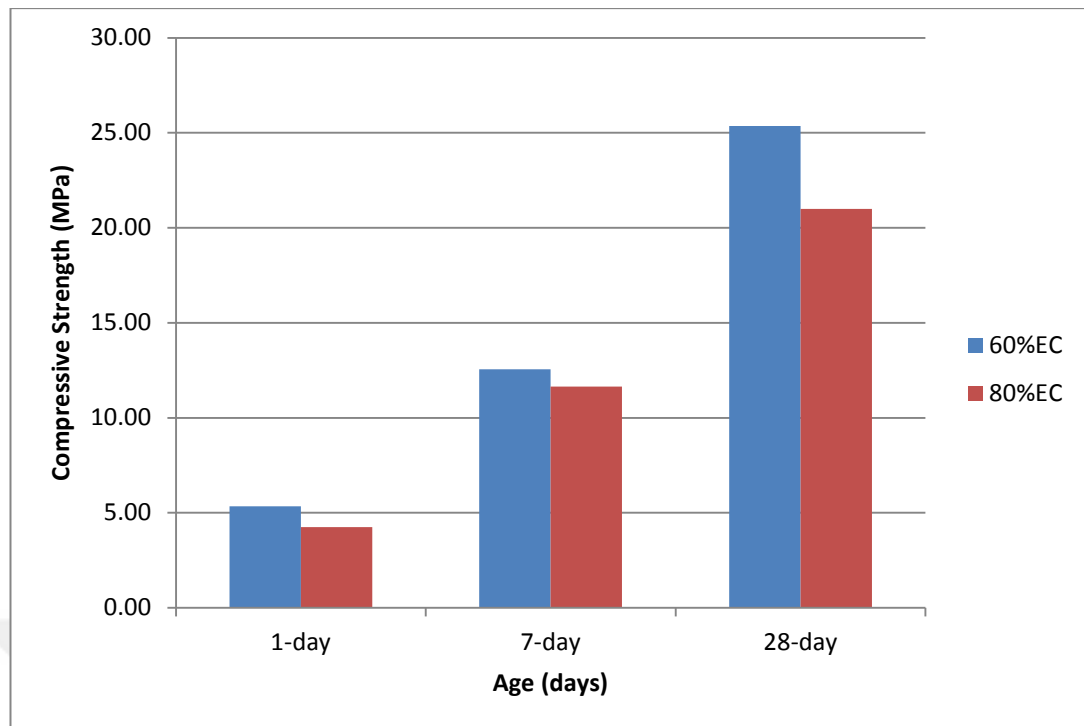


Figure 4.3 Compressive strength of LWGM at different ages

Figure 4.4 demonstrates the compressive strength of LWGM samples with and without fibers at room temperature. From the figure, it is clear that lightweight geopolymer mortar with 60% LECA has a higher compressive strength compared to all the other samples. Whilst, the LWGM having PVA fibers had the lowest compressive strength. So, it can be seen that the addition of fibers to lightweight geopolymer mortar has decreased its compressive strength. The compressive strength of LWGM with 1% PVA fiber was about 7% lower than that of unreinforced LWGM samples at the same level of LECA replacement. The reason for the lower compressive strength of LWGM with PVA fibers can be attributed to the fact that the inclusion of fibers making the mixture more difficult to consolidate, resulting in an increase in air voids as reported by Ling et al. (2019). A similar investigation was also reported in previous work (Borges et al., 2017). However, it is worth noting that the cube samples with PVA fibers exhibited ductile failure under compression test by keeping their original shapes. This owing to the bridging effect of PVA fiber. Figure 4.5 shows the failure mode of LWGM sample with and without fibers. Previous studies have also found similar observations (Xu et al., 2018; Malik et al., 2019; Tajunnisa et al., 2019).

High-temperature resistance is one of the most essential attributes of building materials. As a result, in the following part, the impact of elevated temperatures on compressive strength was examined. Figure 4.4 also illustrates the compressive strength findings after exposure to elevated temperatures at 250°C and 500°C. From the figure, it was observed that there was an increase in compressive strength for samples exposed to 250°C. For instance, at this temperature, the compressive strength of 60%EC, 80%EC, and 80%EC-1%PVA was increased by 17%, 30%, and 15%, respectively, compared with their counterparts at room temperature. The increase in the strength at 250°C was attributed to evaporation of free water owing to sintering at this temperature as well as a combination of geopolymer matrix and aggregates. This led to an improvement in bonding and strength at 250°C (Ameri et al., 2019). This is confirmed by the visual observations of the failure patterns following the compressive test, as illustrated in Figure 4.6.

On the other hand, when the temperature was increased to 500°C, the strength of all samples decreased, as shown in Figure 4.4. For demonstration purposes, the compressive strength of the 60%EC sample was reduced from 25.35 MPa at room temperature to 20.40 MPa at 500°C. This loss of strength at 500°C may be due to the significant thermal shrinkage resulting from the vaporization of water from the geopolymer structure. The water is converted into water vapor and the pressure of the water vapor increases as the heating temperature increases. As the vapor pressure reaches its absolute limit, the matrix which has lower permeability will not be able to withstand the high thermal stresses, resulting in extreme thermal cracks on the surfaces or within sections of the samples, resulting in a reduction in compressive strength. Another reason for the deterioration of strength is the variation in thermal expansion among the geopolymer matrix and lightweight aggregate (Abdulkareem et al., 2013). A similar observation on the deterioration of compressive strength of lightweight geopolymer mortar after exposure to elevated temperature has been confirmed by Ameri et al (2019). Furthermore, it can be observed from Figure 4.4 that the lightweight geopolymer mortar with PVA fibers has a lower strength loss rate at 500°C than the non-fiber specimen. This means that samples with PVA fibers displayed enhanced resistance to spalling at high temperatures due to higher mechanical strength (Malik et al., 2019).

