

Microwave Heating of Geopolymers in a Construction 3D Printer

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Submitted in fulfillment of the requirements

for the degree of Master of Science

in Mechanical & Aerospace Engineering



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March 2024

DECLARATION

I hereby, declare that this manuscript, entitled “*Microwave heating of geopolymers in a construction 3D printer*”, is the result of my own work except for quotations and citations, which have been duly acknowledged.

I also declare that, to the best of my knowledge and belief, it has not been previously or concurrently submitted, in whole or in part, for any other degree or diploma at Nazarbayev University or any other national or intentional institution.



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Date: 18.03.2024

ABSTRACT

This MSc research thesis delves into the mechanical behavior of copolymer-based structures fabricated through 3D printing, specifically focusing on the transformative influence of microwave heating. Centered on geopolymers, recognized for their eco-friendly and sustainable attributes, the study aims to elucidate the nuances in stress and deformation dynamics introduced by microwave heating in the 3D printing process.

A comprehensive literature review outlines the various applications of microwave heating within geopolymer chemistry, advancements in 3D printing technology, and materials science. This review synthesizes the concepts to establish a theoretical framework, enabling a deep understanding of the intricate interactions between the application of microwave energy and geopolymerization processes.

Empirical data were collected through stress-strain experiments conducted on geopolymer samples subjected to microwave heating and conventional 3D printing techniques. This investigative approach required meticulous experimentation and systematic modification of parameters such as treatment duration, microwave energy exposure period, and the resultant voltage-strain profiles. These parameters were scrutinized to ascertain the impact of microwave heating on the mechanical performance of geopolymer structures.

Findings from stress and strain tests provide reliable insights. It was observed that microwave heating alters the polymerization process, thereby influencing the material's response to external forces. A comparative analysis of stress-strain curves between specimens exposed to microwave radiation and those treated conventionally reveals differences in structural integrity and load-bearing capacities.

Discussions elucidate these findings, pondering the implications for construction methodologies. Microwave heating emerges as a promising catalyst for enhancing the mechanical performance of geopolymer-based constructions. This revelation holds the potential to refine procedures for 3D printing recyclable building materials, optimizing them for better performance and sustainability.

Key words: Additive manufacturing, Construction 3D Printing, Geopolymer, Polymerization, Microwave Heating

ACKNOWLEDGEMENTS

I would like to show my sincerest thank to Nazarbayev University considerable providing me with the an invaluable chance to undertake education under the guidance of the best professionals and in well-equipped laboratories. I would like to acknowledge my gratitude first and foremost to my mentor, Professor Md. Ali and Co-supervisor Professor Essam Shehab for their constant and dedicated support and advice during the course of my conduct of this interesting research.

I also got to be attributed to Professor Yerbol and Professor Dmitry for the invaluable knowledge they gave me on how to organize and structure thesis up to academic needs.

Besides, I would like to sincerely show my gratitude to the Civil Engineering department for having places having great convenience and laboratory facilities that were very clean and which greatly facilitated my own studies.

In the end, I have my family to thank for being there by my side; for donating their conviction in me and for helping me tirelessly. Their belief in me, that is to say support and encouragement, has actually been my constant lifting force and motivation.

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List of Abbreviations & Symbols

FA	Fly Ash
GGBS	Ground granulated blast-furnace slag
3D	3 Dimensional
3DCP	3D Construction Printer
CC	Contour Crafting
FDM	Fused Deposition Modeling

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Chapter 1 – Introduction

1.1. Background and Context

The advent of additive manufacturing technologies in the 1980s opened up new opportunities due to the unique capabilities of producing complex geometry shapes. Because it is feasible, additive manufacturing (AM) techniques like three-dimensional printed (3DP) concrete are becoming increasingly popular in the building industry (Qaidi et al., 2022). Compared to traditional construction methods, additive manufacturing offers increased safety, faster construction times, reduced chance of construction errors, and complete 3D geometry flexibility. (Xia & Sanjayan, 2016). Some examples of three-dimensional printed construction (3DPC) are shown in Figure 1.



a) Additive Manufactured Home by Icon



b) Building in Dubai manufactured by 3DPC

Figure 1: Large-scale printed objects (Amran et al., 2022)

c

- Architectural Detailing and Ornamentation;
- Construction in Challenging Environments;
- Customized Modular Construction;
- Infrastructure Development;
- Rapid Prototyping and Iterative Design;
- Energy-Efficient Construction;
- Waste Reduction and Recycling.

1.1.1 Significance of Microwave Heating in Construction Materials

The birth of the microwave, after all, is a great breakthrough in how to prep construction stuff in a very short while. Besides this, the unique technology that requires the use of electromagnetic waves not only substantially results in the quick and wide heating, but also introducing many other great benefits that eventually transform the conventional processing techniques (Buttress et al., 2015). Microwave curing would change the methods completely for concrete curing. Although, comparing to traditional method, steam curing, microwave heating contributes to enhance the concrete's early strength faster (Wei et al., 2021). It is through the microwave-assisted heating mechanism that the key to multiple factors in building materials can be highlighted, such as a speedy mortar curing, advanced energy efficiency, and customized material modification (Wei et al., 2019).

Microwave radiation is a form of electromagnetic energy in the interval between infrared and radio frequencies (Fig. 2.) and is a useful tool for fast hardening of built-up materials such as concrete and therefore producing better workability with microwaves. As defined by Reinosa et al.(2019), different from the previous methods, the heating of microwave concentrates all over the materials enhancing the uniform heat distribution providing also time and material savings. This directly affects its mechanical properties. It is depicted in Fig.3 a microwave heating system.

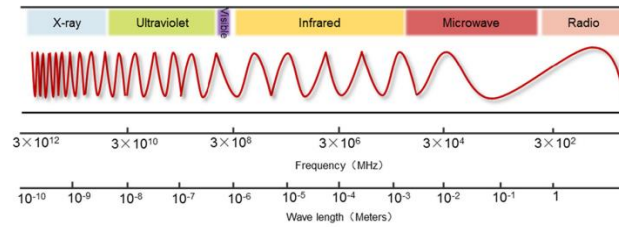


Figure 2: Spectrum of electromagnetic radiation

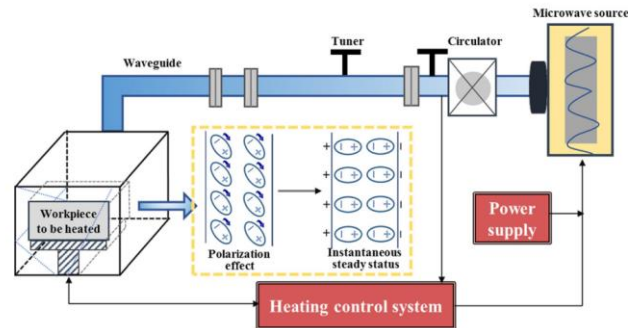


Figure 3: Microwave heating system (Wei et al., 2019)

The use of microwave heating has the specialized accuracy to be selective precisely toward materials or components that are in a building mixture (Makul et al., 2014). At this level, the researchers can work with the various properties of the material and manipulate them individually to achieve an outcome that was previously impractical. This does allow for the innovation of materials design and optimization of material performance. It is more applicable in case of usage of composite materials in which by this technology engineers and builders are able to manipulate the material characteristics (Makul & Agrawal, 2011). Furthermore, microwave heating answers for energy efficiency competency issue which traditional ones do not. The microwave technology means that materials heat up much faster and specifically. Hence, the power consumption and green energy are not compromised in any way (Li et al., 2020). Adaptation of microwave heat gets to the heart of advanced building materials' assortment to the specific systems allowing micro wave heat to change the material design as we knows it.

1.2 Problem Statement

The development of environment friendly building materials has become an essential obligation for the global construction sector in the view of the prevailing environmental problems (Sharma et al., 2022). Nonetheless, preserving a sustainable lifestyle requires patience, tolerance as well as overcoming significant barriers. It is about the conducting comprehensive LCA of the environmental impacts of building materials immediately from the extraction through the waste management procedures, as Bhamare and others indicate (2019). The assessment of a full life-cycle of raw materials from origin to their utilization, and its final ones such as reuse or recycling, is quite challenging. The problem of the practical sustainability assessment is exacerbated by both different data, lack of standardization and the need of full understanding of the actual impact which means that we not only need data but standard procedures and understanding of the whole material cycle that includes the extraction, usage and disposal of a particular material (Kibert, 2007).

However the design acidity are environment friendly building materials in terms of strength and operational principle is a persistent challenge. It has the methodical approach to the point at which we will strike an equilibrium between stability and the need for stability features (Saleh & Alalouch, 2015). While a few pro-ecologies compositions are dynamic but be rigorous enough to suggest structural assurance and high endurance level. Here occurs a clash, where the environmental impact and the technical needs of such a construction are both in contradiction.

Keeping emerging technologies and new materials in line with the empirical layouts and time-tested methods turns to be a very complicated task. Nevertheless, Bon and Hutchinson (2000) state that in spite of the wide range of beneficial solutions there are still many factors which together impede the widespread environmental friendly practices in the construction sector: upfront refunds, low awareness, and resistance to overcome their ways of doing this. Giving the ride to the innovation to go forth and join the implementation in the context of fostering the environmentally friendly building materials is still a glaring problem.

1.2.1 Rationale for Investigating Microwave Heating in Geopolymer-Based 3D Printing

The scientific merit of the microwave heating approach in 3D printing based on Geopolymers is brought by its multidimensional nature that not only leads to the wonderful discoveries of science but also serves to reduce environmental pollution as well as to pursue new technological achievements (Ma et al., 2021). This study wishes using microwave efficiency and

accuracy, which are the main components, widely in the conventional treatment methodologies of construction materials.

