



**REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKER SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MATERIALS ENGINEERING**

SYNTHESIS AND PROPERTIES OF GEOPOLYMERS

**İLKİN ALTINSOY
MASTER OF SCIENCE**

ADANA 2023



**REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKER SCIENCE AND TECHNOLOGY
UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MATERIALS ENGINEERING**

SYNTHESIS AND PROPERTIES OF GEOPOLYMERS

**İLKİN ALTINSOY
MASTER OF SCIENCE**

**SUPERVISOR
Asst. Prof. Dr. MİNE TAYKURT DADAY**

ADANA 2023

ABSTRACT

SYNTHESIS AND PROPERTIES OF GEOPOLYMERS

İlkin ALTINSOY

Department of Materials Engineering

Supervisor: Asst. Prof. Dr. Mine TAYKURT DADAY

July 2023, 60 pages

Continuous cement manufacture has increased the quantity of CO₂ released into the atmosphere, increasing the level of global warming, which has a negative impact on the environment. As a result, a more sustainable strategy, as well as a comprehensive review of the existing admixtures used to replace traditional concrete, has become critical. Many studies on geopolymer binders, which has equivalent or higher durability and strength than traditional concrete, have been conducted for this purpose by many researchers. Geopolymers offer the advantage of using multifunctional materials mixed with alkali-activated solutions to replace traditional cement. As a result, this study offers a comprehensive review of geopolymer material, including its ingredients, manufacturing procedures, and curing regimes, as well as a comparison of its physical and mechanical properties to traditional cement structures.

Keywords: Alkali-Activated Solutions, Binders, Geopolymers

ÖZET

JEOPOLİMERLERİN SENTEZLENMESİ VE ÖZELLİKLERİ

İlkin ALTINSOY

Yüksek Lisans, Malzeme Mühendisliği Anabilim Dalı

Danışman: Dr. Öğr. Üyesi Mine TAYKURT DADAY

Temmuz 2023, 60 sayfa

Sürekli çimento üretimi, atmosfere salınan CO₂ miktarını artırarak, çevre üzerinde olumsuz etkisi olan küresel ısınma sorununu artırmıştır. Sonuç olarak, geleneksel betonun yerine kullanılan mevcut katkıların kapsamlı bir incelemesinin yanı sıra daha sürdürülebilir bir strateji kritik hale gelmiştir. Geleneksel betona göre eşdeğer veya daha yüksek dayanıma sahip olan jeopolimer bağlayıcılar ile ilgili birçok araştırma bu amaçla birçok araştırmacı tarafından yapılmıştır. Geopolimerler, geleneksel çimentonun yerine alkali ile aktive edilen solüsyonlarla karıştırılmış çok işlevli malzemelerin kullanılması avantajını sunar. Sonuç olarak bu çalışma, bileşenleri, üretim prosedürleri, kürleme rejimleri yanı sıra geleneksel beton ile fiziksel ve mekanik özellikleri karşılaştırması dahil olmak üzere jeopolimer malzemeler hakkında kapsamlı bir çalışma sunmaktadır.

Anahtar Kelimeler: Alkali-Aktif Solüsyonlar, Bağlayıcılar, Jeopolimerler

Dedication

Dedication to my mom and dad, whom I love dearly

To my family who have supported me so far.

ACKNOWLEDGEMENTS

I would like to thank everyone who helped me in my thesis with the pride of completing this thesis with difficulties. I am deeply grateful to my advisor, Asst. Prof. Dr. Mine TAYKURT DADAY, for their unwavering support and guidance throughout my master's program. Their expertise and patience have been invaluable to me and have played a crucial role in the success of this thesis. I would also like to thank Prof. Dr. Özen KILIÇ and Assoc. Prof. Dr. Ali Sinan DİKE for serving on my thesis committee and providing helpful feedback and suggestions. I am deeply thankful to my friends and family for their love and support during this process.



TABLE OF CONTENT

ABSTRACT	i
ÖZET	ii
TABLE OF CONTENT	v
LIST OF FIGURES.....	vii
LIST OF TABLES.....	viii
1. INTRODUCTION	1
2. LITERATURE REVIEW	6
2.1. Terminology of Geopolymers.....	6
2.2. Common Characterization Tests for Cement Like Materials	9
2.3. Materials Used in Production of Geopolymers	11
2.3.1. Binding Materials	11
2.3.1.1. Fly Ash in Geopolymer Synthesis.....	16
2.3.1.2. Blast Furnace Slag in Geopolymer Synthesis.....	17
2.3.1.3. Red Clay Bricks in Geopolymer Synthesis.....	17
2.3.1.4. Construction and Demolition Wastes in Geopolymer Synthesis.....	18
2.3.1.5. Other Wastes.....	19
2.3.2. Alkaline Activators	19
2.4. Production Process and Methods	20
2.5. Taxonomy	22
3. RESULT AND DISCUSSION	26
3.1. Properties of Geopolymers.....	26
3.1.1. Mechanical Properties	26
3.1.1.1. Compressive Strength.....	26
3.1.1.2. Flexural Strength	30
3.1.1.3. Split-Tensile Strength	32
3.1.2. Fresh Properties.....	34
3.1.3. Physical Properties	35
3.1.3.1. Apparent Porosity.....	35
3.1.3.2. Water Absorption.....	36
3.1.3.3. Bulk and Apparent Densities.....	36

3.1.4. Microstructural Properties and Analyses	37
3.1.4.1. Fourier Transform Infrared Spectroscopy (FTIR) Analysis	37
3.1.4.2. Scanning Electron Microscopy (SEM) Analysis	39
3.1.4.3. X-Ray Diffraction (XRD) Analysis	44
3.2. Factors Affecting the Geopolymer Properties.....	46
3.2.1. Raw Material Type.....	46
3.2.2. Alkali Activator Concentration.....	46
3.2.3. Liquid/Solid Ratio	47
3.2.4. Curing Regime	47
4. CONCLUSION	49
5. REFERENCES	51

LIST OF FIGURES

Figure 1.	Near-surface temperature differences between 2022 and the 1991–2020 average	2
Figure 2.	Monthly globally averaged measure of atmospheric concentration from 1984 to 2021 of CO ₂ in parts per million.....	2
Figure 3.	Geopolymer properties diagram	5
Figure 4.	Classification of geopolymer structures	8
Figure 5.	Compressive strength test	9
Figure 6.	Flexural strength test.....	10
Figure 7.	Split tensile Test.....	11
Figure 8.	Compressive strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16	29
Figure 9.	Flexural strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16	31
Figure 10.	Split tensile strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16	33
Figure 11.	FTIR analysis for the series A, B and C	38
Figure 12.	FTIR spectra of red clay brick waste-based geopolymers.....	39
Figure 13.	SEM image of the geopolymer sample.....	40
Figure 14.	Microstructures of geopolymers of series A, B and C.....	41
Figure 15.	SEM micrograph of red clay brick waste (RCBW) geopolymers, RCBW-Low, RCBW-Opt and RCBW-75°C.....	42
Figure 16.	SEM for gopolymer concrete mixtures prepared with waste glass powder and fly ash.....	43
Figure 17.	XRD spectra for supplementary cementitious material based red clay brick waste (RCBW) geopolymers	44
Figure 18.	XRD pattern for different fly ash (FA) and blast furnace slag (BFS) geopolymer samples	45

LIST OF TABLES

Table 1. Chemical Compositions of the Raw Materials (by weight)	15
Table 2. Taxonomy of the study	22



LIST OF ABBREVIATIONS

FTIR	: Fourier Transform Infrared Spectroscopy
OPC	: Ordinary Portland Cement
SEM	: Scanning Electron Microscopy
XRD	: X-Ray Diffraction



LIST OF SYMBOLS

cm^3 : Cubic Centimeter

g : Gram

μm : Micrometer

M : Molar

nm : Nanometer



1. INTRODUCTION

As a result of changes in the World and developing in the civilization, the necessity for construction materials has been increasing. These materials, such as concrete, bricks, mortars, and cement, are consumed a lot compared to all the other commercial materials that we use, and in fact, concrete is the second most consumed product around the World after water. The number of construction materials is increasing day by day, and their production process should be investigated carefully due to potential harm to the environment (Provis & Bernal, 2014). Apparently, cement production alone contributes to greenhouse gas emissions, and it causes a huge amount of CO₂ to be released into the environment. According to investigations about the cement industry's effect on carbon footprint, it is concluded that it contributes to about 5% of global environmental pollution (Mikulčić et al., 2016). The CO₂ emissions from the manufacture of cement are primarily due to the thermal decomposition of calcium carbonate to create the reactive phases of calcium silicate and aluminate, which is the base of Portland cement. The gross pollution footprint of approximately 0.8 tons of CO₂ equivalent per ton of Portland cement produced is split between the emissions from the burning of fossil fuels and the CO₂ emitted from the conversion of calcium carbonate to oxide form (Provis & Bernal, 2014).

All these effects contribute to climate change, which is the biggest problem that mankind faces in the modern World. The temperature changes in the World is the most discernable evidence of climate change. World Meteorological Organization (WMO) presents climate change reports every year, and the most recent report shows the global mean temperature in 2022, which incorporates readings of the temperature near the surface of the ocean and land, was 1.15°C higher than the pre-industrial average between 1850 and 1900. The year 2022 will either rank fifth or sixth in terms of global warming since 1850. The eight hottest years on record across all data sets are from 2015 to 2022. Also, near-surface temperature differences between 2022 and the 1991–2020 average show high record temperatures observed especially in Western Europe, the western Mediterranean, parts of Central and Eastern Asia, and New Zealand, as can be seen in Figure 1 below (World Meteorological Organization, State of the Global Climate 2022 3-4).

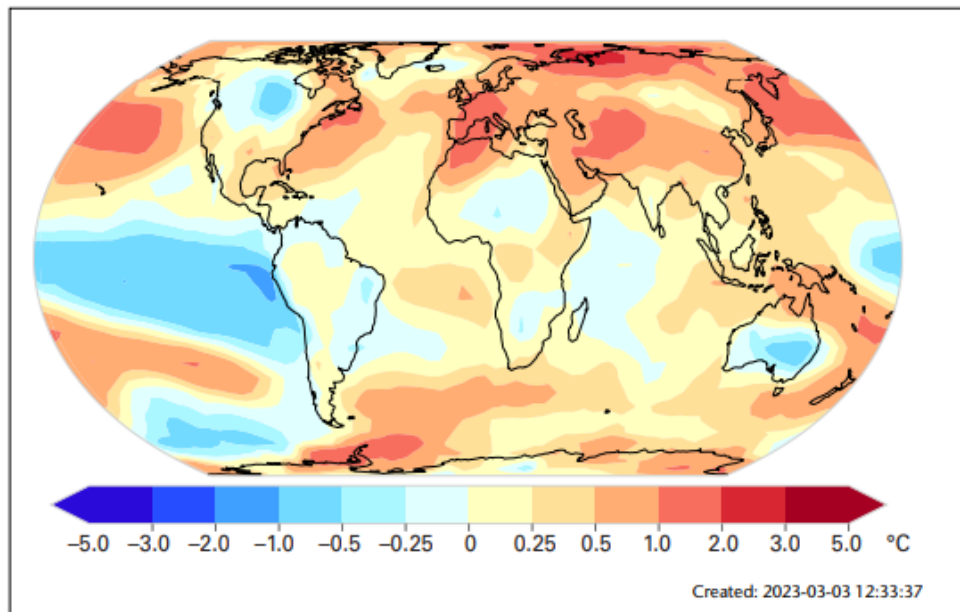


Figure 1. Near-surface temperature differences between 2022 and the 1991–2020 average

Also, greenhouse gas concentrations in the atmosphere reflect a balance between emissions from human activities, natural sources, and sinks in which the removal of gas from the atmosphere by conversion to a different chemical compound. Human-caused increases in greenhouse gas levels in the atmosphere have been a primary driver of climate change since at least the Industrial Revolution. As shown in Figure 2, the same report states that the rise in CO₂ between 2020 and 2021 was comparable to that seen between 2019 and 2020, although it was greater than the average yearly growth rate over the previous ten years (World Meteorological Organization, State of the Global Climate 2022 2).

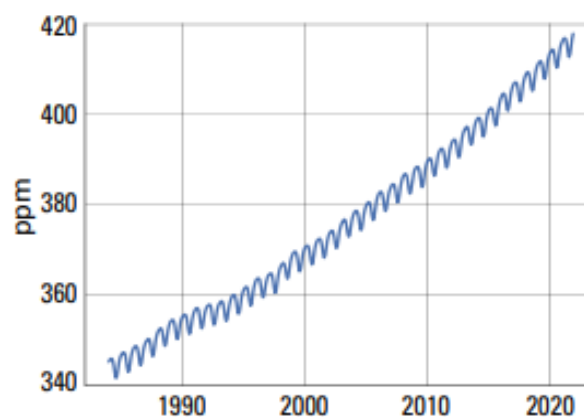


Figure 2. Monthly globally averaged measure of atmospheric concentration from 1984 to 2021 of CO₂ in parts per million

To reduce the harmful effects of industrial production, there was a need to find some sustainable options. For that purpose, French professor J. Davidovits proposed a material named geopolymer to be used as construction binders. These materials can be high-profile example of alternative binders and solutions for the problems that the World faces regarding environmental concerns. He describes geopolymers as ceramic-like inorganic polymers produced at low temperatures, generally below 100 °C. They consist of mineral molecules' chains or networks connected with covalent bonds (Davidovits, 2017). Using this material as an alternative to cement and concrete would significantly lower greenhouse gas emissions. Simply put, the CO₂ savings gained by the use of these binders were primarily attributed to the prevention of carbonate precursors, such as limestone (CaCO₃), and the high-temperature processing of all cement components in a fossil fuel-fired furnace (Provis & Bernal, 2014). However, geopolymers offer these environmental benefits; it's important to note that their full lifecycle impact, including extraction of raw materials, production, transportation, and disposal, should be carefully considered and compared to traditional cement to assess their overall environmental performance. Additionally, as with any material, there may be specific challenges and trade-offs in certain contexts or applications, so thorough assessment is crucial (Zhang et al., 2020).

If explained in detail, geopolymers are materials that consist of a semi-crystalline three-dimensional inorganic network, and they can be produced from the natural or synthetic aluminosilicate minerals or aluminosilicates that obtained from industrial by-products or wastes (Davidovits, 2015). To be more specific, aluminosilicates are compounds that contain both aluminum (Al) and silicon (Si) atoms, along with oxygen (O) atoms. They are a type of mineral or chemical compound commonly found in nature. The structure of aluminosilicates consists of a three-dimensional framework of aluminum and silicon atoms bonded together by oxygen atoms. These compounds are abundant in the Earth's crust and are essential components of many rocks, soils, clays, and minerals. Examples of aluminosilicates that are commonly used in geopolymer synthesis can be listed as metakaolin, fly ash, granulated blast slag, glass, rice husk ash, ceramics, or a combination of these materials. Besides aluminosilicates, an aqueous solution that includes reactive ingredients such as potassium or sodium hydroxide, potassium or sodium silicate, and phosphoric acid is needed to obtain a geopolymer structure (Bai & Colombo, 2018). The main concern in the production of geopolymers is that within so many choices in the precursors and the alkali activator, the best option to obtain this material is still one of the main focuses of the studies of geopolymers.

These choices affect the properties of geopolymers, which show great promising results considering their usage compared to conventional construction materials such as Ordinary Portland Cement (OPC). Good physical properties, high strength, and fire-resistant ability, besides the lower impact on the environment and low carbon footprint in its production, make it a great binder. Also, a wide range of raw material choices for its production and cost-friendly systems appeal to the interest in this green material (Amran et al., 2020; Bai & Colombo, 2018; Mohajerani et al., 2019). All these features are shown in a diagram in Figure 3. With these great abilities, geopolymer binders can be used in nuclear waste immobilization, high-value composite manufacturing, and high-volume infrastructure construction (Provis & Deventer, 2014).

The scope of this review study is to reveal an overview of geopolymer production conditions for the construction industry and contribute to the literature for future works. The optimum conditions in the synthesis, the effects of precursor and alkali activator type as well as the other parameters on the mechanical, physical, fresh, and structural properties were discussed in this paper.