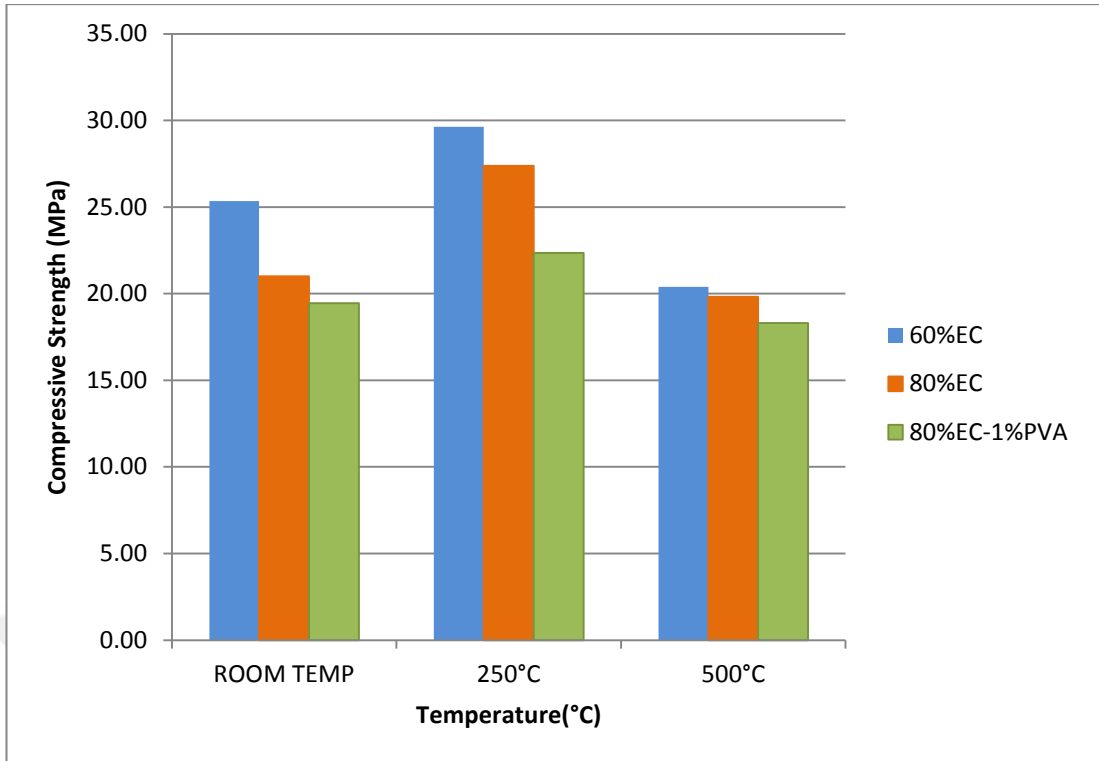


Figure 4.4 Compressive strength results before and after exposure to elevated temperatures



Figure 4.5 Failure modes of cube samples after compression test. (a) 80%EC ;(b) 80%EC-1%PVA

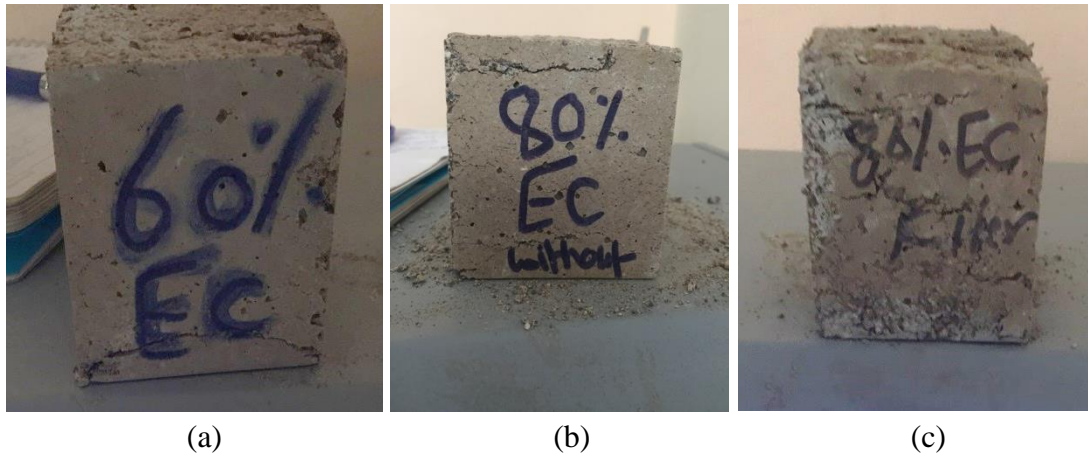


Figure 4.6 Failure characteristics of samples after subjected to 250°C. (a) 60%EC ; (b) 80%EC ; (c) 80%EC-1%PVA

4.4.2 Stress-Strain Relationship of Cylinder Samples

Figure 4.7 illustrates the stress-strain curves of cylinder specimens examined under compression at different temperatures. Generally, curves are divided into three stages: elastic deformation stage, plastic deformation stage, and the dropping stage which occurs after reaching the peak load. As shown in Figure 4.7, the sample with 60% EC gained the highest peak load value at ambient temperature as compared to the other samples. However, it also observed that the sample containing PVA fibers had the highest compressive strain as compared to its counterpart without fibers. The samples with fibers exhibited the ability to continue to deform and maintain a high load level even after reaching the peak strength, exhibiting steady-state cracking. There was no sudden and brittle failure occurred owing to the bridging capacity of the fiber (Kan et al., 2020).