Microwave heating though not anew, but a promising approach for speeding up the processing process of Geopolymer compositions is the (Ma et al., 2021). The typical methods involves the old ways of healing that require a split long time, but having the microwave can make you all modernize and have quick and even distribution of heat. Therefore, they performed weaker after several layers because of the weight of geopolymer that hast been placed on the bottom layer. Therefore, nothing is left to chance as we make sure the initial layers have the right strength to stand any high pressure experienced in the depths (Sun et al., 2021). This efficiency is consistent with and support the global efforts to encourage the developing of environmentally friendly construction methods which at taking reduce the construction time period (Al-Qutaifi et al., 2018).

This study is based on the environmental factors which are related to Geopolymers good characteristic that is environmentally friendly. Geopolymers are considered as more eco-friendly alternative building materials that are gaining ground due to their recycling-oriented construction approach. This helps lower the carbon footprint and waste production. The Microwave heat function in the Environmental Responsibility System is meant to achieve a full load with environmental sustainability features using Geopolymers; this creates a system where both current environmental priorities and sustainability features are achieving the same goal.

Microwave heating studies are therefore also important to the reformation and reprofiling of the performance of Geopolymers in 3D printing (Ilcan et al., 2022). The radiation from a microwave means that the radiation's desired effect on some critical features of a product gets achieved. Therefore, their high accuracy reveals the fascinating fact that Geopolymer materials can be used to improve structural and mechanical properties of the construction components. This results in more durable and adaptable materials (Al-Qutaifi et al., 2018).

1.3 Motivation

The idea of using 3D printing through microwave construction of Geopolymers grows straight from the profound providence of making a society which is devoid of barriers to

sustainable construction. Besides being compelled to a rapid deviation from conventional construction methods by the climbing ecological problems there should be high level of creativity to propose the solutions to these issues. Introductory part of the thesis paper will deal with an available and essential gap in which we need groundbreaking changes that will re-write the rules of construction and positively contribute to transforming our Built Environment.

The goal of this study is to unfold the complex interactions between microwave irradiation and geopolymerization and to eventually establish a firm foundation for these processes. Determining the untapped efficiency of it can save time and energy wastage, and as a result, construction of structures consisting of Geopolymers is faster and uses less material. This event becomes one of milestones which is related to general international achievement whose intention is to mitigate the negative effect of construction and having the more sustainable construction work.

The purpose of this is to enrich the already existing sustainable building toolbox based on the use of 3D construction printing by a geopolymer reinforced by microwave radiation. Hence, it supports the idea that it is one of the important instruments in the world of sustainable building technologies. Being evaluated for precision and saving energy in the process, microwave is promising to alter the treatment procedure by cutting down power utilization and production planning time. On this basis the innovation of this technology into geopolymerization process has birthed a novel and unique role for building materials with value-added benefits that are designed as a first step toward environmental sustainability.

Along with this, this study is also trying to find a growth path of the construction industry towards the world where tech and renewables work complementary. Promoting already proven techniques is not only to suggest new approaches to scientific identification of new problems but also to solve practical problems appearing in the real world. The aim of this research is to change the way that people build by bringing in technological and sustainable aspects of the environmental concerns.

The reason, which is the main is that Geopolymers and such structures if they are 3D printing and microwave heating based can fundamentally alter the construction field. Emulating the spirit of meeting the challenges of the construction industry by ways of research that will go on with the development of green materials which apart from their strength, toughness and flexibility of the material, integrates the attitude of care for the environment. By issuing this thesis

I hope to make an important contribution to the development of the eco-smart technologies in construction, something which will help to create a system of compatible, and, hopefully, friendly relationship between human activity and the nature.

1.4 Research Aim and Objectives

The goal of this research is the investigation of impact of microwave treatment on enhanced mechanical properties of composite polymer on 3D additive printing. Below are several research objectives that will be achieved during the research: Below are several research objectives that will be achieved during the research:

- Examine the effects of microwave heating parameters (e.g., power, frequency, exposure time) on the printability and layer adhesion of geopolymers during 3D printing with a Construction 3D Printer.
- Assess the mechanical properties of 3D-printed geopolymers when subjected to microwave-assisted curing
- Provide recommendations and guidelines for optimizing microwave heating parameters in the context of 3D printing with a Construction 3D Printer to achieve improved print quality and efficiency.

Chapter 2 – Literature Review

2.1. Introduction

This is very critical research with broad repercussions for the construction field. This work thoroughly investigates the effect of microwave heating on geopolymers for 3D construction printing. These geopolymers aroused great interest through their excellent mechanical properties and an environmentally friendly composition, which is sustainable for substitution of traditional materials. Accordingly, a new approach is introduced that aims at improving the curing process of geopolymer-based structures with the aid of microwave heating techniques, in order to promise reductions in fabrication times and lead to improvements in material performance. One would have to actually look into the present literature on the topic to have an understanding of the capacity that microwave curing can show in the printing of 3D construction because it is an amount of different research, methodologies, and findings. This literature review, therefore, synthesizes and analyses the current state of knowledge with regard to the effect of microwave heating on geopolymers for 3D printing construction. Referring to the key concepts, experimental methodologies, JSON, and empirical findings, this review tries to bring out critical insight and finds the avenue of further research in this fast-growing field.

2.2. Geopolymer Chemistry

2.1.1 Composition and Formation Mechanisms

It is the creation of the formulas and reaction mechanisms of geopolymers in geochemistry where complicated aluminosilicate materials are bonded with alkaline activators, resulting in the establishment of inorganic polymers, which have a great deal of potential applications in the field of green construction and materials science. During the year of 1950s, S.D. Glukhovsky changed the material composed of silica and reactive alumina by applying alkali. The process is broken down into three steps according to the Gluhhovsky model: (a) conversion–verticality; (b) verticality–lateral development; and (c) lateral development–crystallization (Ponomar et al., 2023). Figure 4 shows a conceptual diagram of geopolymerizing process. The thumb rule during geopolymerization is, high silica and high aluminosity (contained in clay and kaolinite) content is a must (Duxson et al., 2007).

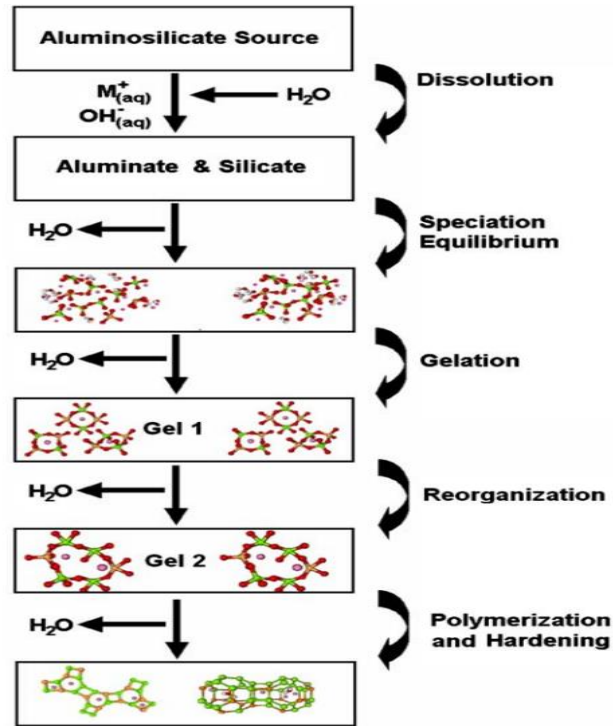


Figure 4: Geopolymerization conceptual model (Duxson et al., 2007)

Fly Ash

Risk of fly ash, a refractory material produced in the course of coal burning, which is further utilized as an aluminosilicate compound in geopolymer mix, has been pointed out within the study continued by Zhuang et al. (2016). This is the case particularly where it is easily accessible and is effective to address environmental issues, environmental friendly construction technologies will be user friendly. The fly ash is a reactive substance that is made up of small particles laden with high contents of silicium and alumina trioxide and therefore can be used to unite various substances through eco-friendly way.

During the reaction with the alkaline media like NaOH or KOH, the fly ash gets dissolved and the released SiO₂ and AlO₂ provide a new construction material with a high content of SiO₂ and AlO₂ (Panas et al., 2007). Later that, these disintegrated components go to the reaction of polycondensation processes that result in a complex copolymer structure in three dimension (Fig 5.) (Ponomar et al., 2023). This new copolymer will stand out because it would have evolved properties, such as increased compressive strength, and long service life. The employment of fly ashes in geopolymer chemistry play the leading role in forming environment-friendly and

environmentally neutral waste exposure processes in contrast to the traditional cement industry bringing about negative effects on the ecology.