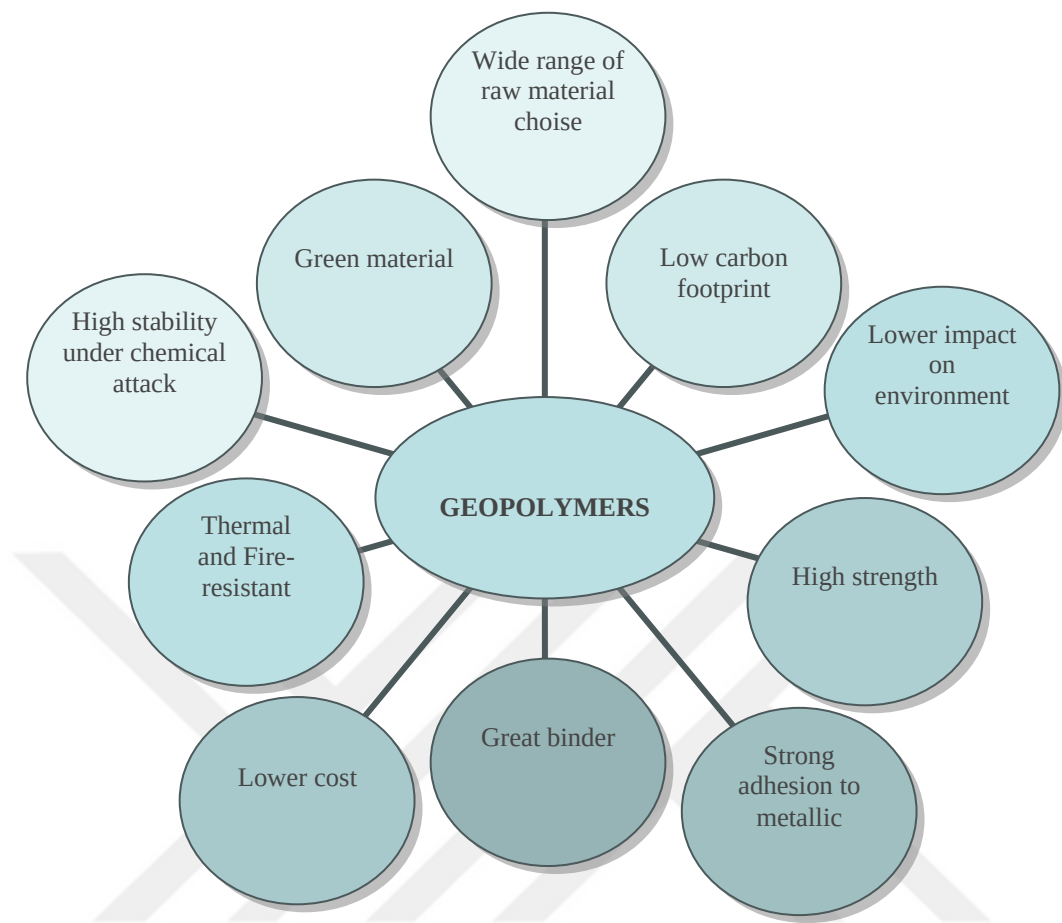


Figure 3. Geopolymer properties diagram

2. LITERATURE REVIEW

2.1. Terminology of Geopolymers

Before going into the details of geopolymers, Ordinary Portland Cement (OPC), which is the main type of construction material when comparing the alternative solutions, should be explained. OPC is the most widely used type of cement in the construction industry. It is a hydraulic cement, meaning it sets and hardens when mixed with water. OPC is primarily composed of three main constituents: limestone (calcium carbonate), clay (silica, alumina, and iron oxide), and gypsum (calcium sulfate). These ingredients are finely ground and then heated in a kiln at high temperatures, resulting in chemical reactions that produce clinker. The clinker, which is a sintered material, is then ground into a fine powder to produce the final product, Ordinary Portland Cement. OPC is known for its strength and durability, making it suitable for a wide range of construction applications, such as concrete production, mortar, and grouting. It provides binding properties that help hold together aggregates like sand and gravel, forming a solid structure. OPC is widely available and versatile, making it a popular choice for general construction purposes (Hlobil et al., 2022; Huntzinger and Eatmon, 2009; Vivian et al., 2022; Zhang, 2011). However, the production of OPC has certain environmental and sustainability challenges. Here are some of the cons associated with its production:

1. Carbon emissions: The production of OPC involves high-temperature kilning, which requires significant energy consumption. This process releases carbon dioxide as a by-product, contributing to greenhouse gas emissions and climate change.
2. Energy consumption: The production of OPC requires substantial amounts of energy, primarily for the heating of kilns. This energy often comes from non-renewable sources, leading to increased reliance on fossil fuels.
3. Resource depletion: OPC relies on finite natural resources like limestone and clay. The extraction and depletion of these resources can have long-term environmental consequences and impact local ecosystems.
4. Water consumption: Cement production requires substantial amounts of water for the cooling and grinding processes. This can put a strain on water resources in regions already experiencing water scarcity.

5. Dust and air pollution: The grinding and handling of raw materials during cement production can generate dust and particulate matter, contributing to air pollution and potential health hazards for workers and nearby communities.

To address these concerns, there is ongoing research and development of alternative cement formulations, such as geopolymers which is the main focus of this study. While geopolymers offer potential environmental benefits, there can be certain negative impacts and considerations associated with their use:

1. Raw Material Sourcing: Geopolymers often rely on industrial by-products such as fly ash and slag. The availability of these materials can vary regionally, potentially leading to increased transportation and associated carbon emissions if they need to be transported long distances.
2. Energy Intensive Process: While geopolymers generally require lower temperatures during production compared to traditional cement, the manufacturing process can still be energy-intensive, depending on factors such as the type of precursor materials used and the specific production methods.
3. Chemical Usage and Alkalinity: The alkaline nature of geopolymers can pose challenges during production, handling, and disposal. It may require careful management of chemicals and waste to prevent negative impacts on soil and water quality.
4. Lack of Standardization: Geopolymers are not as widely standardized as traditional cement. The lack of standardized testing methods and regulations can make it difficult to ensure consistent quality and performance.
5. Long-Term Behavior and Durability: While geopolymers show promise for improved durability, their long-term performance in real-world conditions is still being studied. There might be unforeseen issues that arise over time, affecting their environmental impact.

It's important to conduct thorough life cycle assessments and consider these potential negative impacts alongside the benefits when evaluating the environmental sustainability of geopolymers. As research and development continue in this field, some of these challenges may be addressed through technological advancements and improved practices (Kohout et al., 2023; Zhang et al., 2020).

If we talk about geopolymers in detail, they are very similar to naturally occurring zeolite minerals, and the term was first introduced to the literature by Davidovits (Davidovits, 1991). His research in his early years aimed to produce a plastic material that is heat-resistant and non-combustible for structural applications (Mohajerani et al., 2019). The “geo” part represents the geological materials, and it symbolizes the inorganic aluminosilicate, which reacted with an alkaline solution to obtain the binder thanks to the polycondensation reaction (Liew et al., 2016). Briefly, geopolymerization is carried out by the zeolitic-like raw material's conversion to alumino-silicate gels that are a type of gel material network structure and harden subsequently. As a result, polymeric Si-O-Al bonds are formed by geopolymers from the chemical reaction. Three-dimensional silico-aluminate structures in amorphous to semi-crystalline forms were obtained with this reaction. These forms are categorized into three basic forms, poly(sialate), poly(sialate-siloxo), and poly(sialate-disiloxo) regarding its Si/Al ratio (Davidovits, 1991), as seen below in Figure 4.

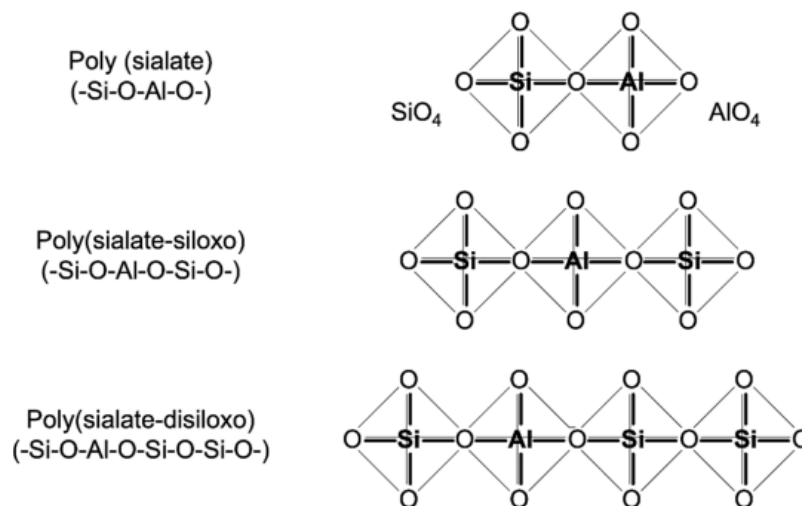
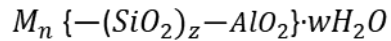


Figure 4. Classification of geopolymer structures

The geopolymers' empirical formula is as,



where M is a cation such as K^+ , Na^+ or Ca^{2+} ; n is the degree of polycondensation; z is 1, 2, 3, and w is the amount of binding water (Davidovits, 1991).

2.2. Common Characterization Tests for Cement Like Materials

Several strength tests are applied to Ordinary Portland Cement (OPC) to assess its performance and suitability for various construction applications. The three primary strength tests conducted on OPC are:

1. **Compressive Strength Test:** This test measures the ability of OPC to resist compressive forces. Cylindrical or cubic specimens, prepared according to standard procedures, are subjected to gradually increasing compressive loads until failure occurs. The maximum load sustained by the specimen before failure is recorded, and the compressive strength is calculated. OPC typically exhibits compressive strength values ranging from 15 MPa to 50 MPa or higher. However, the specific requirements for compressive strength can vary based on the intended application. For example, structural concrete for buildings may require compressive strength in the range of 20 MPa to 40 MPa, while high-strength concrete for specialized applications may have compressive strength exceeding 50 MPa. The test is shown in Figure 5 below (Jamal, 2017).



Figure 5. Compressive Strength Test (Jamal, 2017)

2. Flexural Strength Test: This test evaluates the bending or tensile strength of OPC. Prismatic specimens, typically beams or bars, are loaded in a three-point or four-point bending configuration. The load is applied until the specimen fractures, and the maximum load sustained is recorded as the flexural strength. The flexural strength of OPC is generally lower than its compressive strength. Typical values can range from 2 MPa to 8 MPa, depending on various factors. Again, specific project requirements and design considerations will determine the desired flexural strength. The test is shown in Figure 6 below (Ramiz, 2020).

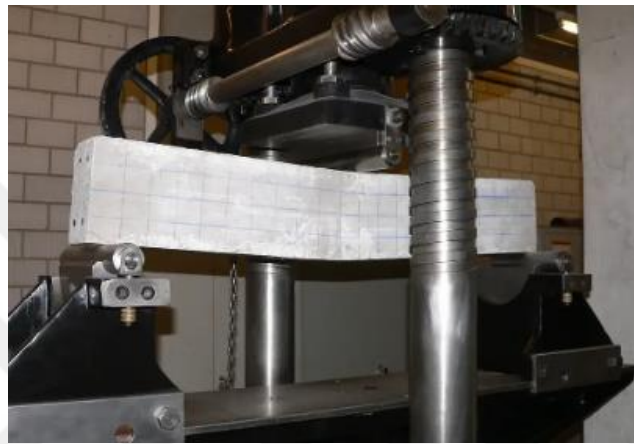


Figure 6. Flexural Strength Test (Ramiz, 2020)

3. Split Tensile Test: This is another strength test that can be applied to OPC to assess its tensile strength. While the compressive strength test measures the material's resistance to compressive forces, the split tensile test evaluates its ability to resist tensile stresses. In the split tensile test, a cylindrical specimen of OPC is placed horizontally between two parallel platens or loading jaws. The axial compressive force is applied along the length of the specimen until it fractures. This causes the specimen to split apart, and the tensile strength is calculated based on the maximum load sustained and the cross-sectional area of the specimen. The split tensile strength of OPC provides an indication of its ability to withstand tensile forces, which is particularly important in scenarios where the material is subjected to bending or tension. The split tensile strength of OPC is usually around 1/10th to 1/15th of its compressive strength. Therefore, typical values can range from 1 MPa to 5 MPa. The test is shown in Figure 7 below (Gundaraniya, 2022).



Figure 7. Split Tensile Test (Gundaraniya, 2022)

These strength tests help determine the performance characteristics of OPC and its suitability for various structural applications. In addition to these standard strength tests, OPC may undergo other specialized strength tests based on specific requirements or project specifications. These could include modulus of elasticity or bond strength tests, depending on the application or construction scenario (Hlobil et al., 2022; Huntzinger and Eatmon, 2009; Vivian et al., 2022; Zhang, 2011).

2.3. Materials Used in Production of Geopolymers

To obtain a geopolymer material, there are two main ingredients needed. These ingredients are raw materials that provide the alumino-silicate oxides and dissolution agent for the aluminosilicate, such as an alkaline liquid of silicates or hydroxides. The selection of these ingredients will affect the properties of the geopolymer product.

2.3.1. Binding Materials

Silica and alumina-rich materials are preferred in geopolymer synthesis to be activated by high alkali solutions. For this purpose, some commonly used binding materials such as metakaolin, fly ash, red clay bricks, demolition wastes, and blast furnace slag were used in the studies that this review included, as in Table 1 and Table 2. Easy availability and providing strong mechanical properties make these raw materials favorable (Huseien et al., 2017). These common binding materials used in geopolymers can be explained as follows:

1. **Metakaolin:** Metakaolin is a high-reactivity aluminosilicate material. It has a high content of reactive amorphous silica and alumina, which can participate in the geopolymerization reaction and form the binding matrix. Metakaolin is derived from the calcination of kaolin clay. Kaolin clay is a naturally occurring mineral that is primarily found in deposits formed by the weathering of rocks rich in aluminum silicate minerals.
2. **Fly Ash:** Fly ash is a byproduct and is typically obtained from coal-fired power plants that burn pulverized coal. It contains silica (SiO_2), alumina (Al_2O_3), and other mineral components. Class F fly ash, which is low in calcium content, is commonly used in geopolymer production.
3. **Slag:** Slag is a byproduct of the iron and steel industry. It consists of silica, alumina, and other oxides. Blast furnace slag and other types of slag with suitable chemical composition are used in geopolymerization processes. It is produced during the smelting and refining processes. The sources of slag include blast furnaces (producing iron) and electric arc furnaces (producing steel) in the steelmaking industry.
4. **Silica Fume:** Silica fume, also known as micro silica, is an ultrafine powder collected during silicon metal and ferrosilicon alloy production. It consists of highly reactive amorphous silica particles and is used as a supplementary binder in geopolymer formulations. It is collected as a fine powder from the flue gases generated during production.

These materials are often available as industrial waste products, and their utilization in geopolymers offers a way to recycle and reuse these by-products, reducing environmental impact. It's worth noting that other industrial waste materials or natural minerals with suitable chemical composition can also be used as binding materials in geopolymers, depending on availability and desired performance characteristics. Different kinds of materials are investigated extensively to get better results on their usability (Hasnaoui et al, 2019; Huseien et al., 2018; Komnitsas et al., 2015; Mahmoodi et al., 2020, Novais et al., 2016; Panizza et al., 2018; Phoo-ngernkham et al., 2015; Sun et al., 2013; Sun & Vollpracht, 2019; Vásquez et al., 2016). The ability to find these raw materials from recycled industrial and construction wastes also has a positive effect on the purpose of this synthesis. For example, fly ash can be found in power and mining plants, and blast furnace slag can be obtained from the iron production process (Mehta & Siddique, 2018). Demolition wastes are already huge threats to the

environment in the long term. Using these products to obtain geopolymer makes a good impact on the environment. Besides the type and composition of the binder material, the particle size of these materials is also very important (Chindaprasirt & Rattanasak, 2010; Hadi et al., 2018; Komnitsas et al., 2015). All these should be considered for the production of geopolymers. When considering the binding material for the synthesis, other factors like particle size reduction should be taken into account. Particle size reduction can have a significant impact on the geopolymer synthesis when wastes are raw material. Here's how it can affect the process:

1. **Reactivity and Reactivity:** Smaller particle sizes increase the surface area of the waste materials, leading to greater reactivity. This can enhance the kinetics of the geopolymerization reaction, potentially reducing curing times and increasing the rate of strength development.
2. **Alkali Activation:** Geopolymerization involves the reaction of alumino-silicate materials with alkaline activators. Smaller particles provide more sites for the alkali activation process to occur, potentially resulting in more extensive and complete geopolymer formation.
3. **Strength Development:** Finer particles can contribute to higher early-age strength due to increased reactivity and better distribution of reactants. However, there could be an optimum particle size range that balances early-age strength with long-term performance.
4. **Homogeneity:** Smaller particle sizes can lead to a more homogeneous mixture, reducing the risk of particle segregation and ensuring consistent properties throughout the geopolymer material.
5. **Porosity and Microstructure:** Particle size distribution can influence the porosity and microstructure of the resulting geopolymer material. Finer particles might lead to denser and more compact structures, potentially improving mechanical properties and durability.
6. **Environmental Impact:** Particle size reduction often requires additional energy and resources for grinding and milling. This can impact the overall environmental footprint of the geopolymer synthesis process.