The stress-strain curves of cylinder specimens after exposure to 250 °C are also presented in Figure 4.7. An increase in the compressive stress was observed for all the specimens when exposed to 250 °C. This can be attributed to the evaporation of free water and further geopolymerization, allowing the matrix to densify (Zhang et al., 2018). Similar to room temperature condition, 60%EC sample has the highest compressive stress at this temperature.

Furthermore, with the increasing temperature to 500°C, it was clear that the compressive stress of all the samples was lower than that at the room temperature, as shown in Figure 4.7. This is due to the increased pressure in the geopolymer mortar caused by the expansion of water vapor. This pressure leads to cracking and a

reduction in strength. Also, it can be seen that fiber-reinforced specimens had the highest compressive strain. In addition, when the temperature was increased to 500°C, the ductile failure mode that characterized PVA fiber-reinforced samples was lost. This is caused by the physical changes that occur in fibers when exposed to elevated temperatures (Masi et al., 2015). From the results, it can be concluded that the samples containing PVA fibers have the highest compressive strain at all temperatures. Figure 4.8 depicts the fracture or failure shapes of all the cylinder samples.

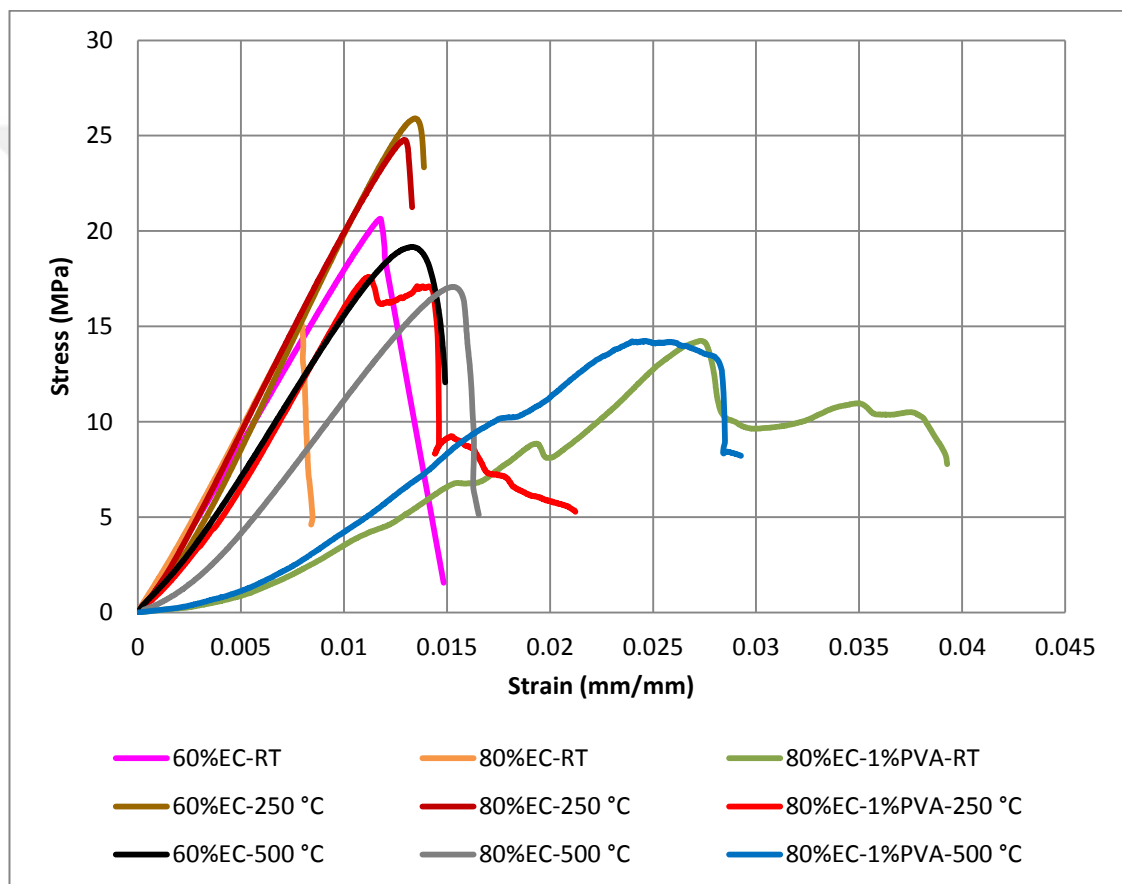


Figure 4.7 Stress-strain curves of cylinder samples at different temperatures



Figure 4.8 Failure patterns of cylinder samples under different temperatures (RT: Room temperature)

4.5 Flexural Behavior

4.5.1 Load–Displacement Curves

The flexural test was performed on prism and beam samples. Figure 4.9 shows the load-displacement curves for prism samples. According to the test results presented in Figure 4.9, it was observed that increasing the level of LWA replacement in geopolymer mortar resulted in a reduction in load carrying capacity and displacement. It can be seen that the 60%EC sample has a maximum load of 3236 N, resulting in a displacement of 1.4 mm, while the 80%EC sample has a maximum load of 2758 N with a displacement of 1.2 mm. This can be attributed to low toughness and high brittleness of the LWA particles (Youssf et al., 2018). Also, as shown in Figure 4.9, the PVA-containing sample exhibit ductile behavior since its maximum displacement value is greater. PVA fibers had a direct impact on enhancing the flexural behavior of LWGM. This is mainly due to the fibers' high tensile strength and their crack bridging behavior which was most likely caused by adhesion to the geopolymer matrix (Masi et al., 2015). Furthermore, the PVA fiber reinforcement clearly led to an increase in the area under the load-displacement curve, indicating a change in failure behavior from brittle to ductile. The alteration in failure mode reflects the impact of fibers on the ductility of lightweight geopolymer.