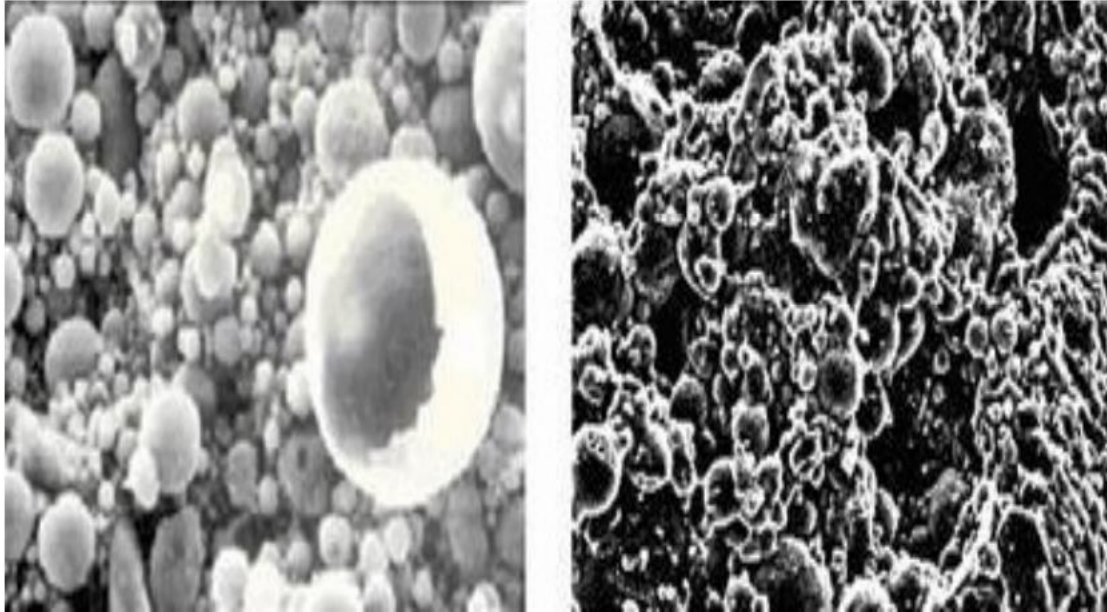


Figure 5: Characterization of the Fly Ash's microstructure prior to and during its interaction with NaOH

Alkali Activation

When the fly ashes are brought into contact with the alkaline solution, the process depicted in Figure 6 begins: yet, the Si and Al will start melting as soon as such temperature is reached. Thereafter, bigger molecules start to fuse and form gel like aqueous solution that ultimately reacts and cleanses the solid surface of the particle. Subsequently, the particle is getting stretched and forms a bigger borer which exposes the small particles from their outer sides. This implies that these small particles are not going to be protected since there is a harmonized alkaline attack from the internal and external sides (Pacheco-Torgal et al., 2008). Thereby, these reactions products paraform in two different directions, they do it inside and outside the particle and the digestacy occurs until the ash particle is totally taken away or vaporized.

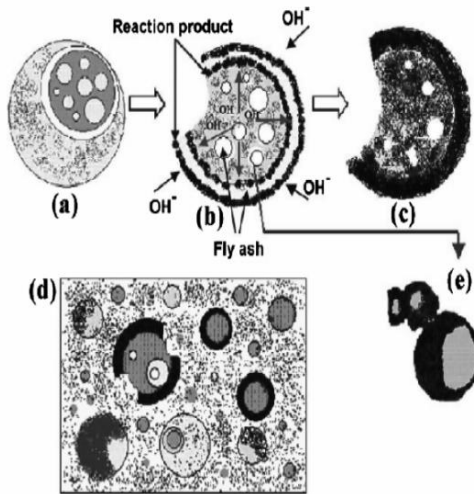


Figure – 6. A model describing fly ash alkali activation (Pacheco-Torgal et al., 2008)

2.1.2 Mechanical Properties of Geopolymer-Based Materials

Nowadays, copolymer based solutions capture the limelight of different construction companies due to its environmentally friendly nature. Hence, cementing materials made from copolymers could be adopted instead of the traditional products which are not environmental friendly. In this study, geopolymers-based materials had been widely recognized for their imperative in the engineering field; thus, the mechanics of them were carefully analyzed. It is remarkable that there are so many researches on the compressive strength of materials produced from Geopolymer. In 1952, Glushenkov determined this field of geopolymer viscous substances sliding and showed that their compressive force may rival or even exceed concrete (Ponomar et al., 2023). Other work by Cheng and Chiu in the year 2003 also focused on the impact of many contributing factors on compressive strength of the sample. Besides these factors are the type and the ratio of the aluminosilicate precursors and the strong component of alkaline activator that was applied. The strength of bending and rigidity are also examined in addition to compressive strength of the geopolymer materials which have become the most investigated subject recently. Research by Xie, et al, in 2020 can be referred to as the position of Geopolymer Composite in bending motion and has been associated with the ability of hardening condition to lead to increase in bending strength. Also, Duxson and)etal (2007) and Korniejenko and)etal(2016) ascertain the post-cracking behaviour and strengthability of the Geopolymer-based materials, showcasing the

fascinating phenomenon that they are able to show higher strength value than the conventional concrete.

Moreover, the audit focused on the prospects of deploying reinforcement into Geopolymer to make the material’s mechanical properties better. The study had been conducted by Wang et al (2023) to discover the effectiveness of increasing the tensile strength and hardness of Geopolymer composites by the means of introducing fibres like polypropylene and steel. The table 1 represents the mechanical basis properties of steel fibers The experiments conducted by them, supposedly tell that the Geopolymers-based materials, ie structural and civil infrastructures, can be made stronger which is due to the reasoning behind fibre reinforcement. Furthermore, publications on geopolymers as natural material that are resilient have been abundant, and this is the fact that is hard to utilize in real life activities. Significantly, Zhao et al. (2019) and Jiao et al. (2021) have investigated the Geopolymer resilience in extreme conditions as well as appreciable exposure to harsh chemicals (i.e., acids and alkalis) and the freeze-thaw cycles. The results from those experiments are crucial for understanding the cardinal properties of Geopolymer materials which eminently include their long-term performance and stability. Furthermore, the nanolevel analysis of the microstructure of Geopolymer based products enhances the information on the mechanical properties significantly. Xu et al. (2021) combined microscopic examinations with the pore structure and discussion of all bonding inside Geopolymers and subsequent connection to the properties that underlay the mechanics. The skills in microstructure analyses are key in optimizing the formulation of geopolymers and in designing special-grade geopolymers according to the particular technical needs.

Table 1: Basic mechanical properties of steel fibers for geopolymer compositions (Wang et al., 2023)

Types	Reference	Diameter	Length	Elastic Modulus	Density	Tensile Strenght
		(mm)	(mm)	(GPa)	ρ /(g/cm ³)	(MPa)
Hooked end	(Da Silva et al., 2022)	0.19	12.5	200	7.85	1950
	(Kim et al., 2015)	0.55	29.5	200	7.85	1050

	(Tran et al., 2019)	0.56	35	210	-	1300
Crimped	(Vijaya Prasad et al., 2022)	0.5	25	205	-	1150
	(Kumar et al., 2020)	0.45	25	-	-	2655
Straight	(Al-Majidi et al., 2017)	0.15	13	210	7.8	2470
	(Liu et al., 2021)	0.13	14.5	210	7.9	1200
	(Liu et al., 2021)	0.12	9.8	210	7.8	1150

2.3. Advances in 3D Construction Printing

2.2.1 Evolution of 3D Printing Technology in Construction

The extraordinary development in the fields of construction and construction has been annexed to that of the 3D printing technology. It allows the humans to generate small micro-scale 3D objects quickly, of certain design, while access to labor and material necessity can also be decreased. Therefore, apart from the speed of destination, navigating through harsh and difficult areas of the Earth where human labor is impossible, for example, remote locations and outer space (Thomas et al., 1996), 3D printing technology has great potential.

It was in 1995 when Dr. Behrokh Khoshnevis actually used 3D printing not only in the space or vehicle making but as well in the buildings and construction industry. However, he used stereolithography to create the ceramic prototypes, though it was not yet sufficient to meet the required mechanical properties of the real product (Hinczewski et al., 1998). The year of 1996 was the time when he applied for a patent of the "Additive Fabrication Apparatus and Method" invention that described the device with ability to making 3D objects by the aid of additive manufacturing technologies. This equipment consisted of two controllable directional devices for nose positioning and movement, two supply sources for the material transmission, and two noses for the fluid formation. Also, the equipment provided the trowels which became the quick construction vines that enabled creation of perfectly smooth surfaces with a relative highest accuracy. However, using two trowels for plastering managed to create range of shapes without

having the need to have many of the previous traditional molds (Hinczewski et al, 1998). Fig. 7 is the demonstration by Dr. Khoshnevis of his recent clever invention.

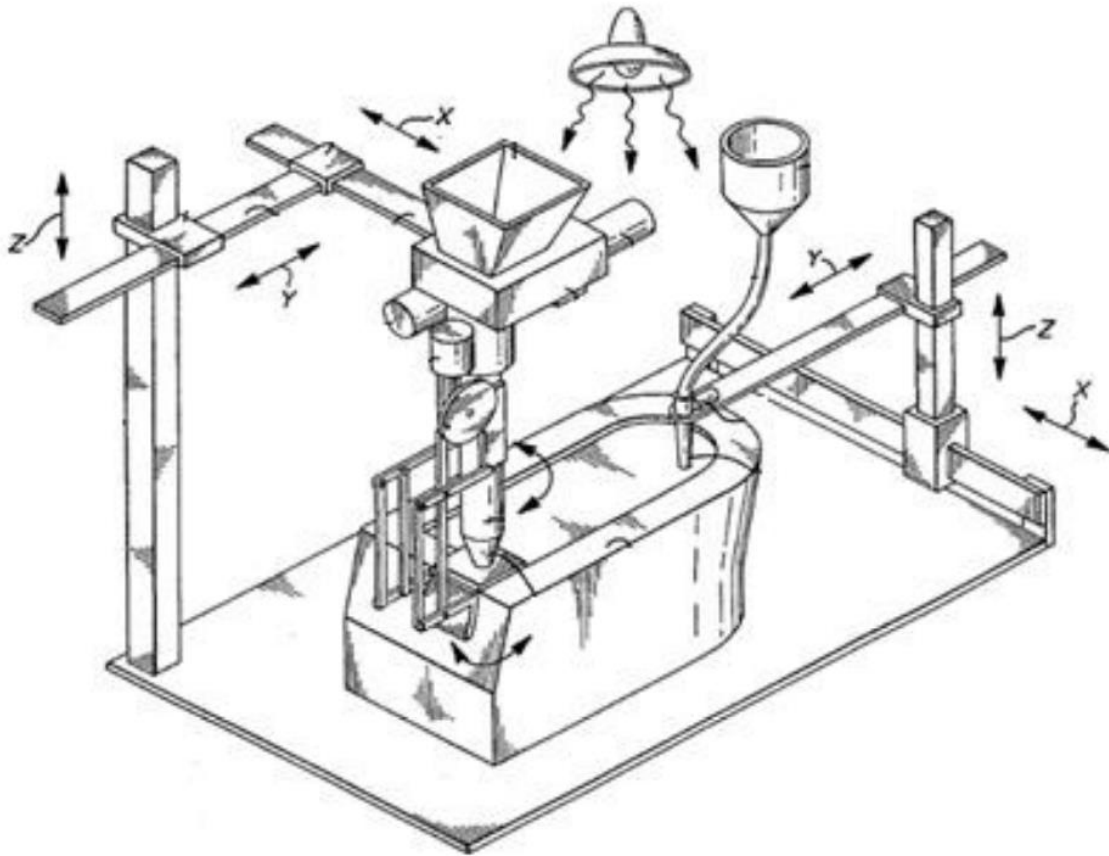


Figure 7: Dr. Khoshnevis's machine (Alzarrad & Elhouar, 2019)