It's important to note that the optimal particle size for geopolymer synthesis using wastes may depend on various factors, including the specific waste materials, the type of alkali activators used, the desired properties of the final product, and the intended application. Experimentation and testing are necessary to determine the most suitable particle size distribution for achieving the desired performance and environmental outcomes ((Kohout et al., 2023; Zhang et al., 2020)).



Table 1. Chemical Compositions of the Raw Materials (by weight)

<i>References</i>	<i>Material</i>	<i>SiO₂</i>	<i>Al₂O₃</i>	<i>Fe₂O₃</i>	<i>CaO</i>	<i>MgO</i>	<i>K₂O</i>	<i>Na₂O</i>	<i>SO₃</i>	<i>LOI</i>
Allahverdi & Najafi, 2009	Bricks	53.40	10.48	5.80	24.92	1.40	2.18	1.46	-	0.52
Komnitsas et al., 2015	Bricks	57.79	14.95	6.00	8.79	4.75	2.80	1.03	-	1.89
Mahmoodi et al., 2020	Bricks	60.31	15.61	7.72	5.6	3.05	4.48	0.56	-	0.41
Vásquez et al., 2016	Construction- Demolition Waste	56.21	10.68	10.39	15.37	3.35	0.36	2.08	-	-
Sun et al., 2013	Ceramic	65.52	21.00	1.11	6.00	1.95	3.31	0.36	0.17	0.14
Fan et al., 2018	Fly Ash	52.06	20.54	5.50	14.07	3.29	0.69	0.94	0.57	0.10
Phoo-ngernkham et al., 2015	Fly Ash	52.31	27.04	6.85	3.32	1.23	1.29	1.15	0.99	1.60
Ramujee & PothaRaju, 2017	Fly Ash	60.54	26.20	5.87	1.91	0.38	1.02	0.23	2.0	-
Ranjbar et al., 2015	Fly Ash	52.72	27.28	5.15	5.31	1.10	1.00	0.43	1.01	6.80
Sun et al., 2019	Fly Ash	52.72	21.67	9.55	4.85	1.89	2.27	2.61	1.09	3.27
Novais et al., 2016	Glass	70.57	2.48	0.28	5.59	3.05	1.35	14.49	0.19	0.95
Hasnaoui et al., 2019	Slag	35.9	11.2	0.3	42.3	8.0	0.7	-	-	-
Huseien et al., 2018	Slag	30.53	13.67	0.33	46.02	5.09	0.36	0.24	-	0.22
Kua et al., 2017	Spent coffee	-	-	3.61	33.99	-	43.10	-	-	-

2.3.1.1. Fly Ash in Geopolymer Synthesis

Fly ash, which is a coal-burning by-product, can be obtained from thermal power plants in two different forms, low calcium fly ash (Ranjbar et al., 2015; Saha et al., 2017) and high calcium fly ash (Phoo-ngernkham et al., 2013). Both two types are proper to use in geopolymer production since their high SiO_2 and Al_2O_3 contents (Phoo-ngernkham et al., 2015). Fly ash is considered a good option in recyclable materials for geopolymer synthesis. To generate an aluminosilicate-hydrate (A-S-H) cementitious gel, fly ash reacts with an alkaline liquid solution in geopolymerization (Mohajerani et al., 2019). The resulting geopolymer mostly shows high compressive strength properties, so that it is promising (Fan et al., 2018; Hadi, et al., 2018; Phoo-ngernkham et al., 2015; Ramujee & PothaRaju, 2017; Ranjbar et al., 2015; Sun & Vollpracht, 2019).

Ramujee & PothaRaju (2017) examined the mechanical properties of geopolymer concrete composites while using fly ash as raw material. The experimental design was set to determine geopolymer concrete's compressive strength and split tensile strength with different mix proportions. Results were compared to the OPC. Sun & Vollpracht (2019) investigated long-term observation of fly ash and metakaolin-based geopolymers on mechanical and chemical properties. Initial curing condition effects are taken into account in Sun & Vollpracht's paper, and the results show that fly ash-based geopolymers provide many advantages in mechanical strength. Ranjbar et al. (2015) conducted a different study, which includes graphene nanoplatelets. In this study, the effect of the addition of graphene nanoplatelets on the microstructure and mechanical properties of a fly ash-based geopolymer was investigated. Results emphasize that the addition of graphene nanoplatelets filler, even at low filler weight fractions, improved the toughness, stress, and strain at the first crack and rigidity. Hadi et al. (2018) studied the compressive strength of fly ash-based geopolymer mortar, which was synthesized by using five different fly ash sources. Up to 67 MPa compressive strength was achieved in this study, and optimum parameters were conducted. Similarly, high values of compressive strength and residual strength were obtained in the study of Fan et al. (2018). All these studies and results of these experiments show fly ash could be a promising raw material to be used in geopolymer synthesis. The chemical compositions of fly ash used in these studies are shown in Table 1.

2.3.1.2. Blast Furnace Slag in Geopolymer Synthesis

Blast furnace slag is a byproduct of operations like the production of iron and the burning of coke, or it may result from the fluxing of minerals like limestone. Given that it is harmless, it can be a great raw material for the development of geopolymers (Cheng & Chiu, 2003). Numerous investigations on this raw material have been done (Hasnaoui et al., 2019; Huseien et al., 2018).

Huseien et al. (2018) report the different proportions of metakaolin and ground blast furnace slag-based geopolymer mortars synthesis for potential repair applications. Parameters like alkali activator concentration and binder-to-aggregate ratio were also investigated. Results stated that 63.1 MPa compressive strength can be achieved for ground blast furnace slag-based geopolymers with 15% metakaolin addition. An optimization study of granulated blast furnace slag and metakaolin-based geopolymer mortars was carried out by Hasnaoui et al. (2019). Setting time, porosity, and mechanical properties were obtained and compared with the Portland Cement Mortar (PCM). The results were promising based on the comparison since the geopolymer mortars showed better or similar properties to the PCM. Optimum geopolymer mortar was found to have ratios of 50:50 granulated blast furnace to metakaolin, which is activated by sodium silicate solution according to the results with approximately 50 MPa compressive strength and low values of porosity, setting time, and flow time. Blast furnace slag chemical compositions are shown in Table 1.

2.3.1.3. Red Clay Bricks in Geopolymer Synthesis

One of the major problems of the environment is waste management, and clay bricks contribute a lot to this problem since they represent an average of 30% of the total construction and demolition wastes in Europe (Böhmer et al., 2008). So, there is an urgent requirement for alternative applications of these wastes. Fortunately, geopolymer production studies give some insight into the usage of these materials as raw materials (Allahverdi & Najafi Kani, 2009; Komnitsas et al., 2015; Mahmoodi et al., 2020). Since they have large amounts of calcinated alumino-silicate content in them, they are suitable for production in this manner (Allahverdi & Najafi Kani, 2009).

Allahverdi and Najafi Kani (2009) studied the waste bricks and concrete-based geopolymer by comparing the results to OPC. Compressive strength values were determined great results compared to the OPC. Also, it was concluded that the waste bricks were more reliable than the concrete wastes since they have calcinated alumino-silicate content. An investigation by Komnitsas et al. (2015) analyzed the geopolymerization potential of some wastes, such as concrete, bricks, and tiles, with the effects of alkali activator molarity, curing temperature, and particle size of the raw material on the compressive strength. Results showed that bricks are geopolymerized well, so they reached the highest compressive strength, as 57.8 MPa, compared to the other wastes. In a recent study, Mahmoodi et al. (2020) produced red clay brick waste-based geopolymer binders at ambient temperature curing in their study. Fresh and mechanical properties of geopolymer binders were studied. Also, the addition of fly ash, metakaolin, and ground granulated blast furnace slag into red clay brick binders was carried out in the study to observe the effect of these additions. Appropriate fresh and mechanical strengths were achieved in an ambient environment. Brick characteristics used in these studies are shown in Table 1.

2.3.1.4. Construction and Demolition Wastes in Geopolymer Synthesis

The result of the construction, renovation, and demolition of buildings, roads, bridges, and other structures leads to a huge amount of construction and demolition waste (CDW) accumulation. Typical components of these wastes are mainly concretes, bricks, tiles, and ceramics. The increasing amount of this waste makes the situation prior in the World. The research about using CDW as raw material for the generation of geopolymer products has been studied for a time (Panizza et al., 2018; Vásquez et al., 2016).

Vásquez et al. (2016) studied the demolition waste-based geopolymer synthesis using different alkaline activators. The mixtures of Portland cement and metakaolin with demolition waste were also carried out in different amounts to observe its effects. Especially CDW, with the 10% metakaolin addition, showed promising results based on compressive strength, such as 46.4 MPa at 28 days of the curing period. An extensive study about geopolymers with CDW aggregates was carried out by Panizza et al. (2018). Metakaolin and slag enhancement was also conducted in this study, mechanical and physical properties were investigated for the resulting products to see their potential to be used in building materials. Results showed that

geopolymers with CDW have promising properties mostly higher than 70 MPa for compressive strength. Waste chemical compositions are available in Table 1.

2.3.1.5. Other Wastes

A popular research theme is sustainability in the construction industry and recycling all kinds of materials into useful materials to be used in applications draws attention nowadays (Kua et al., 2017). To meet this purpose, different types of wastes are considered as raw materials for geopolymers, such as waste ceramic, glass, and even spent coffee grounds (Kua et al., 2017; Novais et al., 2016; Sun et al., 2013; Çelik et al. 2023)

Waste ceramics were used to determine the geopolymers in the study of Sun et al. (2013). Then, the characterization was carried out to determine its mechanical behavior. 71.1 MPa compressive strength was obtained in the 28-days test by applying standard curing at 60°C. The results indicated that ceramic waste provides value to geopolymer production. Kua et al. (2017) conducted innovative research about spent coffee grounds-based geopolymers. In this study, different proportions of spent coffee grounds with fly ash and slag were used to create a geopolymers. It was concluded that slag addition contributes to the strength compared with the fly ash addition. In the study of Novais et al. (2016), waste glass from end-of-life fluorescent lamps was used as raw material to create geopolymer. Physical and mechanical properties, as well as the microstructure of the geopolymer product, were evaluated. 14 MPa compressive strength after 28 days of curing was obtained with the contribution of 37.5% waste glass geopolymer. Therefore, this material would be proper to be used in non-structural applications. Related chemical compositions of raw materials in these studies are placed in Table 1. A similar approach was conducted in the study of Çelik et al. (2023). They investigated the influence of waste glass powder (WGP) with fly ash in certain proportions on geopolymer concrete by exchanging different proportions of sodium hydroxide molarity.

2.3.2. Alkaline Activators

A soluble alkali element's aqueous solution is named an alkali activator. Sodium (Na) and potassium (K) are the most commonly used substances to create a silicate or hydroxide solution.—In geopolymer studies, sodium hydroxide (NaOH), sodium silicate (Na₂SiO₃), potassium hydroxide (KOH), and potassium silicate (K₂SiO₃) are generally used as an alkaline solution after they are dissolved in distilled water (Mohajerani et al., 2019). An

alkaline activator is essential to the production process since the alumino-silicates rapidly dissolve to release SiO_4 and AlO_4 tetrahedral units and promote the dissolved species for the polycondensation process (Liew et al., 2016). So, the key of an alkali activator solution is to melt the reactive part of raw materials Si and Al, which are found mostly in raw materials such as fly ash, metakaolin, and CDW, and make up a strong alkaline medium for the polymerization reaction (Amran et al., 2020). Consequently, geopolymers are the materials that are considered as amorphous to semi-crystalline polymeric substances, created by the alkali action of alumino-silicate raw materials using an alkali activator (Usha et al., 2016).

2.4. Production Process and Methods

The mechanism behind geopolymer synthesis is activating different alumino-silicate-based waste material from other industries with highly alkaline medium such as alkaline earth metal silicate or hydroxide components, fine and coarse aggregates, and water (Amran et al., 2020). The SiO_2 to Al_2O_3 ratio and alkali activator purity are the important parameters that should be considered in the synthesis. To synthesize geopolymer paste, Rattanasak & Chindaprasirt (2009) submitted two different types of mixing. These were separate and normal mixing procedures. In Rattanasak & Chindaprasirt's study, sodium hydroxide and sodium silicate were used as alkali activators, and fly ash was used as binder. For the separate mixing, sodium hydroxide and the binder material were mixed for the first 10 minutes, and then sodium silicate activator was added to the mixture. For normal mixing, all the necessary materials were mixed at the same time. The results showed that the mixing sequence affects the geopolymerization reaction, and therefore, it affects the compressive strength too; the more effective one seems to be the separate mixing. However, most of the studies used similar mixing order, such as solids were prepared based on their particle size or if there were several solid binders, they were mixed in some proportions, then the alkali activators were prepared based on molarity, and again, if there were several substances for the solution, the mixture of these solutions should be prepared (i.e. NaOH and Na_2SiO_3 mixture), in the case of a single substance, alkali activator solution was prepared with no mixing others. The following step was adding an alkali activator to the binder to obtain a geopolymer paste in proper curing conditions (Hasnaoui et al., 2019; Huseien et al., 2018; Komnitsas et al., 2015; Mahmoodi et al., 2020; Novais et al., 2016; Panizza et al., 2018; Phoo-ngernkham et al., 2015; Sun et al., 2013; Vásquez, et al., 2016).

Curing conditions are so important to obtain high-value geopolymers. It affects the mechanical strength, microstructure, and setting time of the geopolymers. The geopolymerization process takes place in the curing part of the synthesis process. One of the reasons behind the effort to use geopolymers instead of OPC is requiring low temperatures in the production of geopolymers. As a consequence of high temperatures in the OPC process, the climate could be affected negatively (Mohajerani et al., 2019). Ambient curing and elevated curing can be applied to the process. Despite its negative effect on the environment, elevated temperature curing enhances the mechanical properties of the geopolymer product (Komnitsas et al., 2015; Panizza et al., 2018; Sun & Vollpracht, 2019). However, in the study of Mahmoodi et al. (2020) even though the strength values increased up to 75°C, it decreased at 100°C due to the formation of microcracks in the geopolymer.



2.5. Taxonomy

The brief summary of the reviewed papers for this study can be found below.