It should be noted that load-displacement curves of 60%EC and 80%EC specimens drop suddenly after reaching the ultimate load, representing a brittle failure mode. As shown in Figure 4.10a, samples without fibers were broken into two pieces after the peak load. In contrast, the sample with PVA fiber showed a ductile failure, with just one crack occurring after reaching its peak strength. The presence of PVA fiber stopped the specimen from splitting due to the bridging mechanism of fiber.

Figure 4.9 also presents the load-displacement curves of the LWGM with and without fibers after exposure to 250 °C. Generally, as the temperature rises, the load-carrying capacity decreases. However, all of the samples showed an increase in maximum load after being exposed to 250 °C. The ultimate flexural load of 60%EC, 80%EC, and 80%EC-1%PVA samples was increased by 10.29%, 22.31%, and 23.41% respectively, as compared to ambient temperature. It was also observed that when the samples were subjected to this temperature, their ductility decreased. But, owing to the presence of PVA fiber, 80%-1%PVA sample showed the

deflection-softening performance and some ductility. Only a few cracks were found in the PVA-containing sample that was exposed to 250 °C (see Figure 4.10b).

The temperature rises above 250 °C cause thermal cracks between the geopolymer matrix and the aggregates due to differences in thermal expansion, resulting in a significant reduction in the load carrying capacity of all specimens. After subject to 500°C, it was noted that the maximum load of specimen drops suddenly, as illustrated in Figure 4.9. Furthermore, the ductility of the sample decreased when exposed to the temperature of 500°C. The PVA-containing PVA sample exhibits a brittle behavior. This implies that as the exposed temperature level increases, the ductile nature of the sample containing fibers becomes brittle. This was due to a decrease in the bridging ability of PVA fibers at elevated temperatures as a result of a decrease in the modulus of elasticity of PVA fiber and a decrease in the chemical bond among the PVA fibers and the geopolymer matrix (Pourfalah, 2018). The failure modes of the samples after exposure to 500°C are illustrated in Figure 4.10c.

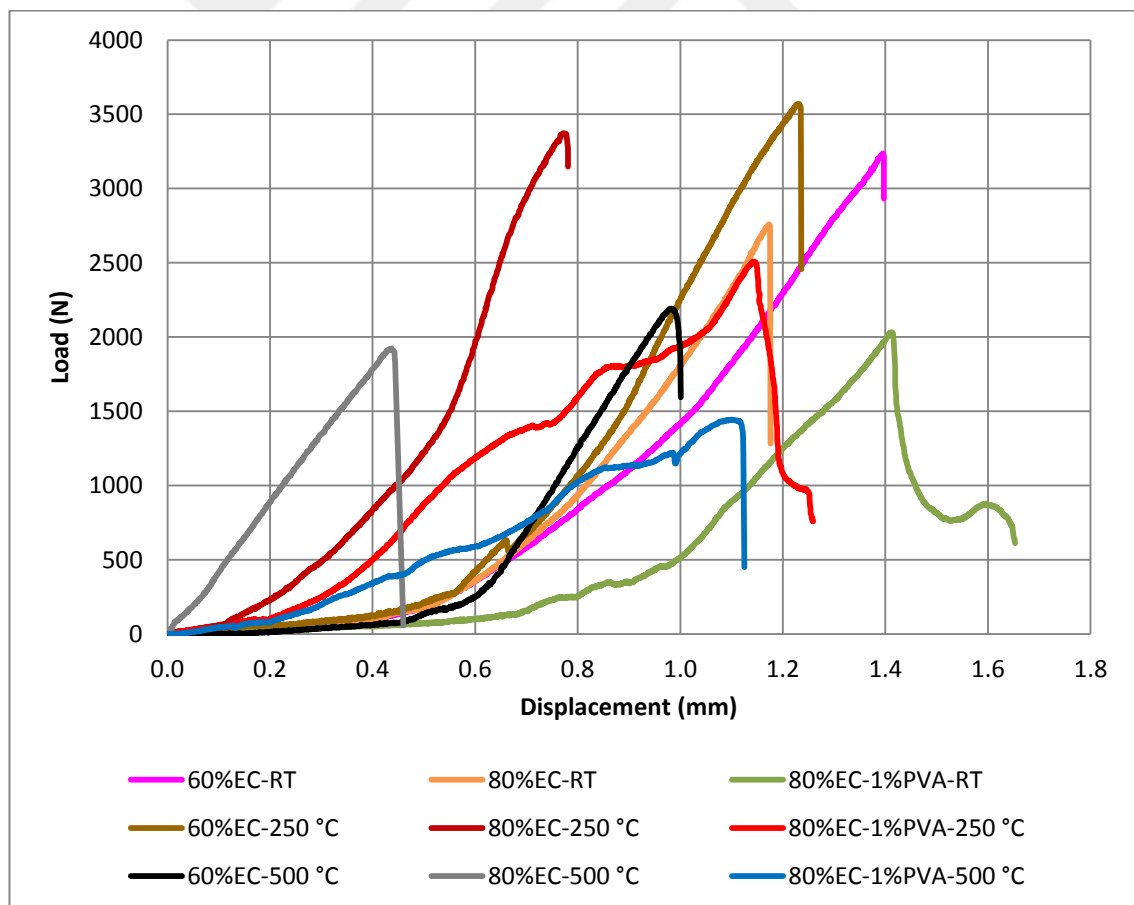
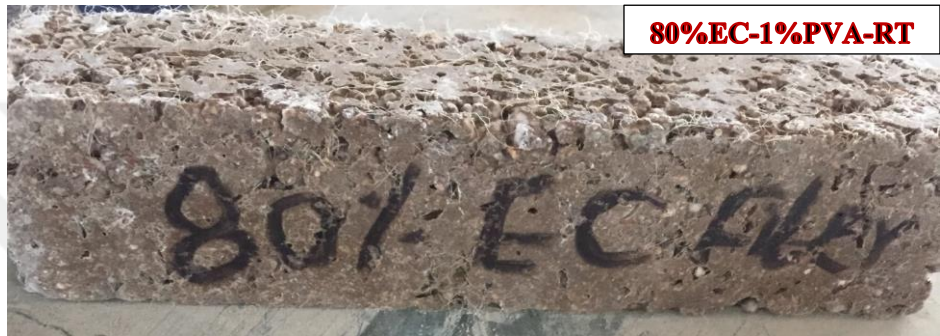