For Dr. Khoshnevis, 3D printing was a novel approach, and he used an extrusion head mounted on a robotic arm to print with concrete and build a wall in 2001. His new device he named Contour Crafting (CC) devices that bring about innovations in construction processes. CC, the process which uses computer control to direct extruding the material and has the possibility of producing a smooth surface by seconding the imperfections removing works of the troweling, is a procedure that generates the surfaces with good accuracy and finish.(Zhang & Hu, 2011). CC technology is similar to other additive manufacturing processes, it internally demonstrated all the necessary and required attributes for an expansion of building sector, e.g. reduction in construction site expenses, material waste and accidents, increased construction speed and ability to manufacture complex architectural designs. On top of that, the moldability of this method incorporating concrete designs that were hardly achieved using the old way of pouring cement

means that housing production would speed up and more importantly, it prevents environmental pollution (Lim et al., 2012). 3D printing evolved even further to the extent that it could be utilized for the fabrication of goods either with plastic or nylon that are frequently seen in construction projects like pipe fittings, window frame fittings and plug fixtures. Moreover, this technology will make it possible to print complex geometrics on concrete products dissimilar to in the past where flawed products occurred. Such processes will equate to smaller and consequently more effective products. However, 3D concrete printing can create huge precast concrete components but we need to figure out if the product is in demand enough to cover the persistent need for customization and leave space for economies of scale.

2.2.2 Applications and Challenges in Geopolymer-Based 3D Printing

Geopolymer-based 3D printing has emerged as a cutting-edge and environmentally friendly technique in building technology, with the potential to transform conventional construction practices completely.

Application

Geopolymer-based 3D printing which is the latest technology of sustainable construction delineates itself as a game-changer idea. Zhong and Zhang (2022) observation on how much reduction of Carbon emission is associated with the geopolymer materials is an indication of global response towards the impact construction have on environment. This novel technique has a geopolymer-based 3D printing as a more sustainable choice, compared to regular concrete that has a high-environmental impact due to its Portland cements content. By demonstrating the customization of the building parts with 3D printing with geopolymers method we can see this in the work of Xia and Sanjayan (2016). It proves that such prints done with geopolymer are capable of producing very detailed and original décor elements characteristic not only of traditional but also futuristic architecture. Besides this inventive step, 3D printing expands the possibilities for some projects that might have been a challenge or even unachievable beforehand. The acting in the way of geopolymer-based 3D printing has converted into a new funnel of possibilities in the mills of restoration and the renovation of the existing buildings. A work of Raza et al. (2022) based on a research trial gives significant highlights for applying geopolymer 3D printing for the joins and reinforcement of the failed structures. Via this method not only the durability of the old ones

is prolonged but also environmental goals are sought to be achieved by placing less demands on clean-up and demolition crews.

Challenges

A Comprehensive Look at Geopolymer 3D Printing's Environmental Impact: While the predominant impressions of geopolymers as an environmental-friendly option are deeply rooted, a great deal of effort should be expended to figure out the ecological ramifications through the life cycle analysis. Experts like Ma et al. (2021) are reviewing the environmental consequences of geopolymeric materials and printed structures according to their biography from their manufacture to the end of their life cycle. It involves an analysis of minerals and metallic elements extraction, a conversion of them into industrial final products, transportation and, finally, disposal of worn-out items as well when they are no longer needed.

Integration of 3D printing with geopolymers will be successful in some of the established construction procedures that work together with some of the major players. Rules must be established that allow for the use of both geopolymer 3D printing and the integration of traditional techniques for building purposes (Voney et al., 2021). This will involve the behavior scrutiny of products manufactured by 3D printing and those manufactured by the conventional method. For the 3D printing technology using geopolymers to be adopted, it is very paramount that technological standardization is embraced. Leading scientists, such as Bong et al. (2019), are involved during the process of geopolymer 3D printing in developing the standardization of guidelines and methods. This has happened only because of the standardization of their printing techniques, material standards, and design elements, allowing better regulation while bestowing on them the identity of industry-recognized procedures.

2.4. Intersections of Geopolymerization and Microwave Heating

Geopolymerization is the emerging trend of an innovative method to convert aluminosilicate minerals into inorganic polymers and has found increasing acceptance due to its friendliness toward the environment as an alternative to conventional cementitious construction material. For this reason, scientists have studied the possible effects of combining geopolymerization with microwave heating, and they have reported that a microwave source added to the process improves both the efficiency of the reaction and the kinetics. Sun et al., 2020, reported that if the fly ash-based geopolymer is not mixed with LS addition, it reacted with the

alkali activator to make a three-dimensional network structure, as shown in Figure 8. Furthermore, lead slag contributes to the improvement of three-dimensional networks. This condition, due to such input, has resulted in the weakening of compressive strength and speeding up the leachate release rate.

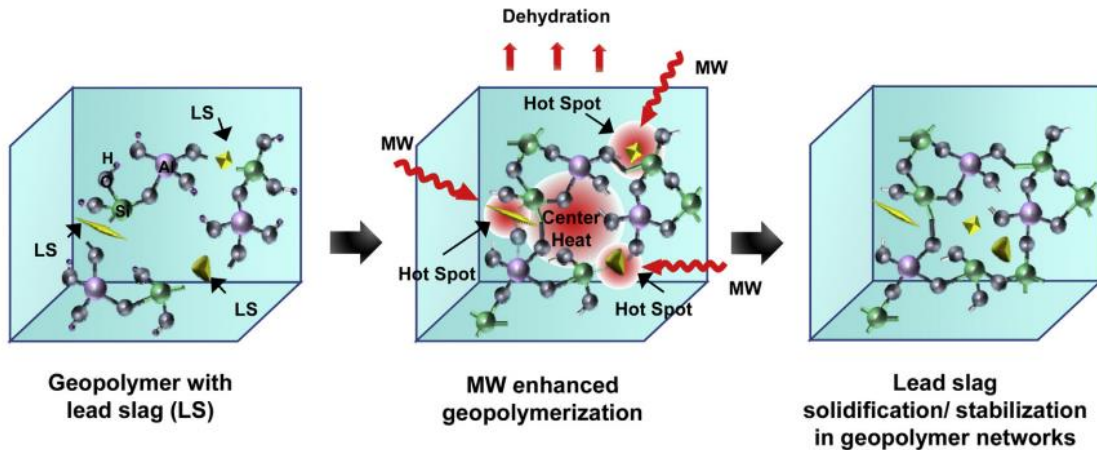


Figure 8: MW enhanced geopolymer mechanism (Sun et al., 2020)

In a total novel parameter of conventional methods of synthesis, microwave heating—depending on the process—may increase setting times of geopolymers and enhances the gain of early strength in the geopolymerization process. Chindaprasirt et al. (2013) have been pioneers in these works, and they referred to microwave heating as an effective method to accelerate the geopolymerization reaction dramatically. This would then enable the selective heating of selected constituents within the geopolymer mixture by microwaves of even higher energy efficiency and therefore less process times. Previous research was oriented towards understanding the influence of microwave heating on geopolymerization reaction kinetics. Both Onutai et al. (2016) and Sun et al. (2021) looked at different variables of the microwave, including power and exposure duration, on the aluminosilicate precursor with respect to dissolution rate and successive polycondensation processes. The results revealed that microwave irradiation accelerates the formation of both the active source materials and the gel structure of geopolymer.

Recent studies have reported that the use of microwave energy in the process of geopolymerization can make significant changes in the microstructure of products. It is a study by Muthukrishnan et al. (2020) that applied advanced microscopy techniques to analyze the arrangement and composition of components of geopolymer when conditioned to microwave. According to their team, the reported work of research indicated that, with microwave heating

incorporated, it developed a more uniform and fine microstructure. Hence, from this procedure, improved mechanical and thermal behavior of the geopolymer-based material could be realized (Fig. 9). Still, to exploit the concepts of geopolymerization with microwave heating, though potential benefits are there, there are drawbacks and issues involved. For example, according to Hong and Kim (2019), questions have been raised on the even distribution of heat, homogeneous states, and thermal gradients in the geopolymer mix during microwave irradiation. Further, practical considerations are given to the optimization of scaling up the microwave-assisted geopolymerization to the level required for large-scale construction. Moreover, others have put to record that microwave heating results in high energy efficiency and sustainability during the geopolymerization process (Shi et al., 2020). Embracing these new technologies in construction would first require understanding the life cycle assessments and comparative analysis of the same with conventional techniques being followed at present.