Table 2. Taxonomy of the study

<i>Ref</i>	<i>Material Type</i>	<i>Raw Material</i>	<i>Alkali Activator</i>	<i>Curing Time</i>	<i>Curing Temperature</i>	<i>Aging time</i>
Phoo-ngernkham et al., 2015	Geopolymer Pastes	Fly Ash	NaOH, Na ₂ SiO ₃		23 °C	7,28,60 days
Santhandam et al., 2017	Geopolymer Concrete	Fly Ash (Glass fiber added)	NaOH, Na ₂ SiO ₃	24 h	Natural curing(27°C), Thermal curing(100°C)	7,14,28 days
Çelik et al. , 2023	Geopolymer Concrete	Fly Ash (Glass fiber added)	NaOH		85 °C	
Ramujee & PothaRaju, 2017	Geopolymer Concrete	Fly Ash	NaOH, Na ₂ SiO ₃	24 h	60 °C	28 days
Sun & Vollpracht, 2019	Geopolymer Mortar	Fly Ash (with the addition of metakaolin)	Na ₂ SiO ₃	12,24 h	20,30,40,60 °C	3,7,14, 28,96, 180,365 days
Ranjbar et al., 2015	Geopolymer Composites	Fly Ash (graphene nanoplatelets added)	NaOH, Na ₂ SiO ₃			14 days
Hadi et al., 2018	Geopolymer Mortar	Fly Ash	NaOH,	24 h	70 °C	7 days

Fan et al., 2018	Geopolymer Pastes	Fly Ash	Na ₂ SiO ₃ KOH, Na ₂ SiO ₃	20,24 h	22,60,80 °C (elevated to 500-800 °C to observe the thermal effect)	
à Moungam et al., 2017	Geopolymer Pastes	Fired Clay Brick Wastes	NaOH	24 h	Ambient temperature	28 days
Komnitsas et al., 2015	Geopolymer Pastes	Waste Bricks (also include tiles and concrete waste investigation)	NaOH, Na ₂ SiO ₃		60,80,90 °C For the thermal behavior -10 to 60 °C and 400,600,800 °C used)	7,28 days
Mahmoodi et al., 2020	Geopolymer Pastes	Red Clay Brick Waste (addition of fly ash, metakaolin, blast furnace slag included)	NaOH, Na ₂ SiO ₃	24 h	23,50,75,100 °C	7,28 days
Cheng and Chiu, 2003	Geopolymer Panel	Ground Blast Furnace Slag (with the addition of metakaolin)	KOH, Na ₂ SiO ₃	24 h	Room temp, 60 °C	1,7,14,21,28 days
Huseien et al., 2018	Geopolymer Mortar	Ground Blast Furnace Slag (with the addition of metakaolin)	NaOH, Na ₂ SiO ₃	24 h	Ambient temperature	1,3,7,28 days

Saha and Rajasekaran, 2017	Geopolymer Pastes	Ground Blast Furnace Slag up to 50% (with the addition of fly ash)	NaOH, Na ₂ SiO ₃	24 h	Room temperature	7,28,56 days
Hasnaoui et al., 2019	Geopolymer Mortar	Ground Blast Furnace Slag (with the addition of metakaolin)	NaOH, Na ₂ SiO ₃		20 °C	3,28 days
Mehta and Siddique, 2018	Geopolymer Concrete	Ground Blast Furnace Slag (with the addition of rice hask ash)	NaOH, Na ₂ SiO ₃	24 h	80 °C	3,7,28,90 days
Kürklü, 2016	Geopolymer Mortar	Blast Furnace Slag (with the addition of fly ash)	NaOH, Na ₂ SiO ₃	5,24, 48, 168 h	60 °C	7 days
Vásquez et al., 2016	Geopolymer Pastes	Concrete Demolition Waste	NaOH, Na ₂ SiO ₃	24 h	25,70 °C	7,28 days
Panizza et al., 2018	Geopolymer Pastes	Metakaolin, furnace slag with construction and demolition waste aggregates	KOH, K ₂ SiO ₃	24 h	20,30,40,60 °C	3,7,28 days
Sun et al., 2013	Geopolymer Pastes	Ceramic waste	NaOH,KOH, Na ₂ SiO ₃	24 h	60 °C	28 days
Kua et al., 2017	Geopolymer Pastes	Spent Coffee	NaOH,	24 h	21, 50 °C	7,28 days

		Grounds, fly ash, slag	Na ₂ SiO ₃			
Novais et al., 2016	Geopolymer Pastes and Foams	Waste glass and metakaolin	NaOH, H ₂ O ₂ , Na ₂ SiO ₃	24 h, 7 day	40 °C	1,7,28 days
Prasanphan et al., 2019	Geopolymer Pastes	Kaolin processing waste	NaOH, Na ₂ SiO ₃		Ambient temperature	1,3,7,28 days
Abdollahnejad, 2019	Geopolymer Mortar	Waste glass, fly ash	NaOH, Na ₂ SiO ₃	24 h	25 °C	7,28,56 days

3. RESULT AND DISCUSSION

3.1. Properties of Geopolymers

The properties of geopolymers can be varied according to their production process and curing conditions. These varieties of geopolymer properties make them a great material for use in different fields with different purposes. The properties of geopolymers can be examined in detail by dividing them into categories such as mechanical properties, fresh properties, physical properties, and microstructural properties. By looking at their properties under these categories, understanding their usage in different areas would be more clear.

3.1.1. Mechanical Properties

The mechanical properties of geopolymers mostly define their usage area and how effective to use them for necessary purposes. The mechanical properties can be listed as compressive, flexural, and splitting tensile strengths. The main desire for producing a geopolymer that has great mechanical properties is to compare it to OPC. Curing conditions directly affect the properties of the product and there are numerous studies that investigate the optimum synthesis conditions for this purpose (Allahverdi & Najafi Kani, 2009; Hasnaoui et al., 2019; Huseien et al., 2018; Komnitsas et al., 2015; Phoo-ngernkham et al., 2015; Ramujee & PothaRaju, 2017; Ranjbar et al., 2015).

3.1.1.1. Compressive Strength

Compressive strength can be used to define their applications in the construction field. To use them in construction instead of OPC, they should have high strength and high workability. Different methods are used to test these properties. For example, compressive strength tests are carried on mainly on 7, 28 and 90 days periods to see the time effect on the strength in the literature.

In the study of Sathanandam et al. (2017), low-calcium fly ash was used as a raw material to synthesize geopolymer concrete. Besides the fly ash, glass fibers were also used to enhance the properties of the geopolymer concrete. The tests were done using different types of alkaline solutions (NaOH, Na₂SiO₃) with different concentrations as well as changing the glass fiber proportions to examine their effect on the final product. Also, two different curing

conditions were used for this study: normal curing and thermal curing. The results in that paper showed that final product's strength increased with increasing curing age. The highest compressive strength, 23.8 MPa, has been achieved by using 12 M NaOH as an alkaline activator with the addition of 0.2% glass fiber under thermal curing conditions. For the 16 M alkaline solution and 0.3% glass fiber produced, geopolymer concrete showed a better compressive strength value of 24.8 MPa under thermal curing conditions. And 20 M alkaline solution usage in the synthesis gave similar results as in the geopolymer concrete that was produced with 16 M alkaline solution.

In the study of Husein et al. (2018), the effect of metakaolin replaced by granulated blast furnace slag (GBFS) in the production of geopolymer mortar was investigated. The base feedstock of the geopolymer mortar was defined as GBFS, and up to 15% of metakaolin was used to see its effect on properties such as compressive strength. 1, 7, and 28 days of curing time were observed in the study, and for the 1 day of curing, it was found that increasing the metakaolin lowers the compressive strength of the mortar. It was 32.8 MPa for the product with no metakaolin and 20.4 MPa with 15% of metakaolin content. However, 28 days of curing showed higher compressive strength results such as 63.1 MPa for the 15% metakaolin content, while it is 44.8 MPa for the geopolymer mortar that is synthesized without metakaolin.

Another study which belongs to Mehta & Siddique (2018), examined the strength of the geopolymer concrete that was produced with ground granulated blast furnace slag and rice husk ash as raw material. For the compressive strength, it was found that 54.2 MPa was achieved at 3 days of testing in the absence of rice husk ash. For the 90 days of testing, it increased to 63.3 MPa. Rice husk ash's contribution of up to 15% to the material had a positive effect on compressive strength, but beyond this percentage, it started to decrease. This behavior was valid for all curing times, 3, 7, 28, and 90 days. The maximum compressive strength was found around 71 MPa with 85% of ground granulated furnace blast and 15% of rice husk ash at 90 days of curing.

Sun & Vollpracht (2019) conducted a study based on the evaluation of the long-term results of the geopolymer mortars. Fly ash and metakaolin-based geopolymer mortars were used for this purpose using different curing temperatures, and the results showed that early-age mechanical strength increases with the initial curing temperature. Furthermore, fly ash-based

mortars showed a tendency to increase compared to metakaolin-based mortars. 60°C curing temperature showed higher compressive strength results compared to 30 and 40°C. The curing period for the materials that are synthesized with elevated curing temperatures has a positive effect on the strength of the fly ash-based mortars. However, long-term results for the fly ash-based mortars showed that the highest value for the compressive strength was obtained with 20°C cured mortar at one-year examination since it gradually increased after 96 days. For the metakaolin-based mortars, the results were similar to those they conducted for fly ash-based mortars except the difference was not that significant.

In the study of Ranjbar et al. (2015), the mechanical strength of fly ash-based geopolymers with the addition of graphene nanoplatelets was investigated, and the results showed that the addition of graphene nanoplatelets increased the compressive strength of the geopolymers up to 45 MPa. Approximately 144% improvement in compressive strength was obtained with the 1% of graphene nanoplatelets-geopolymer composite.

In the study of Çelik et al. (2023), compressive strength was investigated with different variations of waste glass powder addition in the fly ash-based geopolymer concrete samples as well as discussing the change in NaOH molarity. In the geopolymer concrete mixture, the percentages of fly ash to waste glass powder were investigated as 0%, 10%, 20%, 30%, and 40%. The percentage of NaOH molarity was kept constant at 11. According to the evaluation of the mixture, the change in compressive strength was 23% as the fly ash to waste glass powder ratio went from 0% to 10%. The measured compressive strength tended to drop by 40.5%, 56%, and 76%, respectively, when the proportion in the mixture was raised from 0% to 20%, 0% to 30%, and 0% to 40%. Second, the molarity of NaOH was maintained at 13, and the proportions of fly ash to waste glass powder in the geopolymer concrete mixture were 0%, 10%, 20%, 30%, and 40%. The change in compressive strength was 23% in the combination as fly ash content was increased from 0% to 10%. The rate of change in compressive strength fell to 9.4%, 19.8%, 43%, and 56%, respectively, when the proportion of the mixture was increased from 0% to 20%, 0% to 30%, and 0% to 40%. Lastly, the molarity of NaOH was set to 16, and the proportions of fly ash to waste glass powder in the mixture were 0, 10%, 20%, 30%, and 40%. It was observed that the rate of change in compressive strength decreased by 25%, 40%, 44%, and 51%, respectively, when the proportion in the mixture was raised. Additionally, the ratio of fly ash to waste glass powder was maintained, but the molarity of NaOH in the mixture were altered to 11, 13, and 16. Fly

ash to waste glass powder ratios of 0, 10, 20, 30, and 40% were used, while NaOH molarity ratios of 11, 13, and 16 were varied in the concrete mix. The rate of change in compressive strength was shown to have risen between 8% and 17% for WGP0% (0% - waste glass powder), between 21% and 15% for WGP10% (10% - waste glass powder), between 26% and 17% for WGP20%, between 19% and 28% for WGP30% (30% - waste glass powder), and between 34% and 10% for WGP40% (40% - waste glass powder). Because the ideal ratio of fine to coarse particles assures effective attainment, this performance is comparable to that of ordinary concrete. This study led to the identification of the optimal ratio of fly ash to NaOH molarity that provided the maximum compressive strength for geopolymer concrete. As seen in Figure 8 below, compressive strength improved when the NaOH molarity in the mixture increased.

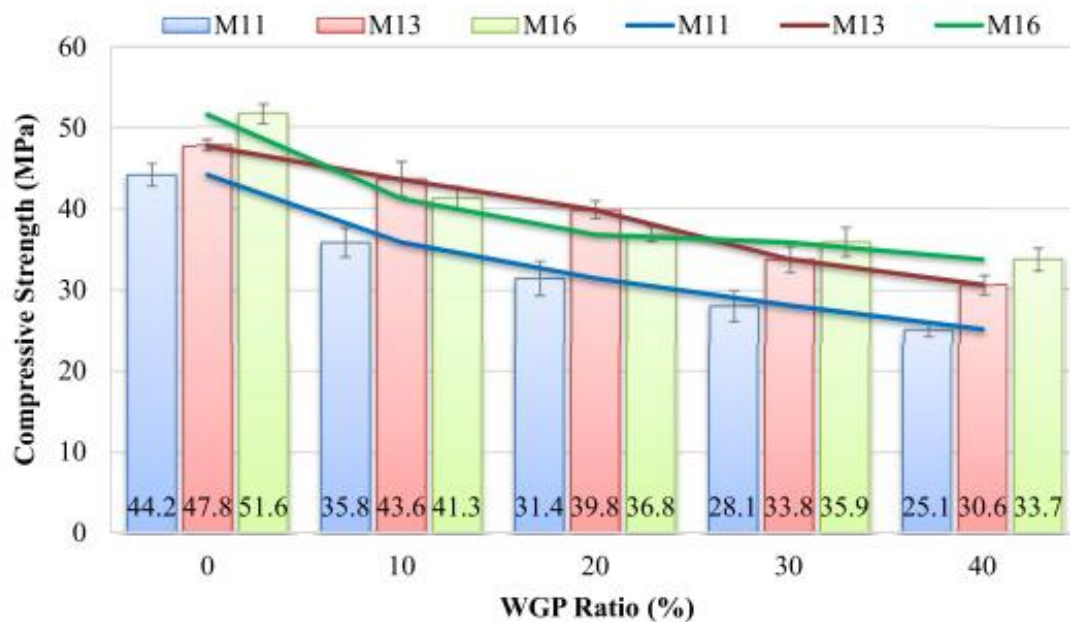


Figure 8. Compressive strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16 (Çelik et al. 2023)

3.1.1.2. Flexural Strength

Geopolymer concrete showed increasing mechanical behavior with the addition of fiber content up to 0.3% and 0.4% for different concentrations of alkaline solution based on the study of Sathanandam et al. (2017). Also, the curing condition such as normal and thermal curing, affects the flexural strength, thermally cured geopolymer concrete showed higher flexural strength than naturally cured one. The highest strength value was obtained with 16 M alkaline solution and 0.3% content of glass fiber.

In the study of Husein et al. (2018), the flexural strength of the 1, 3, 7, and 28 days of curing times was investigated to compare the results with ordinary Portland cement. Results were very promising since after 24 hours of curing the flexural strength was found as 5.7 MPa while the OPC had 0.6 MPa. Increasing the curing time had an improving effect on flexural strength, for example, after 28 days of curing, flexural strength was found as 8.2 MPa while it was around 5 MPa for the OPC.

Flexural strength was examined to observe the one-year effect of the geopolymer mortars in the study of Sun & Vollpracht (2019), as mentioned before for the compressive strength. The results were very similar to the compressive strength and the flexural strength examination. In conclusion, both fly ash and metakaolin-based geopolymer mortars had higher values for flexural strength, especially after some period of time in the long term.

Ranjbar et al (2015), investigated the flexural strength of geopolymer composites with graphene nanoplatelets. It was found that the placement of graphene nanoplatelets in the geopolymers improves their flexural strength significantly. 216% improvement was observed by using 1% of graphene nanoplatelets.

Çelik et al. (2023), studied the capacity of the samples subjected to flexure as the tensile strength of geopolymer concrete. However, flexural strength was frequently higher than the indirect split tensile strength. The samples' flexural strength was assessed. In the geopolymer mixture, the fly ash to waste glass powder ratio was 0%, 10%, 20%, 30%, and 40%, while the molarity of the NaOH was M11. The rate of change in flexural strength was determined to be 6.4% when the ratio of fly ash to waste glass powder went from 0% to 10%. Flexural strength, however, was reduced 18%, 24%, and 45%, respectively, when the ratio of fly ash to waste

glass powder varied from 10% to 20%, 20% to 30%, and 30% to 40%. Afterward, the molarity of NaOH was set to M13, and the proportion of fly ash to waste glass powder in the mixture was 0%, 10%, 20%, 30%, and 40%. It was discovered that when the proportion in the combination increased from 0% to 10%, 20%, 30%, and 40%, respectively, flexural strength decreased by 2.8%, 15%, 19.8%, and 39%. The last step involved increasing the ratio of fly ash to waste glass powder in the concrete mixture from 0% to 10%, 20%, 30%, and 40% while keeping the molarity of the NaOH constant at 16. In this instance, flexural strength fell by 5.5%, 19.5%, 23%, and 29%, respectively. Additionally, it was observed that the rates of variation in flexural strength tended to rise as follows: 1.3% and 2.7% for WGP0%, 4.8% and 3.6% for WGP10%, 3.8% and 1.5% for WGP20%, 4.8% and 3.4% for WGP30%, and 5.6% and 15.8% for WGP40%. The results of the flexural strength tests are shown in Figure 9 in line with the influence of NaOH molarity and waste glass powder ratios. Increasing the replacement percentages of waste glass powder has a negative impact on flexural strength because waste glass powder contains less reactive parent materials.