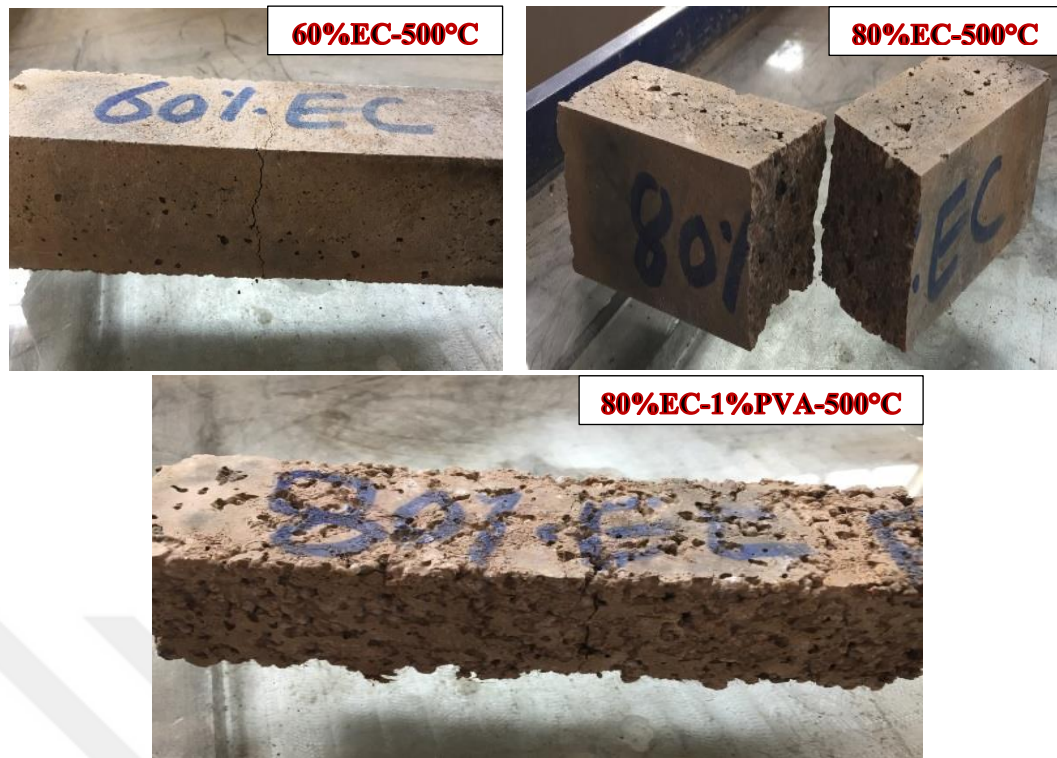
Figure 4.9 Load-displacement curves of the prism samples under different temperatures



(a)



(b)



(c)

Figure 4.10 Flexural failure modes of prism samples at different temperatures (RT: Room temperature)

For beam samples, the load-displacement curves at different temperatures are shown in Figure 4.11. Depending on the temperature level, different behaviors were observed in the load-displacement curves. From the behavior of the two samples at ambient temperature, it can be said that lightweight geopolymer samples reinforced with PVA fibers demonstrated a higher displacement capacity (Figure 4.11), with the first and second peak loads obviously visible in the load-displacement curve. The first peak reflected the first cracking load. Whilst, the second peak showed the capacity of PVA fibers to withstand rises in load after the first cracking appeared. Base on the figure, it can be seen that the displacement value of the beam with fibers at the peak load was 2.3 mm while the displacement value of the beam without fibers was 1.4mm. After high-temperature exposure, the load-displacement curves clearly showed that the ductility of samples decreased as the temperatures increased, as seen in Figure 4.11. At 500°C, it can be seen that the beam sample without fiber showed a linear elastic behavior till failure, indicating that the sample shattered in a brittle manner. Furthermore, it is worth mentioning that the size effect on flexural behavior

increased with increasing temperature. The temperature impact increased as the size of the specimen decreased (Abdulhaleem et al, 2018).

Figure 4.12 (a &b) depicts the failure patterns of lightweight geopolymer mortar with and without fibers for beam samples after flexural testing. For the 80%EC sample, cracking started in the midspan and spread rapidly to the top, splitting the sample into two parts (Figure 4.12a). However, the inclusion of PVA fibers in the lightweight geopolymer mixture enhanced the post-cracking behavior. It can be concluded that the use of PVA fiber improved the flexural performance of lightweight geopolymer mortar by providing significant support and controlling cracking.