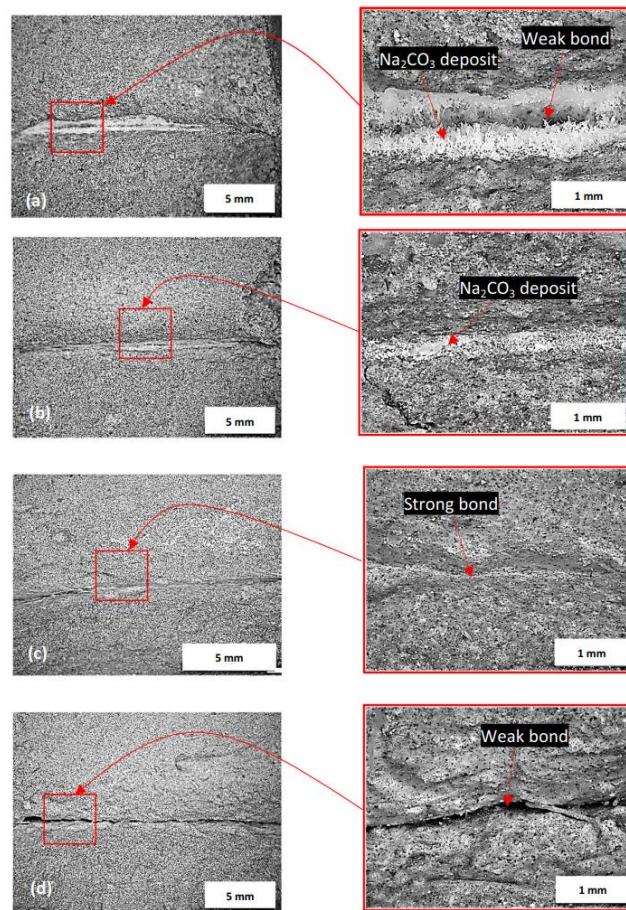


Figure 9: Microscopic images of printed samples' interlayers using microwave-extruded filaments (Muthukrishnan et al., 2020)

Chapter 3 – Methodology

3.1. Introduction

Proper research methodology is applicable to the examination of microwave heating effects on geopolymers in the context of construction 3D printing. In this section, the approach and methods pursued find out the intricate balance between microwave-induced curing and geopolymer-based additive manufacturing. The methodology has been developed to address the key objectives of comprehending the material properties, which are affected by microwave heating; finding the optimized fabrication parameters; and evaluating the feasibility for microwave-assisted 3D printing in construction applications. Conducted after research in a precise and well-conducted methodology, this study aims to derive reliable insights that, in a way, may contribute to advancing an understanding of their application for advancing the understanding in regards to its application for microwave-induced curing in geopolymer-based construction 3D printing.

3.2. Research Design

The investigation on the effects of microwave heating to geopolymer-based 3D structure printing has a set of activities that are well-planned to bring out the details involved in the attainment of research objectives. This type of research design is inclusive of finding the optimal parameters of a geopolymer printer for 3D printing, selecting relevant parameters of the microwave heating equipment, and conducting stress-strain tests using a highly sensitive measuring device to determine the mechanical properties of geopolymer printed products.

Optimal Parameters for 3D Printing

During the first stage, this research shall focus on exploration in the complex world of 3D printing, basically highlighting some key features that can assist in the printing process of geopolymers. It shall comprise the broadest review of issues such as print speed, layer thickness, nozzle temperature, and other fine settings applicable to the geopolymer material. The design of this study places much emphasis on obtaining a delicate balance that would assure that, on one end, the accuracy of the deposition of the layers is achieved, while, on the other, the structural integrity of the geopolymeric structures being printed is preserved. This research is meant to perfect the process of 3D printing, giving a keen adjustment of several factors to bring forth outstanding quality and performance.

Optimal Parameters for Microwave Heating

The second aim is based on the exquisitely chosen settings of the microwave heating equipment in an effort to express the versatility of this technology to facilitate efficient geopolymerisation. Summarizing the method used, the second aim was to target consideration of other significant factors that include curing effect, power level, frequency, and exposure periods. This objective targets the optimization of microwave heating settings to harness the unique capabilities of this technology for fast and uniform curing in order to finally improve the material properties in 3D-printed geopolymeric structures. This assignment is important to critically explore the transformational potential of microwave-induced curing in 3D construction printing.

Stress-Strain Tests conducted on Printed Geopolymers

Third, the stress-strain tests of the printed geopolymers, specifically designed for material testing, are carried out. The stage of the study involves the printed structures in that they will be subjected to carefully controlled mechanical forces, and parameters governing the stress-strain curves shall be deduced precisely. The design of the study outlines the choice of testing apparatus, loading velocities, and the specific conditions under which these tests will be performed.

3.3. The Adopted Research Methodology

This is a critical point from the study that will help in providing insight into the mechanical functionality and structural resilience of printed geopolymers under varied stress levels.

1. Literature Review:

Objective: To conduct a systematic review of all available literature for the most updated information about the production of Geopolymer mixtures, 3D printing methods, and the effect of microwave radiation on printed Geopolymers.

Literature review: through the help of academic databases and machines for the last decade, relevant research papers, conference reports, and research reports will be identified and reviewed.

Inclusion Criteria: Compositions of geopolymer mixture, 3D printing technology which deals with geopolymers, and treating the process of its print samples by microwave radiation.

Data extraction: This includes the extraction of details from the composition of raw material, printing parameters, microwave heating protocols, and mechanical properties of print samples.

Analysis: Explore the data collected during the study of Geopolymers with the treatment of microwaves and 3D printing to determine tendencies, problems, and opportunities presented.

2. Geopolymer Mixture Preparation:

Objective: Preparation of controlled composition polymer mixtures for subsequent 3D printing and microwave testing.

Material: procurement of raw materials like kaolin, additional additives (e.g., ash-unos or GGBFS). The optimal composition is determined from literature review and experimental-oriented investigation on the raw material proportions.

Mixing procedure: Follow the established raw material mixing protocols to obtain homogeneous geopolymer suspensions.

3. 3D Printing of geopolymer specimens:

Objective: development of Geopolymer samples using additive manufacturing technologies for subsequent microwave testing.

Printer setup: install a 3D printer with appropriate options including nozzle size, layer height, and print speed.

Printing process: the prepared polymer mixture is then installed in the printing tank of the equipment, and printing, which at the end of the day will form patterns with the given geometry, is started.

Post-processing: all samples were post-treated by being fully cured with the ultimate removal of all supporting structures or defects of the printed samples before microwave testing.

4. Microwave testing:

Objective: to evaluate the effect of microwave heat on the mechanical properties of 3D printed polymer samples.

Experimental set up: The samples so printed were taken for conducting experiments in microwave heating using a temperature and power-regulated setup of the microwave oven. Microwave heating parameters: From the literature review and some preliminary experiments conducted, the power level, exposure time, and heating profile were calculated.

Heating protocol: exposed to controlled cycles of microwave heating, the printed samples are completely healed, and thereafter the changes in the mechanical behavior were rapidly assessed.

Mechanical testing: carried out on a universal testing machine with other mechanical properties determined by compression, bending, and other properties of the microwave-treated sample.

5. Results Comparison and Validation

Objective: compare the experimental results taken during the preparation of the polymer mixture, 3D printing, and microwave testing with each other to confirm the effectiveness of the proposed methods.

Data analysis: collected data shall be analyzed in such a way as to find correlation and discrepancy between the different parameters and the test conditions in each stage of the experiment. Validation of the applicability of microwave-assisted treatment compared the mechanical properties between microwave-treated samples and normally treated samples.

Discussion: Discuss the consequences of the results obtained with respect to the existing literature and further recommend future research areas.

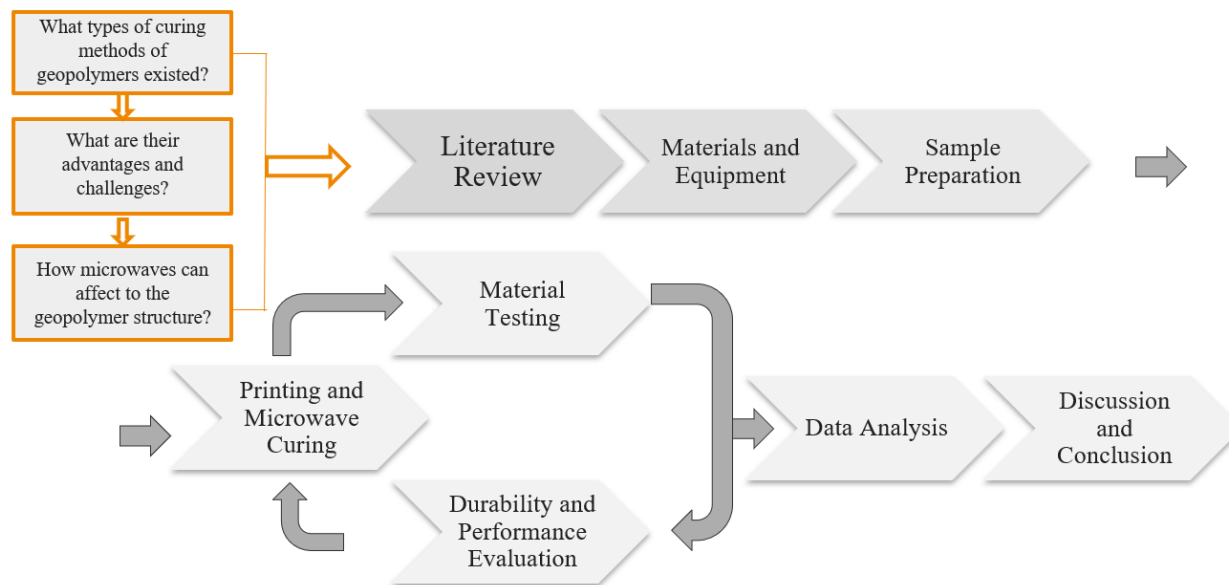


Figure 10: Research methodology stages

3.4. Preparation of Geopolymer Mixture

The source of those materials was either from nearby power plants and local industries or were industrial byproducts with limited end use application. It was thus this mixture which, along with the solution of sodium silicate as the reagent, produced geopolymer suitable for 3-D printing. In this binder, the FA class of "F" material is required from Ekibastuz and Karaganda thermal power plants. Metakaolin contains both elements of aluminum and silicon. From the research, the use of river sand has been maximally used as an infill for 3D-printed geopolymers. Table 5 below outlines the key resources used in this study.