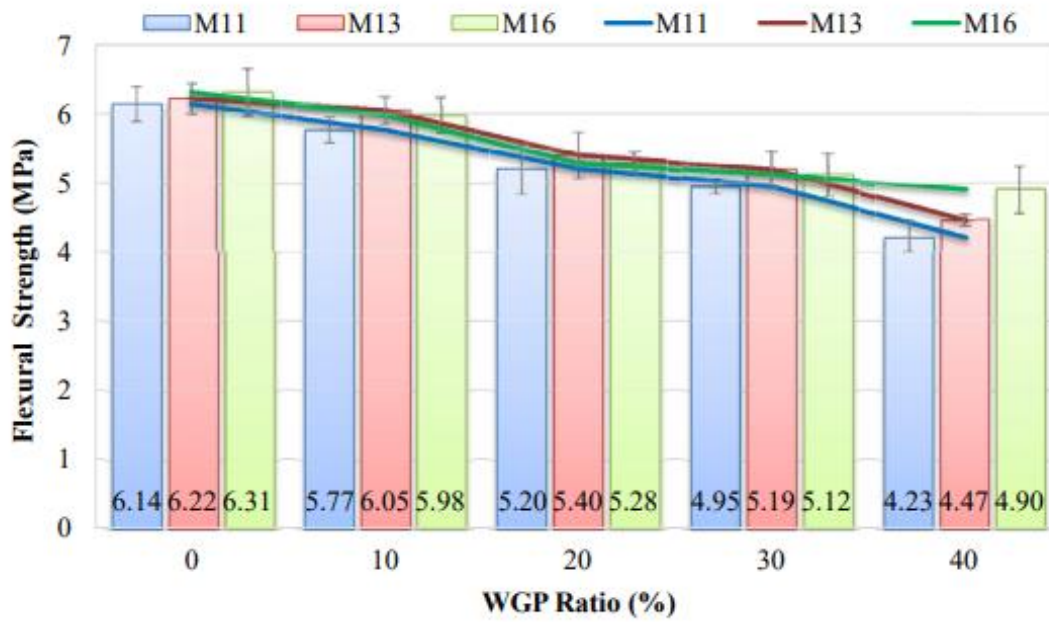


Figure 9. Flexural strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16 (Çelik et al. 2023)

3.1.1.3. Split-Tensile Strength

Sathanandam et al. (2017)'s study shows the increasing split-tensile strength behavior with increasing the curing age. The highest split tensile strength was achieved with the 12 M alkaline activator and 0.5% of glass fiber. The values are 1.63 MPa for thermally cured and 1.45 MPa for normally cured specimens. 16 M alkaline activator usage for geopolymer concrete results in having 1.59 MPa tensile strength for thermally cured and 1.56 MPa tensile strength for normally cured specimens. 20 M activated geopolymer concretes have 1.58 MPa and 1.41 MPa tensile strength under thermally and naturally curing conditions, respectively. In conclusion, 12 M alkaline activator usage resulted in having the highest value of tensile strength among other concentrated alkaline solutions.

The splitting tensile strength of geopolymer mortar in the study of Husein et al. (2018) was compared with the OPC splitting tensile strength. 1, 3, 7, and 28 days of curing times were used to see the effect of them, and the results showed that after 1 day of curing, splitting tensile strength was 2.95 MPa for the geopolymer mortar which is 10 times bigger than that of OPC mortar and also, it was increasing with the curing time.

In the study of Mehta & Siddique (2018), split tensile strength was also examined, besides the compressive strength, as mentioned in section 3.1.1.1. The results are similar to those obtained for compressive strength. Up to 15% replacement of rice husk ash with ground granulated furnace blast increased the split tensile strength value for 3, 7, 28, and 90 days of testing. The maximum strength value was obtained as 7.33 MPa at 90 days of curing in the presence of 15% rice husk ash and 85% of ground granulated blast furnace slag.

In the study of Çelik et al. (2023), split tensile strength tests are applied to the geopolymer concrete samples prepared with different variations of waste glass powder addition in the fly ash-based geopolymer concrete samples as well as discussing the change in NaOH molarity. The split tensile strength results consistently followed the same pattern as those of compressive strength explained in the previous section, as seen in Figure 10 below. The ratio of fly ash to waste glass powder in the concrete mixture was taken as 0%, 10%, 20%, 30%, and 40%. The value of the molarity of NaOH was taken as M11. The examination of the mixture with the fly ash to waste glass powder ratio changed from 0% to 10% revealed a 2.8% change in split tensile strength. Split tensile strength was reduced to 15, 35, and 64%, at 20%, 30%, and 40% of the mixture, respectively. The ratio of fly ash to waste glass powder

was then varied between 0%, 10%, 20%, 30%, and 40%, while the amount of NaOH's molarity was kept constant at M13. When the mixture's percentages were increased to 20%, 30%, and 40%, it was found that the rate of change tended to decline, falling to 14%, 47.3%, and 77.6%, respectively. Finally, the proportion of fly ash to waste glass powder in the concrete mixture was changed from 0% to 10% to 20% to 30% to 40%, resulting in reductions in split tensile strength of 32%, 50%, 61%, and 66%, respectively. The molarity of NaOH was assumed to remain constant at 16 throughout. When the mixture's percentages were increased to 20%, 30%, and 40%, it was found that the rate of change tended to decline, falling to 14%, 47.3%, and 77.6%, respectively. Finally, the proportion of fly ash to waste glass powder in the concrete mixture was changed from 0% to 10% to 20% to 30% to 40%, resulting in reductions in STS of 32%, 50%, 61%, and 66%, respectively. The molarity of NaOH was assumed to remain constant at 16 throughout.

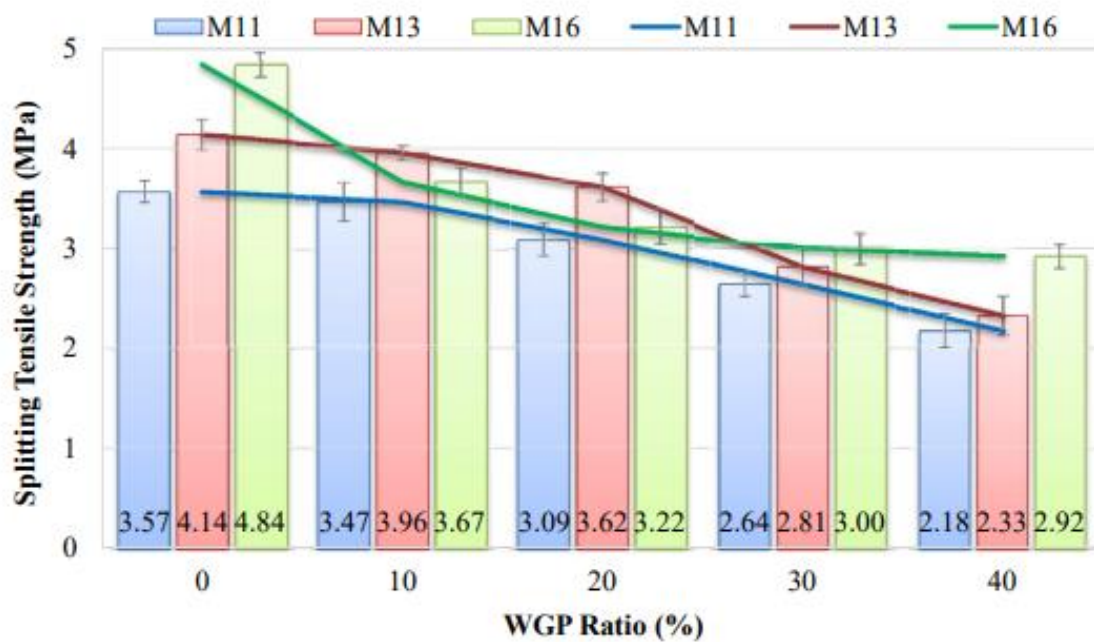


Figure 10. Split tensile strength results for different waste glass powder (WGP) % in the geopolymer concrete mixtures with altering the NaOH molarities as M11, M13, M16 (Çelik et al. 2023)

3.1.2. Fresh Properties

Fresh properties of geopolymers also define their ability and workability in terms of usage as an alternative to ordinary cement.

To examine the fresh properties, different parameters are used, such as flow time and setting time on their fresh states in the study of Huseien et al. (2018). In this study, the metakaolin effect, when using it for some proportions instead of ground granulated blast furnace slag, was investigated for the fresh states of these geopolymer mortars. The results showed that increasing the metakaolin proportion in the mortar has a positive effect on the flow ability, and similarly, decreasing the ground granulated blast furnace slag amount results in a reduced number of angular particles, which leads to improvement of the flow ability. Flow ability's improvement is also related to the calcium content, which decreases with increasing the metakaolin proportion, unlike the silicate and aluminum contents. The increase of silicate content affects the flow ability in a positive way. On the other hand, workability is more related to the particle size of metakaolin. Mixing the metakaolin and ground granulated blast furnace results in a slow setting for the geopolymer mortar, thus improving their workability. Reducing the calcium content increases the initial and final setting times. In other words, increasing the metakaolin amount improves the setting time.

The slump measurement test or slump cone test, which is frequently used to look into the use of geopolymers in their fresh form, was conducted in a different study by Pouhet & Cyr, M. (2016). The slump test is the most basic way of determining concrete consistency. It is not a good option to use it on very wet or very dry concrete. It does not account for all aspects that influence workability, nor does it always reflect the concrete's placeability. Two different parameters were used in this study, H_2O/Na_2O binder molar ratio and the amounts of aggregates. The results showed that having 83% by mass of aggregate resulted in no slump in the concrete.

In the study of Nuaklong et al. (2016) workability of fresh recycled concrete aggregate and crushed limestone-based geopolymer concretes was investigated, and a slump flow test was applied to carry out the study. Using recycled concrete aggregate was found to be favored in workability compared to using crushed limestone in production since recycled concrete aggregate particles have a larger volume of pores and water than crushed limestone particles.

The water content improved the workability of the geopolymers. Also, it was found that a high concentration of alkali activator solution which is sodium hydroxide, decreased the slump flow of the material at the same liquid-to-ash ratio for both recycled concrete aggregate and concrete limestone-based geopolymers because increasing the sodium hydroxide concentration leads to having more silica and alumina in the mixture, and thus increasing the geopolymerization of the synthesis.

3.1.3. Physical Properties

For the investigation of the geopolymers, as well as the mechanical and other properties, physical properties should be considered to have reliable results. Physical properties such as porosity, bulk density, and apparent density were investigated in the studies for this purpose.

3.1.3.1. Apparent Porosity

In the study of Kürklü (2016), the Archimedes principle was carried out to examine the porosity. Geopolymer mortars were prepared with oven curing at 60°C for 5, 24, 48, and 168 hours of curing. The results showed that the 5 hours of curing resulted in the highest apparent porosity values, and the maximum value was obtained in the geopolymers that were produced with 50% of blast furnace slag and 50% of fly ash contribution. The minimum apparent porosity values were obtained with the geopolymer that is cured for 24 hours for 100% blast furnace slag-based material. It was found that the early curing time resulted in higher apparent porosity values since the reaction progressed slowly. After reaching 24 hours of curing, the gels were formed, and the pores were clogged with these formed gels. Therefore, extending the curing time formed more gels, which resulted in clogging the pores.

In the study of Hasnaoui et al. (2019), the highest porosity values were observed for the 75% granulated blast furnace slag, and 25% metakaolin contribution in the geopolymer samples with different $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratios from 1 to 2 and maximum porosity was found as 18.23% for the molar ratio of 2. In conclusion, the increase in metakaolin content has a decreasing effect on the porosity of mortars.

3.1.3.2. Water Absorption

In the study of Kürklü (2016), water absorption was also examined besides the apparent porosity for physical properties. The results showed similar behavior as in the apparent porosity investigation. The highest water absorption values were found for the 5 hours of curing time, and the lowest values were found beyond 24 hours of curing time. The maximum water absorption value was found as 15% for geopolymer mortar that is synthesized with 50% blast furnace slag for 5 hours of curing. Another study belongs to Cheng & Chiu (2003), who conducted research on the properties of geopolymers with considering the effects of alkali activator concentration. The study showed that water absorption values increased with increasing the sodium silicate and metakaolinite.

Water absorption behavior was investigated in the study of Moungam et al. (2017). The maximum value was found as 17.9% for water absorption property for the mixture prepared with sieved crushed fired clay bricks wastes and rice husk ash-sodium hydroxide as an alkali activator. Increasing water absorption can be explained by unreacted gel and undissolved silica contribution.

3.1.3.3. Bulk and Apparent Densities

Bulk and apparent densities were investigated in the study of Kürklü (2016). For the bulk density, the lowest value, 1661.2 kg/m^3 was obtained for the geopolymer mortar, which is produced with 25% of blast furnace slag contribution and 48 hours of curing. The maximum value for the bulk density was observed as 1999.3 kg/m^3 for 100% blast furnace slag content for 168 hours of curing. The increasing behavior was observed with increasing the blast furnace slag content for all curing times. On the other hand, the highest apparent density of the mortars was observed for the samples cured for 5 hours with 100% blast furnace slag contribution in the mortar, and it was found that the apparent density decreased with increasing the curing time. This is mainly related to the increasing curing time can be associated with the deterioration of the geopolymerization process because of the extended curing time.

In the study of Huseien et al. (2018), it was observed that density increased with the metakaolin replacement to granulated blast furnace slag content. The study showed that parameters like particle size and specific gravity of metakaolin define the geopolymer's density. A similar study was carried out by Cheng & Chiu (2003) in terms of investigating physical properties such as density. In that study, alkali activator concentrations' effects on the densities were investigated, and it was found that increasing the potassium hydroxide concentration increased the density of the geopolymers. Nevertheless, increasing the sodium silicate or metakaolin content lowers the density.

3.1.4. Microstructural Properties and Analyses

The microstructural phases of geopolymer materials are also a subject of research in itself, and it is seen that FTIR, SEM, and XRD tests have been carried out in order to clarify this issue in the studies carried out.

3.1.4.1. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

Fourier Transform Infrared Spectroscopy is a widely used method for the investigation of chemical compositions and bonding of the materials, and for the microstructural analysis of the geopolymers, it is an accepted method.

It was applied to the geopolymers named series A, B, and C in the study of Moungam et al. (2017). Series A was prepared with unsieved fired clay brick waste powder and commercial sodium silicate as an alkaline activator; series B was prepared with sieved fired clay brick waste powder and sodium silicate; series C was mixed of sieved fired clay brick waste powder and rice husk ash -sodium hydroxide alkaline activator. A110 is a mixture of 110 g unsieved fired clay bricks wastes (FCBW) powder and sodium silicate; A120 is a mixture of 120 g unsieved FCBW powder and sodium silicate; B110 is a mixture of 110 g sieved FCBW powder and sodium silicate; B120 is a mixture of 120 g sieved FCBW powder and sodium silicate; C110 is a mixture of 110 g sieved FCBW powder and Rice Husk Ash-NaOH gel; C120 is a mixture of 120 g sieved FCBW powder and Rice Husk Ash-NaOH gel. Figure 11 shows the FTIR spectra of these geopolymer series. In the region $1404\text{--}1419\text{ cm}^{-1}$, the absorption bands appeared and were attributed to the asymmetric stretching vibration of carbon dioxide molecules in all FTIR spectra samples. This was probably because carbonation of unreacted Na^+ , which comes from the alkaline activator. Asymmetric stretching of Si-O-Al

and Si-O-Si bonds appeared for series A, B, and C at 1009, 999, and 1005 cm^{-1} . The results concluded that a geopolymerization reaction was carried out for all alkaline activators that were used in this study.