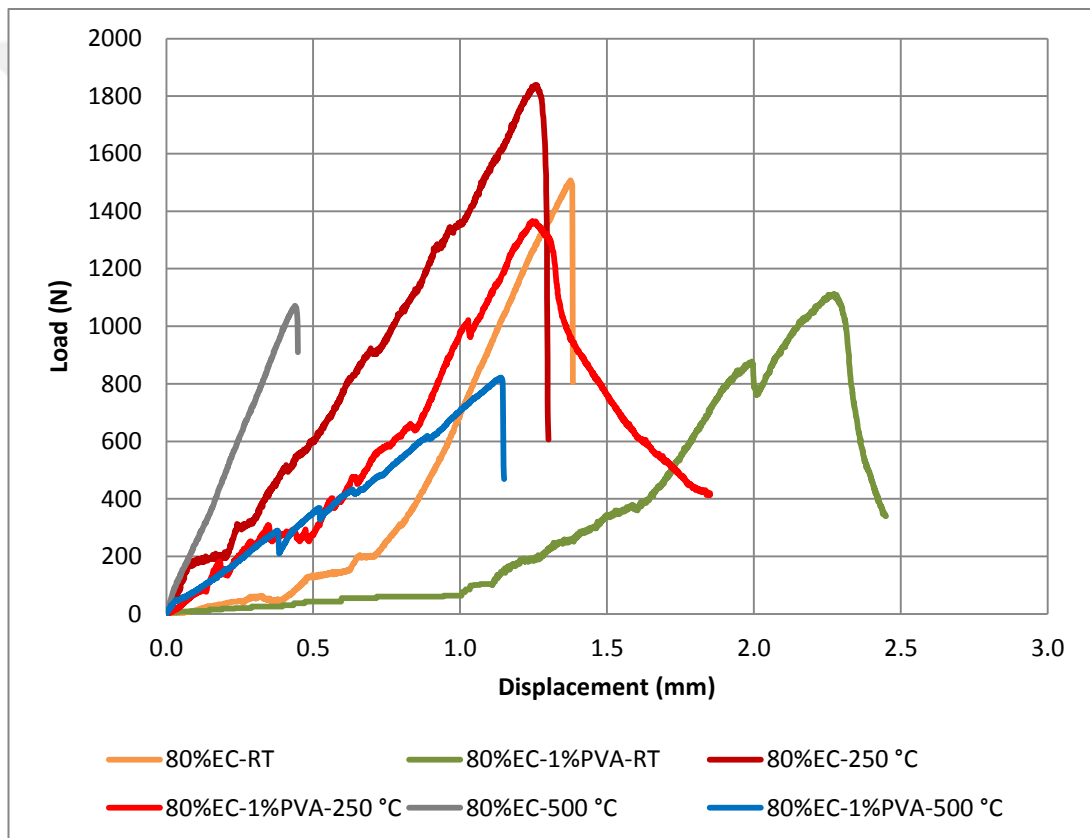


Figure 4.11 Load-displacement curves of the beam samples at different temperatures

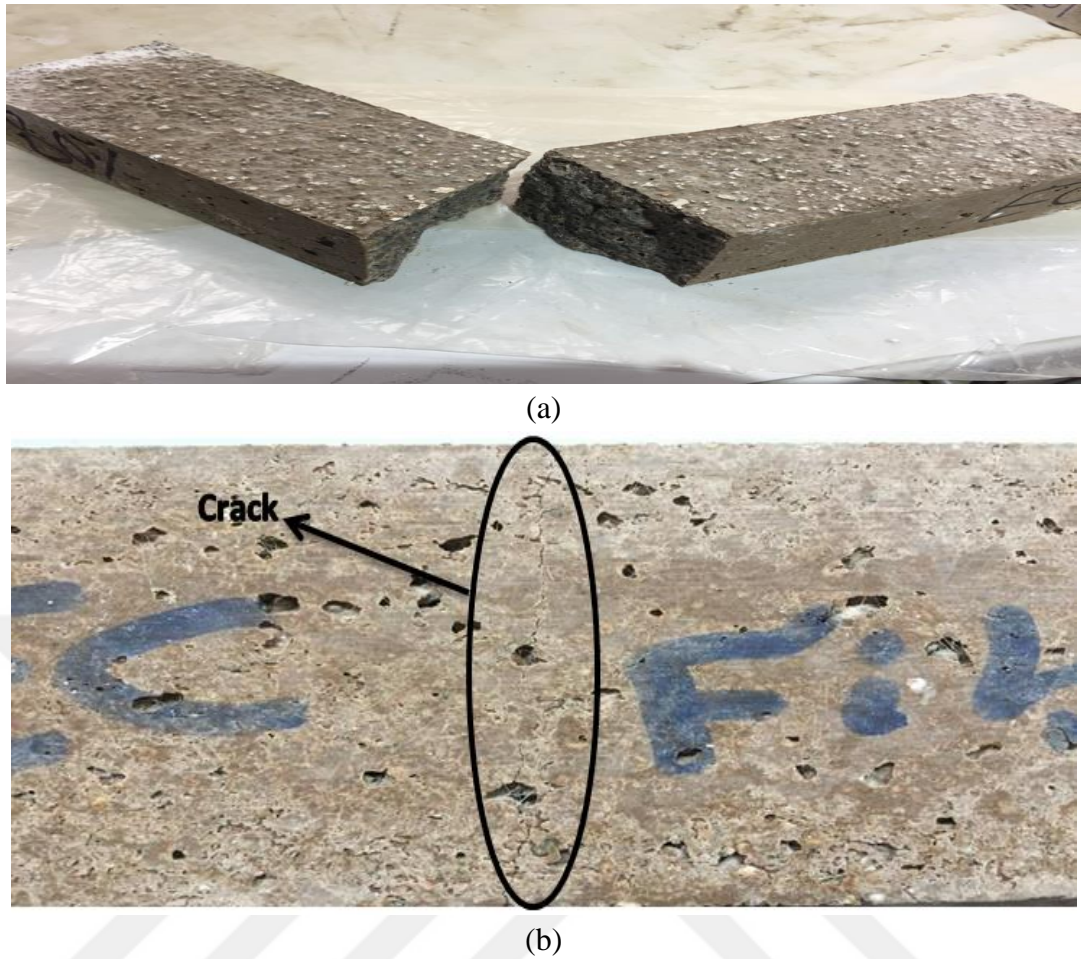


Figure 4.12 Flexural failure patterns of beam samples: (a) without fibers and (b) with 1% PVA fibers

4.6 Uniaxial Tensile Performance

Dogbone samples were used to test the tensile behavior of a lightweight geopolymers mixture having PVA fiber. It is worth mentioning that samples without fiber are brittle, they were broken during demolding.