Herein, the emphasis is on the selection and mixing design of the geopolymer mixture using high-plasticity Kokshetau kaolin as the main material. This was intended for ensuring a flat and consistent experimental platform. Further, it subscribes to a larger goal of finding out the influence of microwave heating on the 3D construction printing of geopolymer. Aim: The aim is to print the 3D structures based on geopolymers. For this, the formula of geopolymer has to be designed with great selection of raw material. Table 2 provides a raw material that is used to get the G1 geopolymer mixture.

Table 2: G1 raw materials

Name	Volume, gr	Mixing time, min	RPM
G1			
Metakaolin	146.49	5 min	150-250
Sodium silicate	100		
GGBS (CB)	20	3 min	150-250
Sand	150+	5 min	100-150
Water	<3.8	homogenius	100-150

The presentment of raw material composition should be such that it presents uniformity in the tests and examines well how geopolymer behaves with the varied environmental parameters.

The production of metakaolin as an extraction from Kokshetau kaolin makes the creation of the geopolymer compositions involve calcination as an important process. In this case, calcination takes a very essential role, and in the process of making it undergo very careful synchronization, it requires a series of steps to be taken very carefully, in a very synchronized manner. Kaolin is converted to metakaolin by calcination at a temperature above 750 degrees Celsius. It results in the dehydration of metakaolin and the removal of crystalline phases (Fig. 10). Afterward, the grinding machine (Fig. 11) melts the product metakaolin after the process of heating has taken place. Thermal treatment parameter regulation is very critical. Vivid details toward transparency and reproducibility will be given in the Technique section.



Figure 11: Heating oven for Kokshetau kaolin



Figure 12: Grinding machine for metakaolin

Calcination is not only essential for extracting metakaolin but also a critical link in the geopolymerization chain. In the 3D printing of the building, it includes the amorphous form of metakaolin as an increase in pozzolanic activity. The elaboration parameter extraction process for

metakaolin allows one to easily understand how to develop such material under heating by a microwave and is very much important. Effects of microwave heating on the geopolymer-based 3D building printer were studied with properly designed sets of equipment used for the investigation. Each constituent has played its due contributory role for accuracy and consistency of tests. The key point of the setup was the big, strong 3D printer with dimensions: 1 m by 2 m by 2 m (see Fig. 12).

3.5. 3D Printing Geopolymer Specimens

Its sheer magnitude enabled the generation of geopolymeric-based structures under controlled conditions, which was able to facilitate research on the transformation potential of microwave heating in a grand scale. Another main advantage of a large size printer is that it will give room for the development of a huge prototype that can be used in reality for real-world building applications. With the use of specialized rectangular nozzles developed to optimize the deposition of the geopolymer mixture for 3D construction printing, there is a possibility of delivering great success in the proposed experimental setup. Sizes of their nozzles range from 40x20mm to 40x8 mm. Such versatility in size allows for the control of the layering process within the printed specimen. Each size has a specific amount of layers within the printed specimen, therefore maintaining consistent specimen geometry despite the change in layering configurations.



Figure 13: 3D Construction Printer

This way, it gives the possibility of full and comprehensive assessment of the material mechanical features, in which all specimens are representative of various configurations of layering and experience quite intensive tests on stress and strain. These may allow us to draw meaningful conclusions regarding the effects of microwave heating on geopolymer-based 3D construction printing, thereby being well aware of the effect of layering on mechanical performance. Our experimental framework is accurate and reliable, thus reproducible. A feature of the set-up was the dedicated microwave oven, which enhanced the integration of the dynamic component of microwave heating in the experimental matrix.



Figure 14: Rectangular nozzles

3.6. Microwave testing

The oven is accordingly set for curing, with the temperature set according to the requirements of geopolymer based products (Fig. 13). A microwave oven acts as an "incubator," which assumes great importance in fast and uniform curing, where controlled exposure of printed items to microwave radiation is a vital factor. Then, the polymer is poured into special metallic moulds to give samples of polymers the necessary form, as it can be seen in fig. 14. Do note that the above-mentioned moulds should not be placed inside a microwave oven, which is fraught with risk to life. To avoid such moments, silicone molds were made as shown in Figure 15.



Figure 15: Microwave oven for experiments



Figure 16: Metallic molds for geopolymer specimen preparation

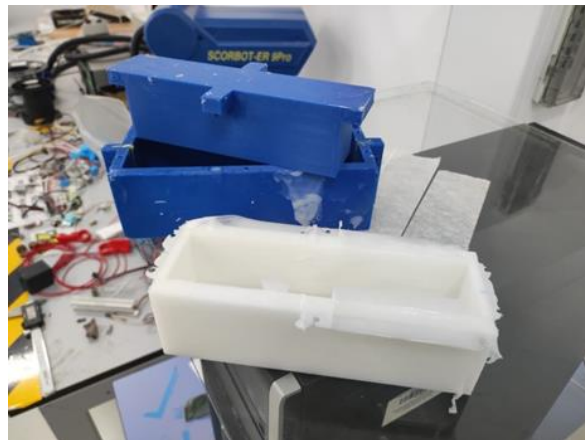


Figure 17: Silicon molds for isotropic geopolymer specimen preparation

The second printer targets the production of a rectangular-shaped nozzle to maximize the deposition of the geopolymer mixes during the printing process. The second printer targets precisely the production of a rectangular-shaped nozzle, which is quite decisive in maximizing the deposition of the geopolymer mixes through the printing. This custom nozzle is designed in a way that allows the flow of the geopolymeric material to be very controlled and regulated, ultimately contributing to the structural and realistic features of the printed prototypes. One such innovation may relate to the amalgamation of a plastic 3D printer with other cutting-edge fabrication technologies. This, again, goes on to prove the great persistence of the research team in fishing out innovative ideas in the area of building materials.

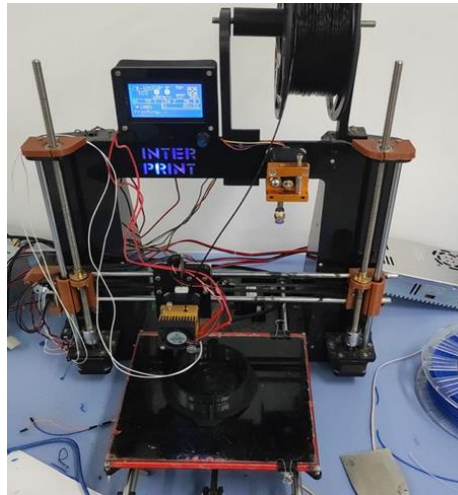


Figure 18: FDM 3D printer

3.7. Stress-strain tests

Further, after defining the 3D-printed object, the system was further developed so that the necessary equipment would be used to perform stress-strain evaluations. In this phase of the research, a series of mechanical tests on the prototypes made of geopolymer base concretes is carried out under control, requiring in turn series of specific or very specific equipment designed to monitor and analyze their reactions. Instrumentation provides load frames, extensometers, and data collection systems used to make sure that the collected data is valid and reliable (Fig.17). The mechanical performance can be determined through these tests made for the stress-strain relationship of geopolymer-based structures. Results from these tests help prove insight toward resistance with damage to the structures and suitability in areas of construction application.



Figure 19: Stress-strain test equipment

Chapter 4 – Experimental Results

4.1. Introduction

The results presented in this paper have been rigorously investigated according to established research protocols. The study tried to show the effect of microwave heating on 3D-printed geopolymer objects, having a very good composition of the geopolymer mixture as the main material. Therefore, geopolymers began to be viewed and researched as an alternative to classical building materials. It is very good due to the properties of the structure, such as an equally homogeneous composition of the material. The advent of this state-of-the-art additive manufacturing process with 3D printing has opened new trends in producing complex geometrical shapes by geopolymeric materials and promises great prospects for modernizations in construction methodology.

The purpose of the given experimental research was to develop the influence of microwave treatment on the mechanical properties of 3D-printed geopolymeric objects. This required the elaboration of a rather full-fledged research methodology that should begin, in fact, with the preparation of a geopolymer mixture adapted to the goals of the experiment. The literature review further guided the process of material selection by ensuring that the chosen material was a reactive, homogeneous mixture that was compatible with three-dimensional printing. Then, the 3D printing techniques were involved in the development of the model of geopolymer with some geometry, which had to provide the background of the microwave tests.

The experiments are focused on utilizing microwave heat as a post-processing method for 3D-printed geopolymer objects. Therefore, the combination of such very rapid and volumetric heating characteristics makes microwave radiation a very attractive source to enhance the curing of Geopolymer materials. The authors, in that study, attempted to determine what effect heating parameters had on the mechanical properties of Geopolymer objects by submitting the printed samples to controlled microwave heating cycles. The design and fabrication of the experimental set-up have been designed and fabricated carefully with an objective to extract useful information for the effects of microwave treatment on the improvement of strength, durability, and mechanical integrity of geopolymer-based 3D-printed components.

This research experiment, through rigorously following the research methods, the results of the experiment should give a thorough understanding of the interactive dynamics between microwave-heating and 3D-printed geopolymer objects. This investigation ultimately can help to

promote the wider use of construction projects by Geopolymer through the creation of a guideline and thus lay a foundation for progress in additive techniques with a view to manufacturing eco-friendly building materials.

4.2. 3D printed samples and microwave heating

Stability of 3D-printed geopolymer samples was studied in conjunction with the effect of microwave heat treatment and interesting relations were found between the production parameters and structural integrity. This is strongly suggestive of the gradual reduction in sample height once it is 3D printed, and hence implies a behavior associated with the compressive forces of the overlay mechanism. Though somewhat expected to an extent, this is one fact that seems to have had a direct relation with the number of layers used in the printed samples (Table 3).