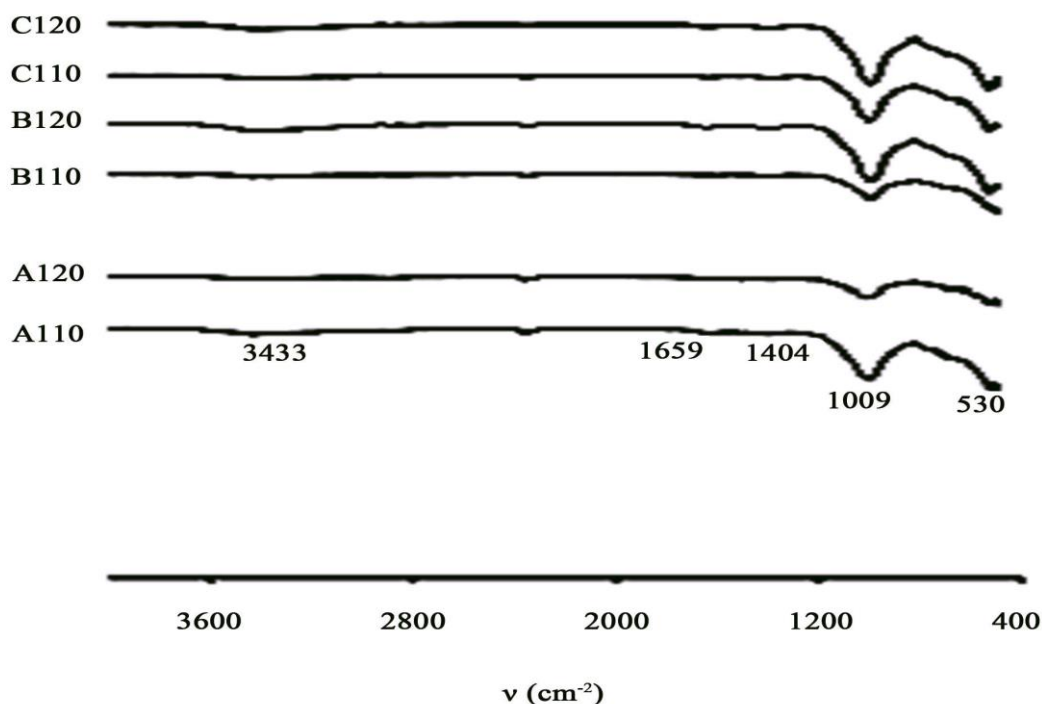


Figure 11. FTIR analysis for the series A, B and C (à Moungam et al., 2017)

In the study of Mahmoodi et al. (2020), the FTIR analysis was applied to the red clay brick waste-based geopolymers with ambient and high-temperature curing applications. As seen in Figure 12, the analysis considered the samples with low, optimized, and high-temperature curing. For the RCBW-75°C, it was seen that the reduced intensity occurred since the bands between 690 cm^{-1} and 773 cm^{-1} ; also, the peaks around 780 cm^{-1} and 1140 cm^{-1} were the effects of the presence of quartz in geopolymeric systems. It is more obvious than the other samples, RCBW-Low and RCBW-Opt. The intense peaks between 955 cm^{-1} and 1001 cm^{-1} were seen for all samples, and it can be explained by the asymmetric stretching vibrations of Si-O and Al-O in the newly formed Si-O-Si and Si-O-Al linkages. It could be the effect of the formation of geopolymeric reaction products in the samples, and it is more obvious for the RCBW-75°C and RCBW-Opt. Stretching vibrations of O-C-O caused the bands between 1428 cm^{-1} and 1500 cm^{-1} , and it is a sign of atmospheric carbonation of the samples; it is more intense for the RCBW-Low samples. The bands around 1630 cm^{-1} and 1650 cm^{-1} , as well as the bands between 3450 cm^{-1} and 3550 cm^{-1} , were related to the stretching vibrations of O-H bonds and H-O-H water molecules, and it can be explained by the hydroxyls alkaline attack

caused by alkaline reagents. It is seen as more intense for the RCBW-75 and RCBW-Opt than for the RCBW-Low since the enhanced degree of condensation during the reaction process and causes higher compressive strength.

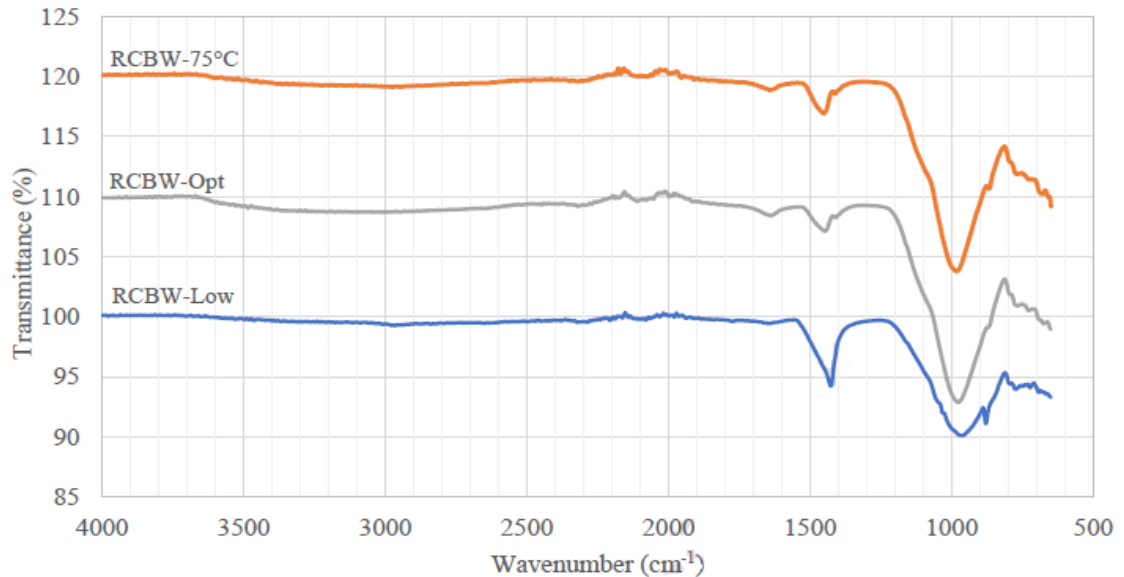


Figure 12. FTIR spectra of red clay brick waste-based geopolymers (Mahmoodi et al., 2020)

3.1.4.2. Scanning Electron Microscopy (SEM) Analysis

Scanning electron microscopy puts important insight into the microstructure and morphology of geopolymers. The studies about geopolymers generally include SEM analysis to get a reliable understanding of them.

In the study of Cheng & Chiu (2003), the SEM analysis was applied to the geopolymer that was prepared with using granulated blast furnace slag and potassium hydroxide as an alkali activator, and the SEM image shown in Figure 4. The SEM analysis showed that the microstructure of the geopolymer was not homogeneous, it can be related to the insufficient mixing time in the synthesis.

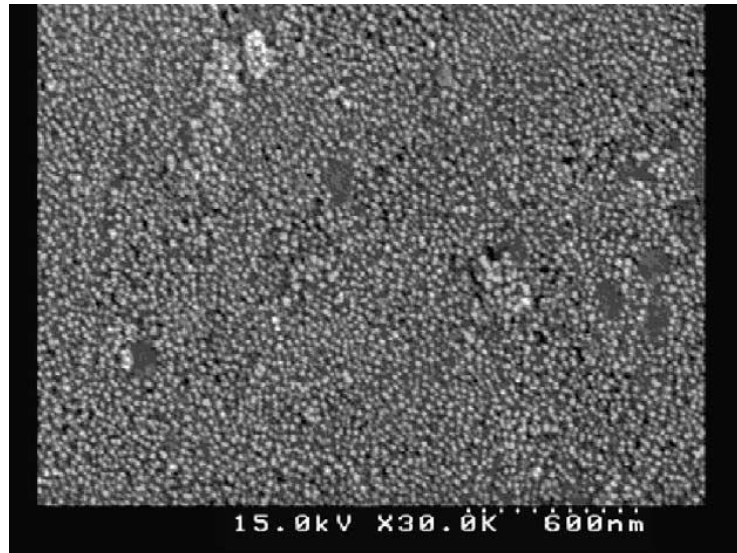


Figure 13. SEM image of the geopolymer sample (Cheng & Chiu, 2003)

Another study à Moungam, et al.(2017) applied SEM analysis on the fired clay brick waste-based geopolymer products (series A, B, and C described in section 3.1.4.1.) as shown in Figure 14. The analysis showed that for series B and C, the amorphous structure of the geopolymer sample appeared more because during the sieving of the raw material, fired clay brick waste powder, unreacted silica particles could be eliminated. So, solid precursor content for the geopolymerization was increased and resulted in a more homogeneous microstructure for the samples. Silica-rich based geopolymers have a more gel-like structure, colloidal and global units of gels appeared on the surfaces as in series B and C.

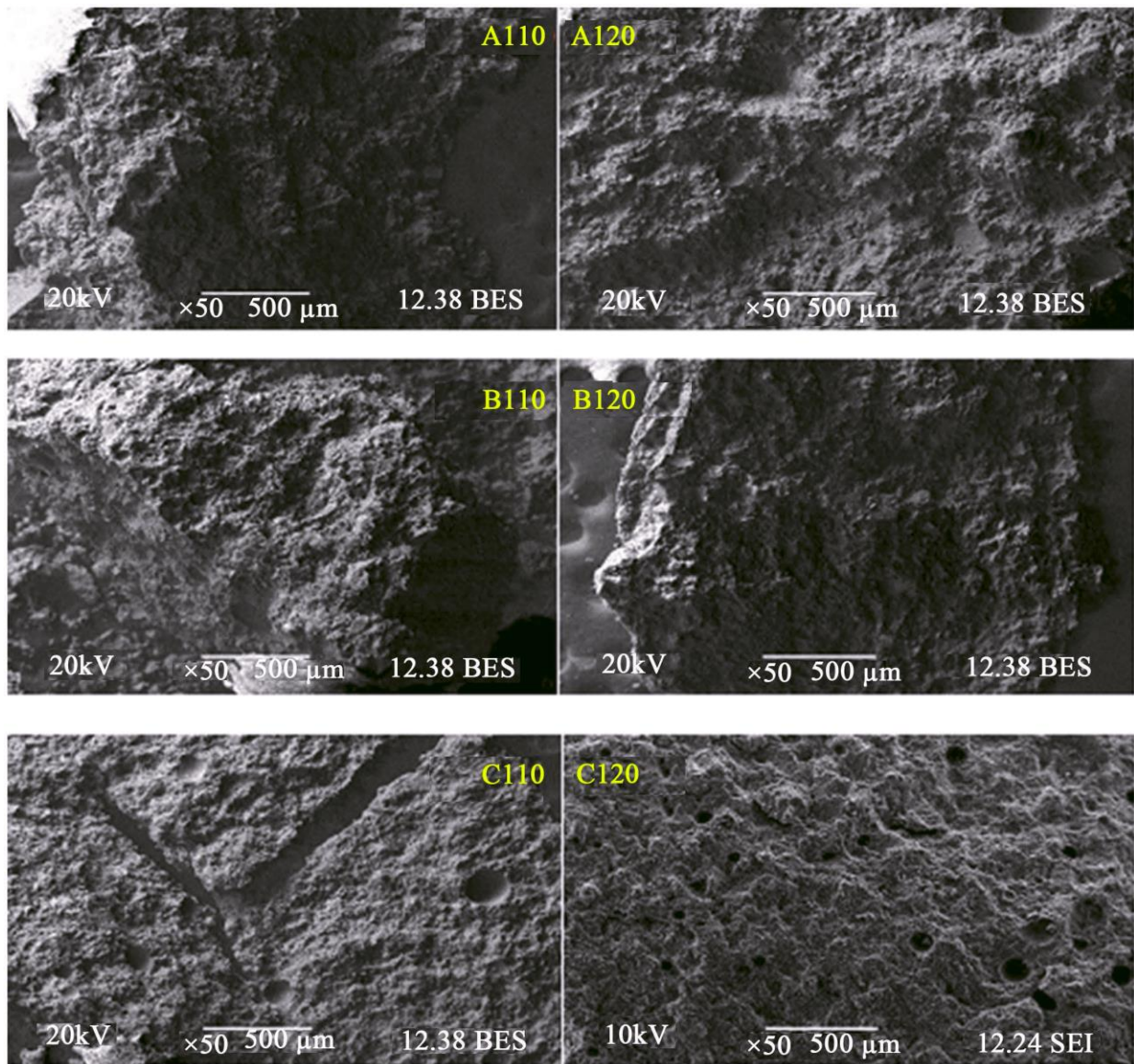


Figure 14. Microstructures of geopolymers of series A, B and C in the study of à Moungam et al. (2017).

In the study of Mahmoodi et al. (2020), the SEM analysis was applied to the samples having the lowest compressive strength, optimized compressive strength and to the samples prepared with a high curing temperature, 75°C. As seen the Figure 15, unreacted granules of red clay brick waste appear more in the samples of RCBW-Low than the others, meaning precursor powder dissolves better with higher strengths. Additionally, for the RCBW-75°C and RCBW-Opt, greater cohesion, denser microstructure, and homogeneous geopolymer matrix were seen compared to the RCBW-Opt and RCBW-Low.

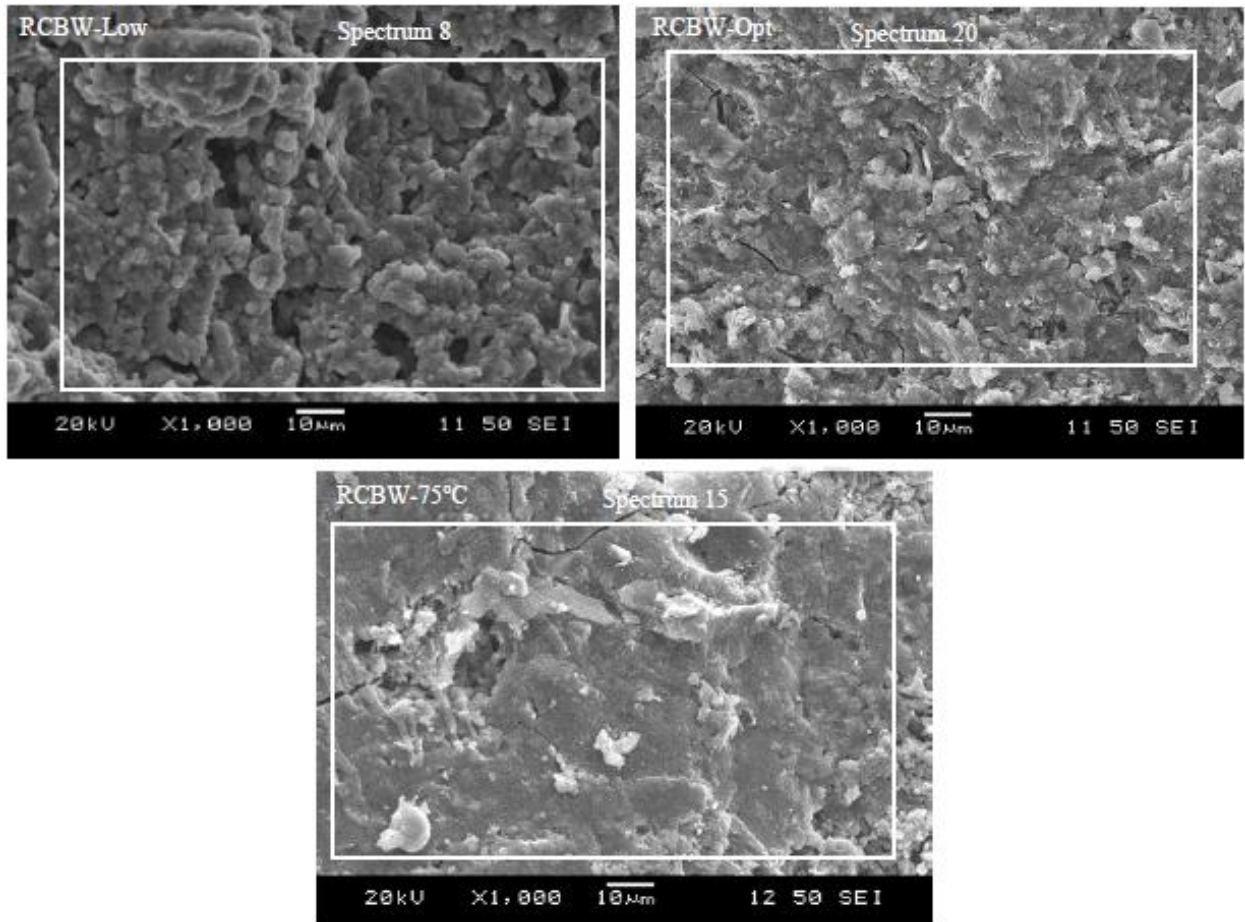


Figure 15. SEM micrograph of red clay brick waste (RCBW) geopolymers, RCBW-Low, RCBW-Opt and RCBW-75°C (Mahmoodi et al., 2020)

In the study of Çelik et al. (2023), the geopolymer samples created using waste glass powder were evaluated using SEM after conducting the compressive and flexural strength tests. The SEM investigation was carried out to display the geopolymer concrete and waste glass powder microscopic structure. When the microstructures of the geopolymer concrete and waste glass powder were examined, sharp-edged irregular formations and glassy features caught the eye. As shown in Figure 7(a), waste glass powder particles exhibited smoother surfaces, sharper prismatic edges, and a higher density than geopolymer concrete particles, which had sharper edges and shapes. Figure 7(b) is a magnified version of Figure 16(a). Figure 16(b) clearly shows unreacted particles (waste glass powder and fly ash). In Figure 16(c), fly ash and waste glass powder particles that have not yet reacted may also be detected. Figure 16(e) reveals interface cracks. More clearly shown is the unreacted waste glass powder and geopolymer concrete in Fig. 16(f). When SEM pictures were evaluated, it was found that

waste glass powder generally offered good binding with fly ash. Despite certain areas having microcracks, a decent microstructure was seen.