The PVA-containing samples subject to a uniaxial tensile test after being exposed to different temperatures. A tensile stress-strain curve was developed according to the load, displacement, and sample dimension. Figure 4.13 illustrates the stress-strain curves of a PVA fiber-reinforced sample at room temperature, as well as after heating to 250°C and 500°C. There was a clear trend for the change in stress and strain curves with temperature. At room temperature, 80%EC-1%PVA has an ultimate tensile strength of 1.3 MPa and a tensile strain capacity of 2.6%. However, after exposure to 250°C, the tensile strength increased compared to the unheated sample. The increase in strength is attributed to the further geopolymers, which

results in a stronger bond between the matrix and the fibers (Chandrakanth and Koniki, 2020). It can be seen that tensile strength increased by 14% at 250°C compared to room temperature. However, as can be observed from the figure that the tensile strain capacity had decreased remarkably. The strain capacity at 250°C was 62% lower than that at room temperature. The decrease in strain capacity may be due to changes that occur in the structure of PVA fibers at this relatively high temperature, because the melting point of PVA fiber is 225°C, as reported by Liu and Tan (2017). Nonetheless, the remaining fibers were still capable of bridging the samples, as shown in Figure 4.14.

Generally, the tensile strength decreased with increasing temperature, following a similar trend to that observed by Bhat et al (2014). As shown in Figure 4.13, tensile strength was reduced by 33% after exposure to 500°C, as compared to room temperature. This was caused by the melting of PVA fibers, which resulted in the creation of voids as well as shrinkage-induced cracks (Zhang et al., 2021). It is worthy to note that after being subjected to 500°C, the tensile strain capacity is slightly increased. This can be associated with the deterioration of 80%EC-1%PVA tension stiffness as a result of varying degrees of thermal decomposition (Liu and Tan, 2017).

In addition, the tensile stress-strain behavior of the control sample and the PVA fiber sample at 250°C can be seen in Figure 4.13. It can be observed that sample without fibers exhibited brittle behavior with a sudden drop after reaching the peak stress. However, the sample with fibers showed a strain-softening behavior which represents a decrease in stress after reaching the peak value with an increase in strain capacity.

Figure 4.14 shows the tensile failure modes of the samples with and without fibers after exposure to elevated temperature. It can be seen that all the cracks of dogbone samples occur in the middle narrow section. Multiple cracks were observed in dogbone specimens with PVA fiber during loading, but many of these microcracks closed after the samples were unloaded. Similar observations were reported by a previous study (Al-Majidi et al., 2017).

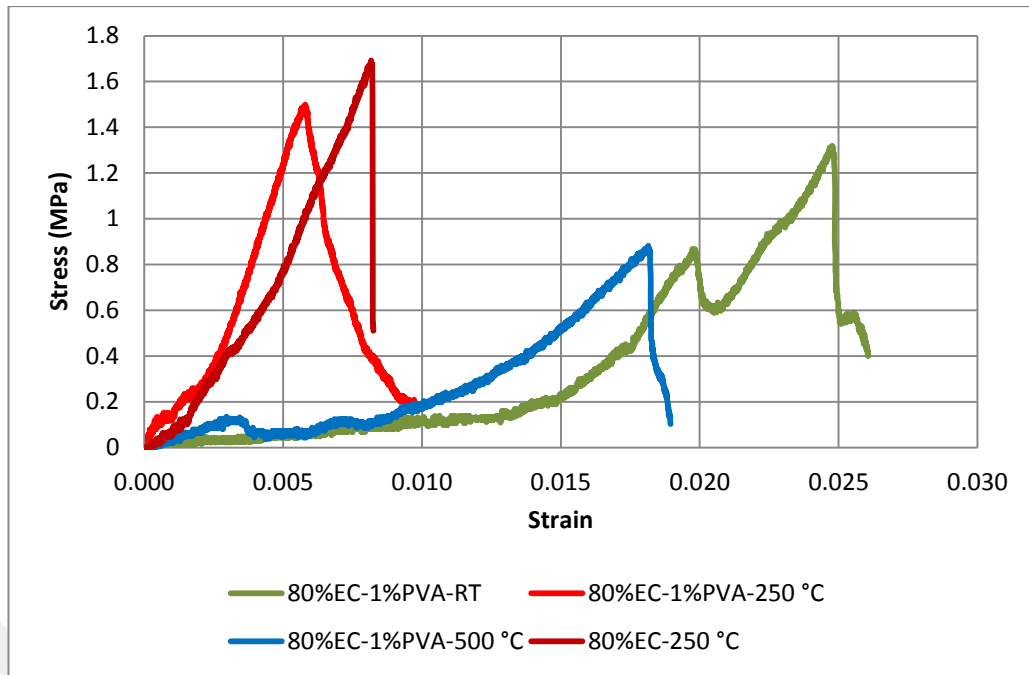


Figure 4.13 Tensile stress-strain curves of dogbone specimens after exposure to different temperatures