Table 3: Change in height of specimens

Number of layers	Expected height, mm	Real Height, mm
2	40	39.1
3	40	38.78
4	40	37.27
5	40	36.87

In this case, use of the 40x20 mm nozzle when developing the samples made of two layers resulted in an appreciable difference, where the height reduced by two millimeters. It actually shows the magnitude of the deformation that occurs for use in the printing process (Figure 20). Moreover, the linear increase in height loss with each added layer shows that the layer-induced compression is cumulative in nature toward the size of the samples. The sample shows only four layers, and that the lowermost layer is at a lower height than the rest. This underscores the need for a pretty delicate balance between getting the structures right and production efficiency.

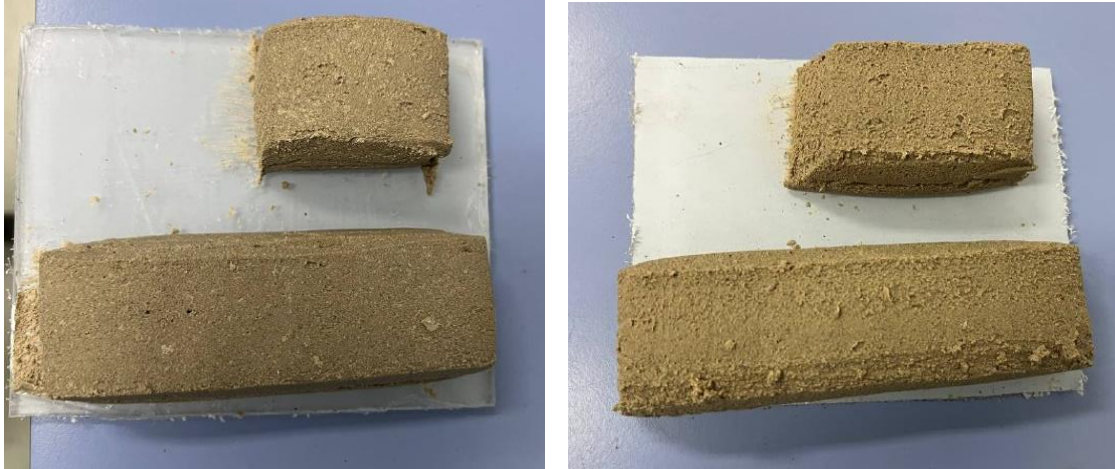


Figure 21: Bulge of layers a) specimen with 4 layers; b) specimen with 2 layers

The curved structure formed by the printed layers comes out after a combination of the depositing conditions and the material properties follows a complex interaction. Although this swelling of components first suggests it is something repulsive, this is a natural stage of the Geopolymer composite. Nevertheless, having an additional visual feature lets the users to evaluate the physical appearance of the prints and the material's performance behavior like pressure during the 3D printing session.

Assessment of layer convexity in geopolymer mixtures requires analytical and observation procedures that aid in understanding the dynamic nature of 3D printing of geopolymer layer. It shows both end-to-end connection as well as mutual influence among material characteristics, production features and structure topology. This aspect of the experiment analyses how the geopolymer material responses are underlined by layer convexity, and the deeper understanding of the additive manufacturing dynamics become sure then.

A curious phenomenon is observed: there is a shock influence of microwave exposure on the 3D-Geopolymer prints structure solidity. The speedy hardness of the Geopolymer content is achieved due to elevated temperatures by microwave radiation which provides a high level of strength improvement (figure 22). It should be mentioned that microwavention had exceptional deformation resistance and provided with the initial geometry of the samples.

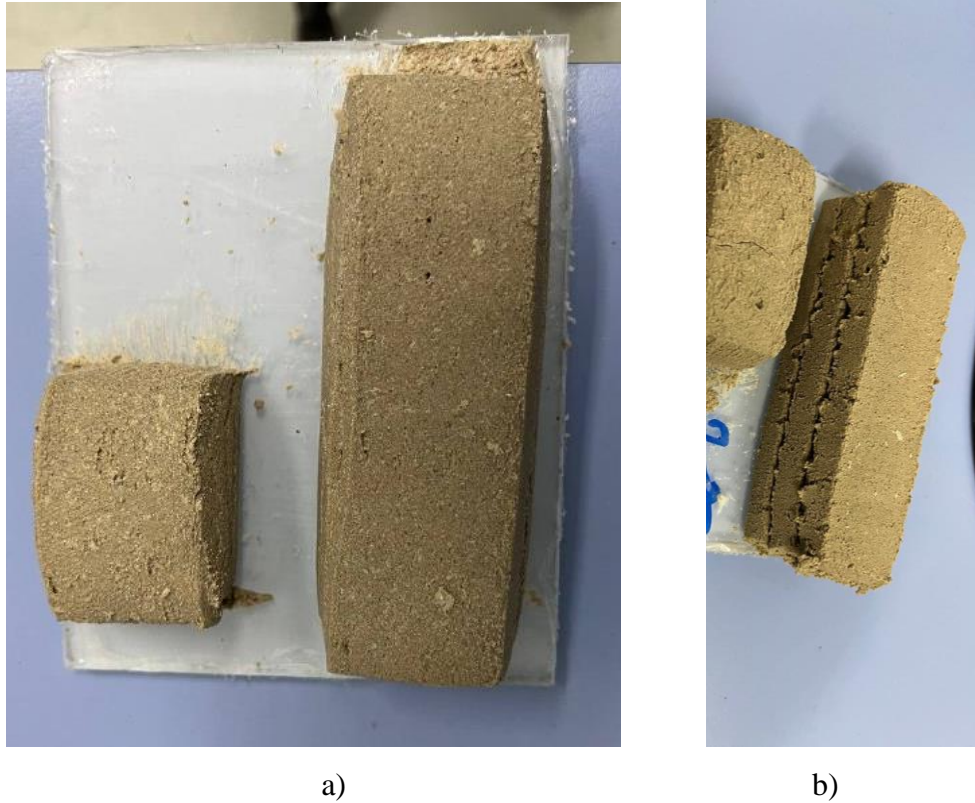


Figure 22: Bulge of layers a) specimen with 3 layers without microwave affect; b) specimen with 3 layers with microwave affect

The higher temperature due to microwave radiation helps in fast and uniform solidification of the geopolymer matrix, providing compact and consistent composition. This further improves the structural strength and hence reduces substantially the tendency of deformation characteristic of samples, which are cured under conventional condition. With the high rigor of the microwave treatment, printed models still maintain all their structural soundness, pointing out to quite an effective subsequent processing technique in terms of preservation of the shape precision.

These give the perfect microwave conditions employed: a power rating of 700 watts and heating time for 20 seconds. These settings are chosen to enhance the thoughtful healing processes of the tissue, therefore reducing the chances of thermal damage or overexposure to heat. These further contribute to uniform and consistent heating of the Geopolymer samples at such power and duration combination, translating to reliable solidification and hardening without any compromise to the structural integrity.

The result is insinuated by the fact that microwave processing can transform the additive manufacturing of the Geopolymer material. Its fast and effective ability to strengthen the material through microwave heating would offer very promising opportunities to increase the mechanical properties and structural soundness of the geopolymer items that are 3D printed.

4.3. Compressive test results

The results of this test of compression might give us valuable insight into the mechanical characteristics of the Geopolymer 3D-printed sample and the influence of the change in its strength upon exposure to microwaves. Samples were divided into two distinguished groups: only those that were 3D-printed and the ones being exposed to microwaves after the printing procedure. Inside each group, there were samples of the different layers which allowed for the study of their structural properties. Figure 23 shows a compression test diagram.

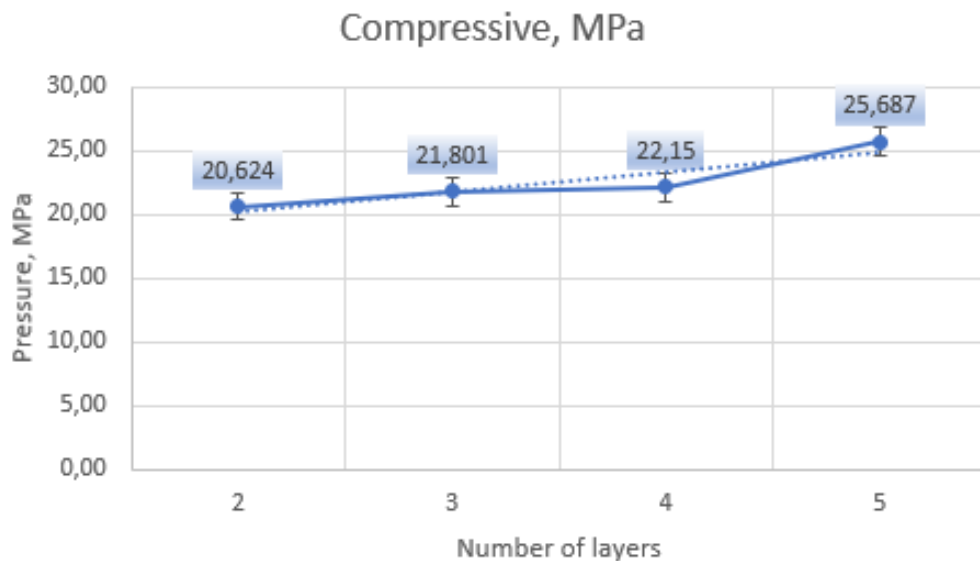


Figure 23: Compression test diagram of non-microwaved geopolymer

The compressive strength values showed a remarkable difference when compared with samples that are not exposed to microwaves, considering the given configuration of the layer. Two-layer samples showed a compressive strength of 20.624 MPa with response to the material at the minimum layer. It is evident that, in comparison, the printed samples with three layers showed slightly higher values in comparison to the compressive strength of 21801 MPa. It shows that there

is a very marginal increase in strength with increasing layers. However, a remarkable improvement was experienced in the compressive strength as the number of layers had readings of 22,150 MPa when four layers were tested and 25,687 MPa when five layers were tested.