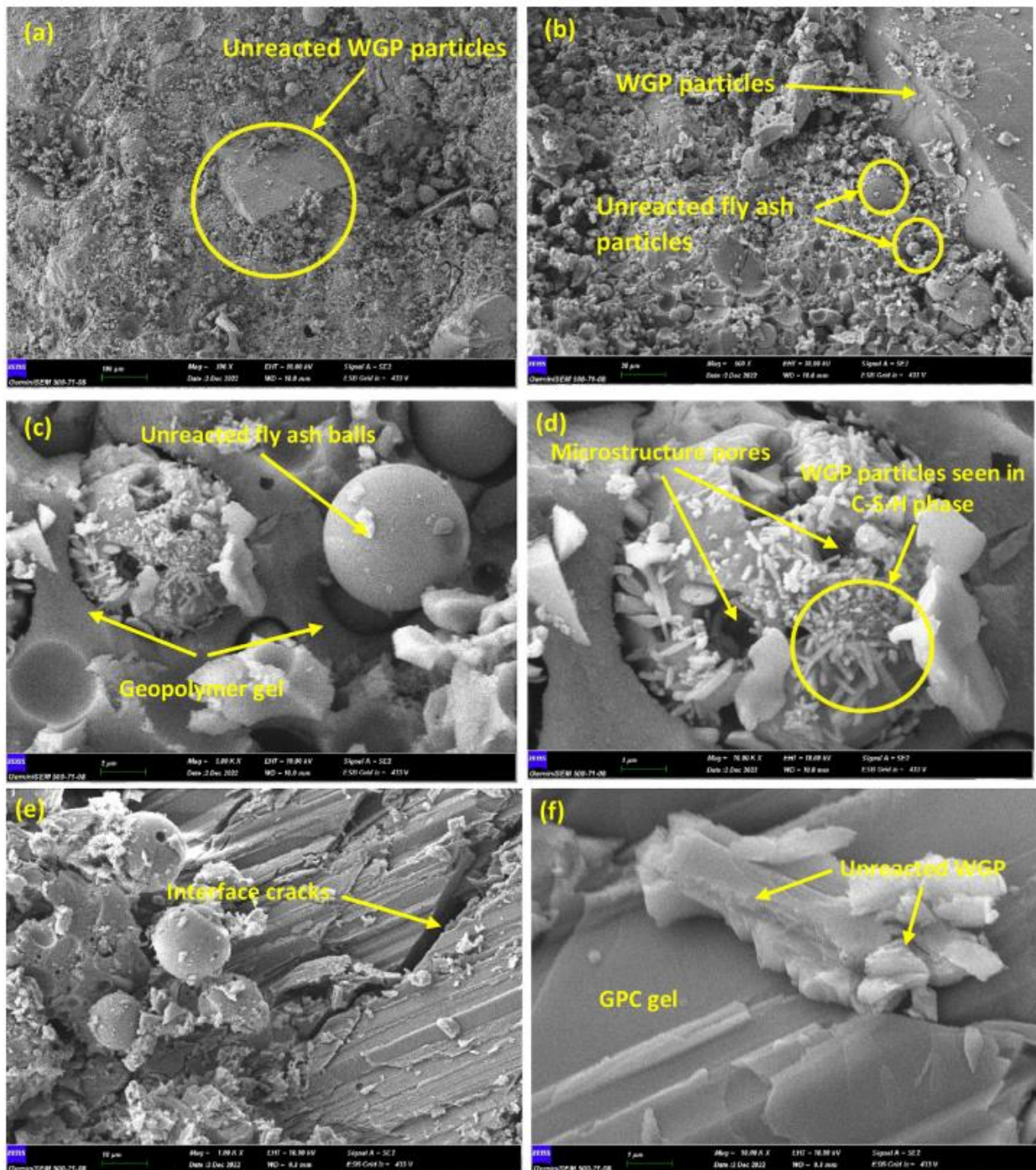


Figure 16. SEM for geopolymer concrete mixtures prepared with waste glass powder and fly ash (Çelik et al. 2023)

3.1.4.3. X-Ray Diffraction (XRD) Analysis

XRD analysis is widely used to determine the phase contents of geopolymers. In the study of Mahmoodi et al. (2020), the XRD pattern can be seen in Figure 17 for red clay brick waste-based geopolymers with fly ash, metakaolin, and ground granulated blast furnace addition. The intensity of quartz, albite, and anorthite, which are crystalline phases, can be seen in all supplementary cementitious material-based red clay brick waste geopolymers compared to the ones without supplementary addition. More amorphous phases were obtained for the geopolymer produced with %55 of red clay brick waste-%45 fly ash (BFAC45), %55 of red clay brick waste-%45 metakaolin (BMK45), %55 of red clay brick waste-%45 ground granulated blast furnace slag (BGGBS45). Furthermore, the concentration of quartz peaks was found as smaller for the BGGBS45 compared to BFAC45. As a result, the highest compressive strength values were observed for BFAC45 samples.

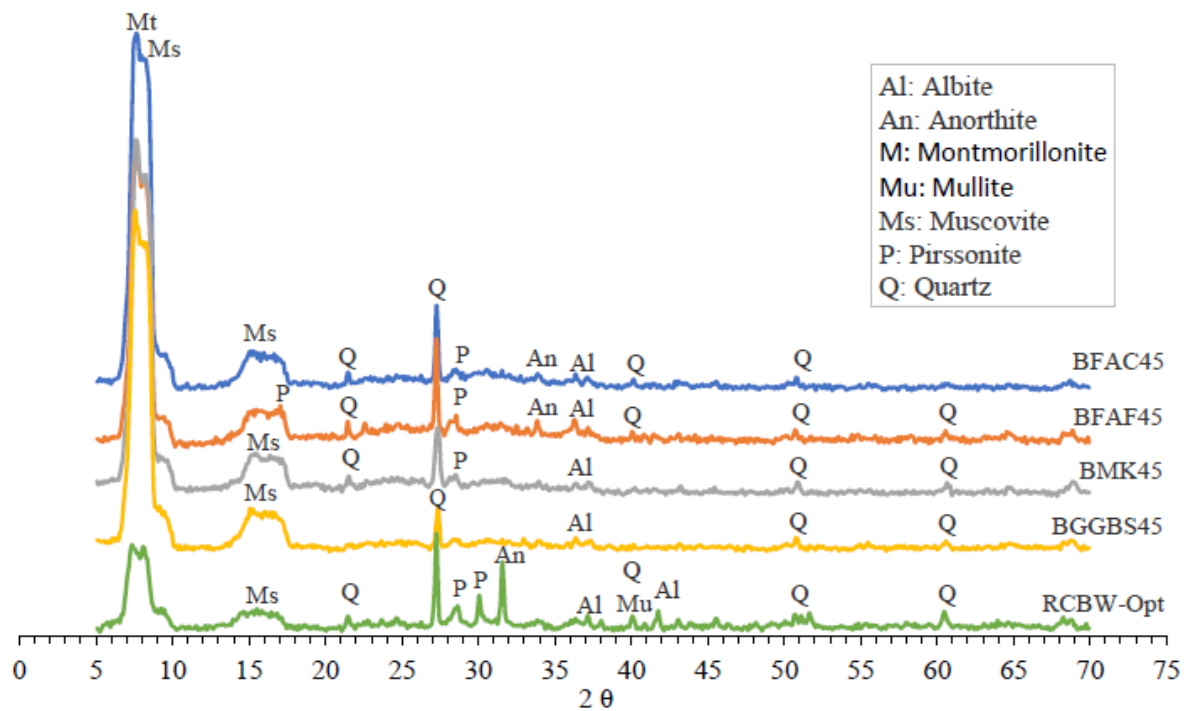


Figure 17. XRD spectra for supplementary cementitious material-based red clay brick waste (RCBW) geopolymers (Mahmoodi et al., 2020)

In the study of Kürklü (2016), the main crystalline phase is found as quartz for all samples, as in Figure 18. Alkali aluminosilicate geopolymer gel was seen for the fly ash samples, and for the blast furnace slag-based samples, calcium silicate hydrate with an aluminum structure was observed as a main reaction product. The peak intensity decreased with increasing the blast furnace slag amount in the sample. In the geopolymerization process, the crystalline phase was transformed into other phases for blast furnace slag-based samples. After the geopolymerization process, the intensity of the peaks decreased for all samples.

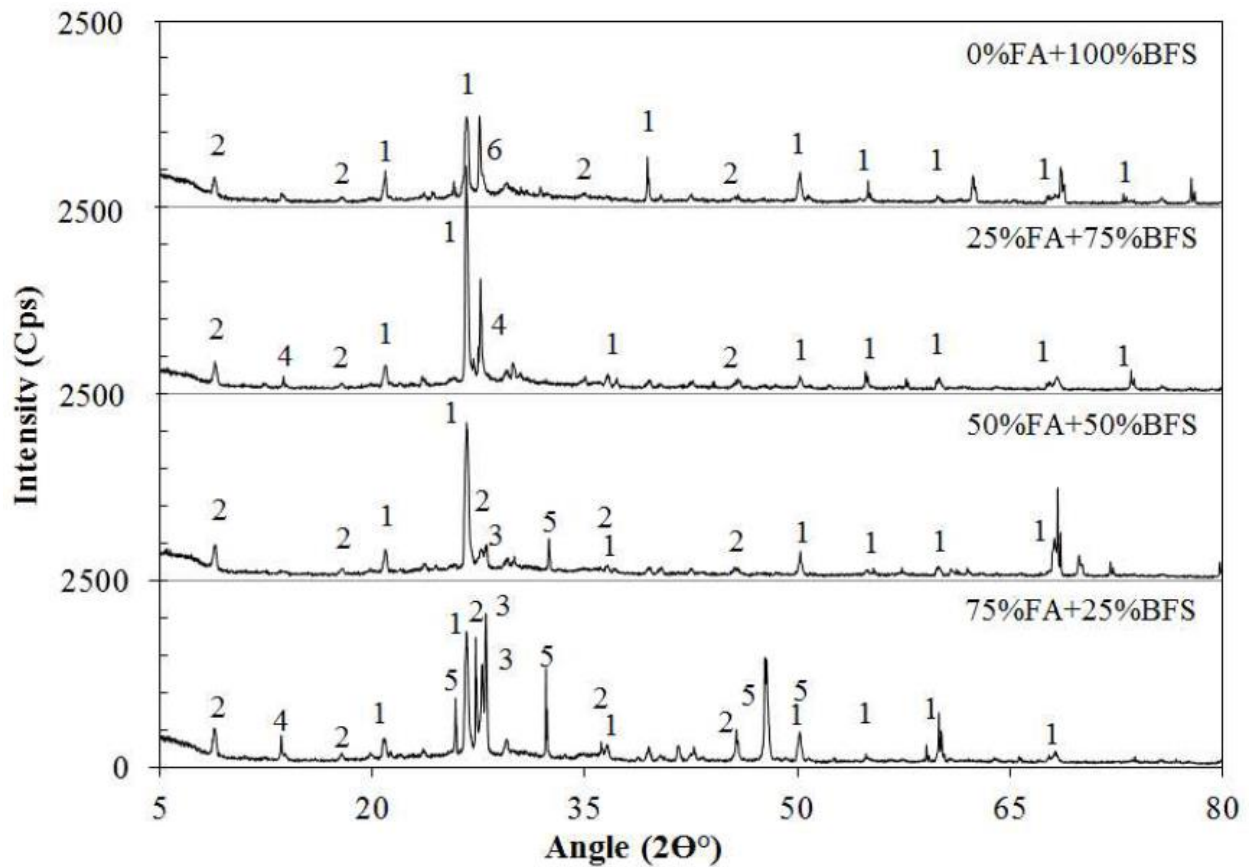


Figure 18. XRD pattern for different fly ash (FA) and blast furnace slag (BFS) geopolymer samples (1: Quartz, 2: Muscovite, 3: Anorthite, 4: Anorthclase, 5: Sodium silicate hydrate, 6: Albite (Kürklü, 2016))

3.2. Factors Affecting the Geopolymer Properties

Geopolymer properties vary according to the synthesis parameters; different kinds of geopolymers with different purposes can be obtained by changing the parameters. Raw material type, alkali activator concentration, Solid/Liquid ratio, and curing regime are the parameters that the studies mostly focus on.

3.2.1. Raw Material Type

Raw material type directly affects the strength of the material. In the study of Nuaklong et al. (2016), crushed limestone and recycled concrete aggregates were used as raw materials. The results showed that the compressive strength of crushed limestone-based geopolymers with 8, 12, and 16 M sodium hydroxide were 40, 41.4, and 38.4 MPa, while recycled concrete aggregate-based geopolymers with the same sodium hydroxide concentrations have lower compressive strengths like 30.6, 38.4 and 34.8 MPa respectively. As a result, an average reduction of 87% occurred for the recycled concrete aggregate-based geopolymer compared to the crushed limestone-based geopolymer. This was explained by having low abrasion resistance from the weakness of attached mortar in the recycled concrete aggregate-based geopolymer.

In the study of Novais et al. (2016), geopolymers were synthesized using metakaolin and waste glass as raw materials. The effect of waste glass amount on compressive strength was investigated in the study. The results showed that containing 12.5% wt. waste glass has a good impact on mechanical strength. 11.5 MPa compressive strength was obtained with 12.5% wt. waste glass-based geopolymers, while metakaolin-based geopolymer has 11.8 MPa compressive strength. However, further addition of glass waste affects the compressive strength negatively. These results can be explained by replacing the metakaolin with waste glass decreased the silicon and aluminum ions release rate, which caused strength increment.

3.2.2. Alkali Activator Concentration

Alkali activator concentration is another important parameter in the synthesis of geopolymer materials. Nuaklong et al. (2016) studied the alkali activator concentration effect by using sodium hydroxide in different concentrations, such as 8, 12, and 16 M. Results indicated that good strength values can be achieved with a 12 M sodium hydroxide alkali activator. It is because the formation of gel depended on the concentration of alkali hydroxide ions, low

hydroxide concentration means weak chemical reaction and low compressive strength. For the splitting tensile and flexural strengths, similar findings were obtained as in compressive strength. Therefore, maximum splitting tensile and flexural strength values were obtained with a 12 M sodium hydroxide alkali activator. And also, the results showed similarity to the conventional concrete.

Another study by Prasanphan et al. (2019) focused on the effects of sodium hydroxide concentration on geopolymer properties such as compressive strength. The concentration of sodium hydroxide solution was investigated for 4, 6, 8, and 10 M and the compressive strength values were found as 22.01, 22.92, 25.70 and 26.98 MPa respectively. The highest compressive strength was found as 27 MPa for the geopolymer with a 10 M sodium hydroxide solution. This was explained by the formation of a geopolymer network dependent on the alkali activator concentration. Therefore, higher concentration leads to higher dissolution of silicon and aluminum ions.