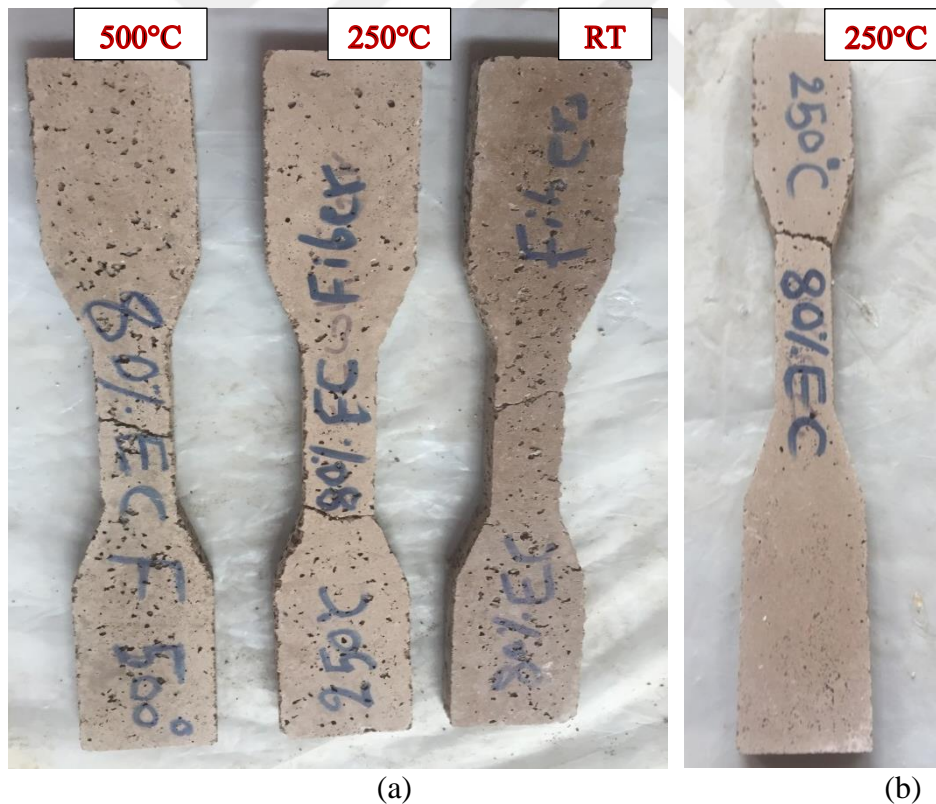


Figure 4.14 Tensile failure modes of dogbone sample (a) with fibers ; (b) without fibers

CHAPTER 5

CONCLUSIONS

In this study, the use of LECA and PVA fibers in the production of geopolymer mortar is investigated. The impact of the temperature level (room temperature, 250°C, and 500°C) on the mechanical properties of LWGM with and without fibers is also examined. In this case, three different mixes were designed and cured at room temperature. Slag was the sole source material in geopolymer mortar. In this research, river sand was partially replaced with LECA at 60% and 80%, by weight. Fresh properties of LWGM were investigated employing workability and fresh density. whilst, mechanical properties were assessed using compressive, flexural, and uniaxial tensile tests. Based on the experimental findings of this study, the following conclusions can be summarized:

- Based on the fresh LWGM test results, it could be inferred that increasing the LECA replacement level reduces LWGM workability. Regarding PVA fibers, it was revealed that the inclusion of fibers in LWGM decreased its workability.
- The fresh and dry density of geopolymer mortar decreased as the LECA content increased due to its low density. It was also observed that the adding PVA fibers resulted in a slight reduction in LWGM density. Based on the results, all of the geopolymer mortar mixes produced in this study can be considered to be lightweight according to ACI committee 213R.
- The substitution of river sand with LECA led to the reduction in compressive strength of geopolymer mortar at 1, 7, and 28 days. This was due to the porous structure of the LECA particles. A slight decrease in compressive strength was observed with fiber samples compared to non-fiber samples. At 28 days, the mixture containing 60% of LECA achieved the maximum compressive strength of 25.35 MPa under ambient conditions.

- Based on the findings of the current study, it can be seen that the mechanical properties of LWGM (with and without fibers) were affected at elevated temperatures. Regarding the compressive strength, there was an increase in the strength of all samples after being subjected to 250°C which occurred as a result of further geopolymerisation. While the strength began to deteriorate when the samples were exposed to 500°C due to vapor impact and also the difference in thermal expansion among the aggregates and geopolymer matrix.
- When the stress and strain curves for cylinder samples were examined, it can be seen that the sample with 60% of LECA had higher compressive stress, while the sample with fibers had higher strain capacity. This implies that the presence of fibers allows geopolymer mortar to continue to deform and sustain a load even after reaching its peak load. After exposure to 250°C, all the stress-strain curves of cylinder samples (with and without fibers) showed an increase in compressive stress. As the temperature increased, the compressive stress of the cylinder specimens decreased.
- The flexural behavior of LWGM (with and without fibers) was investigated utilizing both prism and beam specimens. The experimental load-displacement curves of geopolymer mortar revealed that increasing the LECA content reduces both load carrying capacity and displacement. LWGM with PVA fibers demonstrated ductile behavior as compared to that without fibers, indicating that PVA fibers had a significant impact on improving flexural behavior.
- It has been found that under flexural test at 250°C, the load carrying capacity of all samples increased while the displacement decreased as compared to counterparts at room temperature. When the temperature was increased to 500°C, it was observed that the ductile behavior of the PVA-containing sample changed to brittle due to a decrease in the bridging capacity of fibers under elevated temperatures.
- Dogbone samples were used to study the tensile performance of the reinforced mixtures with PVA fibers under elevated temperatures. The tensile strength of

the tested dogbone samples improved when exposed to 250 °C. However, owing to the low molten point of fibers, there was a substantial decrease in strain capacity as compared to the unheated sample. With increasing temperature to 500 °C, the tested sample showed a decrease in tensile strength (33%) and a slight increase in strain capacity.

Based on the points mentioned above, it is clear that LECA can be utilized to produce lightweight geopolymer mortar. This study also illustrates that the addition of PVA fibers to LWGM enhanced the flexural and tensile behavior. For future study, different source materials such as fly ash with or instead of slag may be examined in the production of geopolymer mortar. Physical properties such as freezing-thawing resistance of LWGM with and without PVA fibers can be investigated. Different types of fibers in various dosages can be used in LWGM. More research is needed to investigate the mechanical and durability properties of LWGM with and without fibers under chemical environments.

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WORK EXPERIENCE

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PUBLICATIONS

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