3.2.3. Liquid/Solid Ratio

The liquid-solid ratio is thought to be a factor affecting the mechanical properties of geopolymers. The compressive strength of the geopolymers depends on this ratio. In the formula, liquid represents the water, and solid represents the raw material and alkali activator. In the study of Pouhet & Cyr, M. (2016), mechanical properties were investigated for different formulations of geopolymer concretes. The maximum value of compressive strength was found as 65 MPa for the geopolymer with a 0.40 liquid/solid ratio. And same investigation was applied to the Portland cement, and the results showed that the geopolymer concretes were more affected by the water content than the Portland cement. Portland cement gives a minimum value of 40 MPa for compressive strength, while geopolymer concrete gives a minimum value of 20 MPa.

3.2.4. Curing Regime

Curing conditions, such as curing temperature or aging conditions, can be varied according to the aim of the studies. These differences in conditions can change the geopolymers' properties. In the study of Abdollahnejad et al. (2019), ambient and elevated temperature curing was applied to investigate the effects of the curing regime on differently proportioned fly ash-based geopolymers. Also, the experiments include curing time investigation for the

materials. The results showed that the compressive strength of the mixtures did not increase with increasing the curing time except the one with fly ash, calcium hydroxide, and waste ground glass all in. Elevated temperature curing caused higher compressive strength results for all mixtures than the ambient temperature curing. The highest compressive strength was obtained as 13 MPa for the geopolymer mixture with the one containing 80% wt. fly ash, 10% wt. calcium hydroxide and 10% wt. waste ground glass with a curing temperature of 80°C for 56 days.

The curing time effect is also investigated through the study of Prasanphan et al. (2019). Different curing times, such as 1, 3, 7, and 28 days, were applied to the geopolymers to observe the effects on compressive strength. The values were found as 18.74, 24.70, 26.98, and 28.55 MPa, respectively. As a result, compressive strength is increasing with increasing the curing time. This can be explained by the reaction between silicon and aluminum ions and geopolymeric gel filled in the pores in the mixtures.

In the study of Novais et al. (2016), the curing regime effect on compressive strength was studied. Three different curing conditions, 1, 7, and 28 days were determined as parameters to examine the effects. In general, the extension of curing time has an improving effect on compressive strength. For the 12.5% waste glass-based geopolymer, the compressive strengths were found as 8, 13, and 14 MPa for 1, 7, and 28 days respectively.

Considering all these components and parameters, it is obvious that geopolymers will be a long-term research topic for many researchers.

4. CONCLUSION

Cement production alone contributes to greenhouse gas emissions and causes a huge amount of CO₂ released into the environment. The cement industry induces about 5% of global environmental pollution. To reduce the harmful effect of the production of these materials, an innovative product named geopolymer was proposed by French Professor Davidovits. They can be considered as green materials because of their low impact on the environment and waste usage as raw material in the synthesis. Many researchers give their attention to geopolymer binders for their potential to be an alternative material for the construction field. Numerous studies and investigations were done accordingly. This study summarizes the studies and experiments that were done for years and creates a mapping for the topic. The review paper includes raw material and alkali activator selection, testing parameters, and the characterization of the geopolymers under different circumstances. The properties of geopolymer materials, such as mechanical, physical, and microstructural properties, were summarized by using different research papers.

Based on the studies reported in this study, the following conclusions are drawn:

- For geopolymer synthesis, silica and alumina-rich materials are preferred to be activated by high alkali solutions. For this purpose, there are some commonly used binding materials such as metakaolin, fly ash, red clay bricks, demolition wastes, and blast furnace slag. Among these binding materials, the studies show that in the case of using construction and demolition waste, the highest values, such as 70 MPa of compressive strength, can be achieved.
- Curing temperature is an important factor when considering mechanical properties. Some studies show that early-age mechanical strength increases with the initial curing temperature. Also, the curing period for the materials that are synthesized with elevated curing temperatures has a positive effect on the strength of the fly ash-based mortars.
- The curing period is also another parameter in the production of geopolymers, and some studies concluded that increasing the curing time has an improving effect on flexural strength and split tensile strength values.
- For the investigation of the geopolymers, as well as the mechanical and other properties, physical properties should be considered to have reliable results. Studies

claim that extending the curing time ends up forming more gels, and more gels result in clogging the pores, which means materials with less porosity. Also, the water absorption property is similar to the apparent porosity results; increasing the curing time results in decreasing the water absorption. Densities were also investigated in the studies, and it was found that the apparent density decreased with increasing the curing time.

- Even though geopolymers have these advantages for the environment, it's crucial to keep in mind that their full lifecycle impact, including raw material extraction, production, transportation, and disposal, should be carefully considered and compared to traditional cement to determine how well they perform in terms of the environment overall. For raw material extraction units, night-shift operations might help with energy conservation, or building solar panels for those extraction units can be beneficial. Also, in order for the product to reach a certain standard, the collected wastes to be used as raw materials should be homogenized and then characterized and put into production. In addition, with the multi-parameter studies to be carried out, geopolymers, which are accepted as an important material in terms of sustainability, need to demonstrate the potential to be produced with lower energy consumption, both with various grinding systems and with different curing approaches. In this way, it should be brought to the literature more clearly whether these materials can be defined as a material in the category of High-Performance Innovative Materials Providing Energy Efficiency, which is among the priority Research and Development issues of the TÜBİTAK and European Union.

5. REFERENCES

- Abdollahnejad, Z., Dalvand, A., Mastali, M., Luukkonen, T., & Illikainen, M. (2019). Effects of waste ground glass and lime on the crystallinity and strength of geopolymers. *Magazine of Concrete Research*, 71(23), 1218-1231.
- Allahverdi, A., & Najafi Kani, E. (2009). Construction wastes as raw materials for geopolymer binders. *International Journal of Civil Engineering*, 7(3), 154-160.
- à Moungam, L. M. B., Mohamed, H., Kamseu, E., Billong, N., & Melo, U. C. (2017). Properties of geopolymers made from fired clay bricks wastes and rice husk ash (RHA)-sodium hydroxide (NaOH) activator. *Materials Sciences and Applications*, 8(7), 537-552.
- Amran, Y. M., Alyousef, R., Alabduljabbar, H., & El-Zeadani, M. (2020). Clean production and properties of geopolymer concrete; A review. *Journal of Cleaner Production*, 251, 119679.
- Bai, C., & Colombo, P. (2018). Processing, properties and applications of highly porous geopolymers: A review. *Ceramics International*, 44(14), 16103-16118.
- Cheng, T. W., & Chiu, J. P. (2003). Fire-resistant geopolymer produced by granulated blast furnace slag. *Minerals engineering*, 16(3), 205-210.
- Chindapasirt, P., & Rattanasak, U. (2010). Utilization of blended fluidized bed combustion (FBC) ash and pulverized coal combustion (PCC) fly ash in geopolymer. *Waste Management*, 30(4), 667-672.
- Çelik, A. İ., Tunç, U., Bahrami, A., Karalar, M., Mydin, M. A. O., Alomayri, T., & Özkılıç, Y. O. (2023). Use of waste glass powder toward more sustainable geopolymer concrete. *journal of materials research and technology*, 24, 8533-8546.

Davidovits, J. (1991). Geopolymers: inorganic polymeric new materials. *Journal of Thermal Analysis and calorimetry*, 37(8), 1633-1656.

Davidovits, J. (2015). *Geopolymer Chemistry and Applications*. 4-th edition. J. Davidovits.—Saint-Quentin, France.

Davidovits, J. (2017). Geopolymers: Ceramic-like inorganic polymers. *J. Ceram. Sci. Technol*, 8(3), 335-350.

Fan, F., Liu, Z., Xu, G., Peng, H., & Cai, C. S. (2018). Mechanical and thermal properties of fly ash based geopolymers. *Construction and Building Materials*, 160, 66-81.

Gundaraniya, N. (2022, January 12). Tensile strength of concrete: What is tensile strength of concrete: Why concrete weak in tension: Split cylinder test of concrete: Tensile strength test procedure. CivilJungle. <https://civiljungle.com/concrete-strength/>

Hadi, M. N., Al-Azzawi, M., & Yu, T. (2018). Effects of fly ash characteristics and alkaline activator components on compressive strength of fly ash-based geopolymer mortar. *Construction and Building Materials*, 175, 41-54.

Hasnaoui, A., Ghorbel, E., & Wardeh, G. (2019). Optimization approach of granulated blast furnace slag and metakaolin based geopolymer mortars. *Construction and Building Materials*, 198, 10-26.

Hlobil, M., Sotiriadis, K., & Hlobilová, A. (2022). Scaling of strength in hardened cement pastes-Unveiling the role of microstructural defects and the susceptibility of CSH gel to physical/chemical degradation by multiscale modeling. *Cement and Concrete Research*, 154, 106714.

Huntzinger, D. N., & Eatmon, T. D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of Cleaner Production*, 17(7), 668–675.

Huseien, G. F., Mirza, J., Ismail, M., Ghoshal, S. K., & Ariffin, M. A. M. (2018). Effect of metakaolin replaced granulated blast furnace slag on fresh and early strength properties of geopolymer mortar. *Ain Shams Engineering Journal*, 9(4), 1557-1566.

Huseien, G. F., Mirza, J., Ismail, M., Ghoshal, S. K., & Hussein, A. A. (2017). Geopolymer mortars as sustainable repair material: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 80, 54-74.

Jamal, H. (2017, June 8). Haseeb Jamal. Concrete Sample Preparation | Concrete Testing Cylinder Molds. <https://www.aboutcivil.org/method-process-compression-test.html>

Kohout, J., Koutník, P., Hájková, P., Kohoutová, E., Soukup, A., & Vakili, M. (2023). Effect of Aluminosilicates' Particle Size Distribution on the Microstructural and Mechanical Properties of Metakaolinite-Based Geopolymers. *Materials*, 16(14), 5008.

Komnitsas, K., Zaharaki, D., Vlachou, A., Bartzas, G., & Galetakis, M. (2015). Effect of synthesis parameters on the quality of construction and demolition wastes (CDW) geopolymers. *Advanced powder technology*, 26(2), 368-376.

Kua, T. A., Arulrajah, A., Mohammadinia, A., Horpibulsuk, S., & Mirzababaei, M. (2017). Stiffness and deformation properties of spent coffee grounds based geopolymers. *Construction and Building Materials*, 138, 79-87.

Kürklü, G. (2016). The effect of high temperature on the design of blast furnace slag and coarse fly ash-based geopolymer mortar. *Composites part b: engineering*, 92, 9-18.

Liew, Y. M., Heah, C. Y., & Kamarudin, H. (2016). Structure and properties of clay-based geopolymer cements: A review. *Progress in Materials Science*, 83, 595-629.

Mahmoodi, O., Siad, H., Lachemi, M., Dadsetan, S., & Sahmaran, M. (2020). Optimization of brick waste-based geopolymer binders at ambient temperature and pre-targeted chemical parameters. *Journal of Cleaner Production*, 122285.

Mehta, A., & Siddique, R. (2018). Sustainable geopolymer concrete using ground granulated blast furnace slag and rice husk ash: Strength and permeability properties. *Journal of cleaner production*, 205, 49-57.

Mikulčič, H., Klemeš, J. J., Vujanović, M., Urbaniec, K., & Duić, N. (2016). Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process. *Journal of cleaner production*, 136, 119-132.

Mohajerani, A., Suter, D., Jeffrey-Bailey, T., Song, T., Arulrajah, A., Horpibulsuk, S., & Law, D. (2019). Recycling waste materials in geopolymer concrete. *Clean Technologies and Environmental Policy*, 21(3), 493-515.

Novais, R. M., Ascensão, G., Seabra, M. P., & Labrincha, J. A. (2016). Waste glass from end-of-life fluorescent lamps as raw material in geopolymers. *Waste Management*, 52, 245-255.

Nuaklong, P., Sata, V., & Chindapasirt, P. (2016). Influence of recycled aggregate on fly ash geopolymer concrete properties. *Journal of Cleaner Production*, 112, 2300-2307.

Panizza, M., Natali, M., Garbin, E., Tamburini, S., & Secco, M. (2018). Assessment of geopolymers with Construction and Demolition Waste (CDW) aggregates as a building material. *Construction and Building Materials*, 181, 119-133.

Phoo-ngernkham, T., Chindapasirt, P., Sata, V., Pangdaeng, S., & Sinsiri, T. (2013). Properties of high calcium fly ash geopolymer pastes with Portland cement as an additive. *International Journal of Minerals, Metallurgy, and Materials*, 20(2), 214-220.

Phoo-ngernkham, T., Maegawa, A., Mishima, N., Hatanaka, S., & Chindaprasirt, P. (2015). Effects of sodium hydroxide and sodium silicate solutions on compressive and shear bond strengths of FA–GBFS geopolymer. *Construction and Building Materials*, 91, 1-8.

Pouhet, R., & Cyr, M. (2016). Formulation and performance of flash metakaolin geopolymer concretes. *Construction and Building Materials*, 120, 150-160.

Pouhet, R., & Cyr, M. (2016). Formulation and performance of flash metakaolin geopolymer concretes. *Construction and Building Materials*, 120, 150-160.

Prasanphan, S., Wannagon, A., Kobayashi, T., & Jiemsirilers, S. (2019). Reaction mechanisms of calcined kaolin processing waste-based geopolymers in the presence of low alkali activator solution. *Construction and Building Materials*, 221, 409-420.

Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related alkali-activated materials. *Annual Review of Materials Research*, 44, 299-327.

Provis J. L, van Deventer JSJ, eds. 2014. Alkali-Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM. Dordrecht: RILEM/Springer

Ramiz, E. (2020, July 15). What is flexural strength of concrete? 5 test steps & problems. Civil Click. <https://www.civilclick.com/flexural-strength-of-concrete/>

Ramujee, K., & PothaRaju, M. (2017). Mechanical properties of geopolymer concrete composites. *Materials Today: Proceedings*, 4(2), 2937-2945.

Ranjbar, N., Mehrali, M., Mehrali, M., Alengaram, U. J., & Jumaat, M. Z. (2015). Graphene nanoplatelet-fly ash based geopolymer composites. *Cement and Concrete Research*, 76, 222-231.

Rattanasak, U., & Chindaprasirt, P. (2009). Influence of NaOH solution on the synthesis of fly ash geopolymer. *Minerals Engineering*, 22(12), 1073-1078.

Saha, S., & Rajasekaran, C. (2017). Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag. *Construction and Building Materials*, 146, 615-620.

Sathanandam, T., Awoyera, P. O., Vijayan, V., & Sathishkumar, K. (2017). Low carbon building: Experimental insight on the use of fly ash and glass fibre for making geopolymer concrete. *Sustainable Environment Research*, 27(3), 146-153.

S. Böhmer, C. Neubauer, E. Schachermayer, B. Winter, B. Walter, “Aggregates Case Study: Data Gathering. Final Report Referring To Contract N° 150787-2007 F1SC-AT,” Vienna, 2008.

Sun, Z., Cui, H., An, H., Tao, D., Xu, Y., Zhai, J., & Li, Q. (2013). Synthesis and thermal behavior of geopolymer-type material from waste ceramic. *Construction and Building Materials*, 49, 281-287.

Sun, Z., & Vollpracht, A. (2019). One year geopolymerisation of sodium silicate activated fly ash and metakaolin geopolymers. *Cement and Concrete Composites*, 95, 98-110.

Usha, S., Nair, D. G., & Vishnudas, S. (2016). Feasibility study of geopolymer binder from terracotta roof tile waste. *Procedia Technology*, 25, 186-193.

Vásquez, A., Cárdenas, V., Robayo, R. A., & de Gutiérrez, R. M. (2016). Geopolymer based on concrete demolition waste. *Advanced Powder Technology*, 27(4), 1173-1179.

Vivian, Soomro, M., & Evangelista, A. (2022). *Recycled Concrete*. Woodhead Publishing.

Wu, Z., Ann, T. W., Shen, L., & Liu, G. (2014). Quantifying construction and demolition waste: An analytical review. *Waste Management*, 34(9), 1683-1692.

Zhang, H. (Ed.). (2011). Building materials in civil engineering. Elsevier.

Zhang, Y., Xiao, R., Jiang, X., Li, W., Zhu, X., & Huang, B. (2020). Effect of particle size and curing temperature on mechanical and microstructural properties of waste glass-slag-based and waste glass-fly ash-based geopolymers. *Journal of Cleaner Production*, 273, 122970.

World Meteorological Association. (2022). State of the global climate 2021.