Figure 24: Non-microwaved samples after compression tests

The results suggested a situation wherein the effect of the ribs' parameters on the strength of the material exhibited subtleties. Additionally to the loudness that the number of the frames affects, the compression performance is also subtly effected by number of layers. Of course the question of the strength stability arises in a layer structure of units where the number of layers increases. Still 4-5 layers show the trend of the additional strength of this structure.

Microwave treated samples present a clear inclination to higher compression strength sign. This means that microwave treatment has a more dramatic effect on material processing, improving performance beyond the anticipated level. Microwave heating, in comparison to other technologies, seems to be increasingly effective and boosts mechanical properties of various layers for samples exposed to microwaves, with their strength values elevated substantially. On Figure 25, the microwave baking time was added to compress the 3D printed sample.

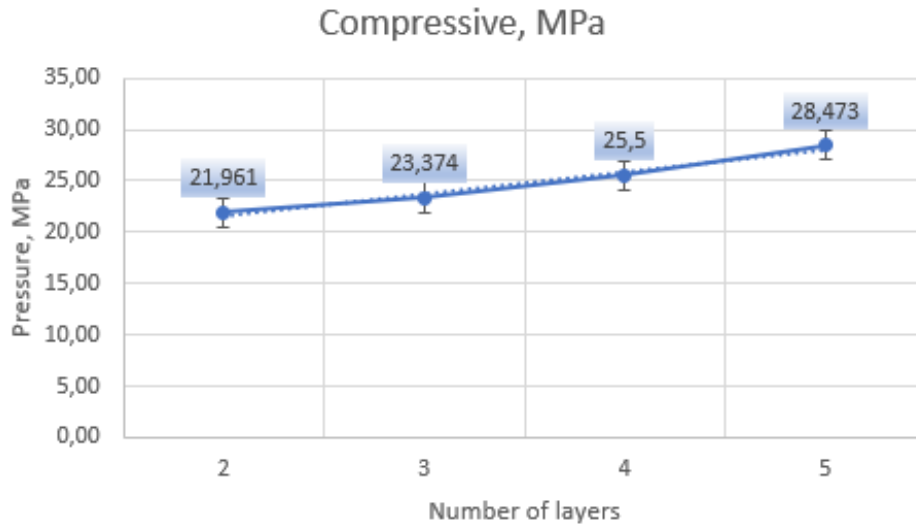


Figure 25: Compression test diagram of microwaved geopolymer

The compressive strength of the treated samples, on the other side, monotonically increased with the number of layers printed. As an example, two-layer-printed samples have presented a strength of 21.961 MPa and agree well with those of the non-processed samples with the same layer configuration. It was remarkable to notice that improvement in the values was recorded with the number of layers going up to three, four, and five. Indeed, it was observed that the three-layer samples showed great improvement, with a compressive strength of 23,374 Mpa under fixed conditions; this was a huge improvement compared to the microwave non-processed samples. The trend is persistent with models having four layers, giving a compressive strength of 25.5 MPa, showing improvement in material persistence.

Moreover, high compressive strengths have been reached in five-layer samples, whereby the highest result accounted for 28.473 MPa, and at that level of isotropy, it came very close to the isotropic result of 28.473 MPa. This result brings out the fact that microwave treatment significantly enhances the mechanical properties of the 3D printed Geopolymer sample materials to an extent where they would be well in a position to give some form of completion to isotropic material. The 40x8mm nozzle has been introduced in order to create a model with five layers. This introduces that the nozzle size of 40x8mm is important for perfect material overlap and sealing.



Figure 26: Microwaved samples after compression tests

Therefore, attention must be paid to uniformity in layer thickness and nozzle diameter, since this can contribute toward even material distribution and evenness of the structure, which would ultimately lead to the enhanced compressive strength. The above findings secure the very significant impact that microwave processing can produce in additive manufacturing of Geopolymer materials and set the basis for the production of structural elements of high reliability and strength.

4.4. Flexural Test Results

The close-up investigation discovers the specific nature of such an effect, which is associated with 3D specimens consisting of Geopolymer material under bending stress. It also investigates the intricate mechanistic relation between process parameters and mechanical properties. Unlike conventional materials, which often exhibit the same response pattern to bending in any layered configuration, our approach of a comprehensive assessment of bending weight allows us to understand how the material reacts or responds to bending stress. It also allows us to focus on the non-microwave samples at the onset to study the behavior under bending stress in contradiction of other materials.

Samples printed in two layers also had quite high strength—24.5 MPa. This preliminary result allows us to consider the material's ability to sustain stress in bending even at a minimum overlap, demonstrating remarkable structural strength with the Geopolymer Matrix. However, a gradual decrease in flexural strength appears with the increase in the number of layers. For instance, a three-layered sample shows a slight decrease in strength to 24.278 MPa (Figure 27).

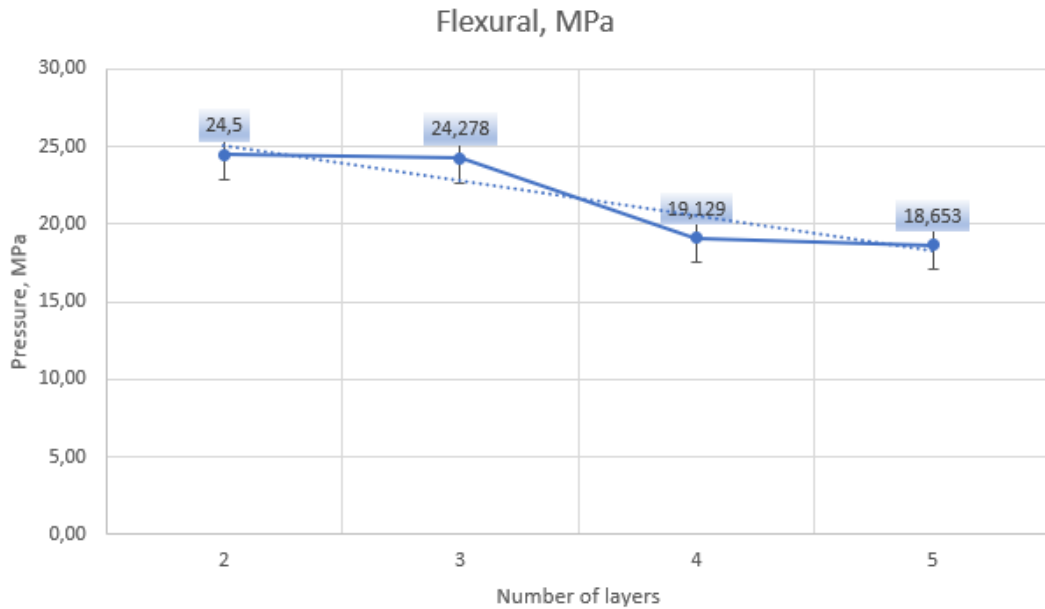


Figure 27: Flexural test diagram of non-microwaved geopolymer

On the other hand, the trend in the bending strength continues downward with the number of layers. Worth noting is that in the four and five layers, samples showed a sharp reduction in mechanical performance. Specifically, the bending strength shows that, in a four-layer sample, it is 19,129 MPa, with the next sample of five layers having a minor decline to 18,653 MPa. This trend of sharp reduction is an indication of how, with the increase of the number of layers, it is very difficult to maintain the integrity of the structure and therefore testifies very clearly to the importance of optimizing the production parameters very carefully.



Figure 28: Non-microwaved samples after flexural tests

The bending strength decreases with more layers; hence, it is a fine balance between the optimization for structural reinforcement and efficiency in production, while considering the use of geopolymer materials in 3D printing. While the first layers will increase the mechanical performance, the compounding effect from subsequent layers may actually increase this until finally, the bending of the material may become too rigid. The findings will thus serve to be useful in balancing the considerations in construction against the limits of production to be achieved with the optimum mechanical performance from 3D-printed geopolymer designs.

Furthermore, the results from bending tests are major basics in material response to the understanding of the basic mechanisms governing the material's response to bending stress. In this case, the aspect of the experimental result reveals the most subtle features of the reaction of the material to the application of bending forces, thus allowing for the enhancement of structural features through the use of Geopolymer-based designs in varied engineering applications. Consequently, it lays the groundwork for making informed decisions in the realm of additive production processes.

When the microwave-treated samples were used for analysis, it is found that there is a pattern of higher bending force due to the changed impact of microwave curing on the performance of the material significantly under bending stress. It is, therefore, valuable to compare the bending properties with treated counterparts and non-treated counterparts for the effectiveness of microwave heating to treat material for improved elasticity and soundness in the structure.

In the case of the samples treated with microwaves, an increase was noteworthy in the value of strength to the bending force; the types of layer configurations varied. Maximum improvement is noticed in the samples with complete 2 layers printed specifically for having remarkable improvement in strength for bending at a fixed value of 27.59 MPa. This large improvement gives the proof of the transforming effect of microwave processing on material properties, which brings out improvement in resistance to bending stress as compared with untreated samples.

This is an imposing bending strength: samples three-layered bending strength of 25.68 MPa, speaking in favor of fortification of material during a long time after microwave exposure. The bending strength observed still presents a higher value than that of the non-microwave samples of a similar layer structure, although there is a clear reduction in the bending strength of two-layer samples. This trend is also observed at higher numbers of layers; four- and five-layer samples provided a bending strength of 23,791 MPa and 20,864 MPa (Figure 29).

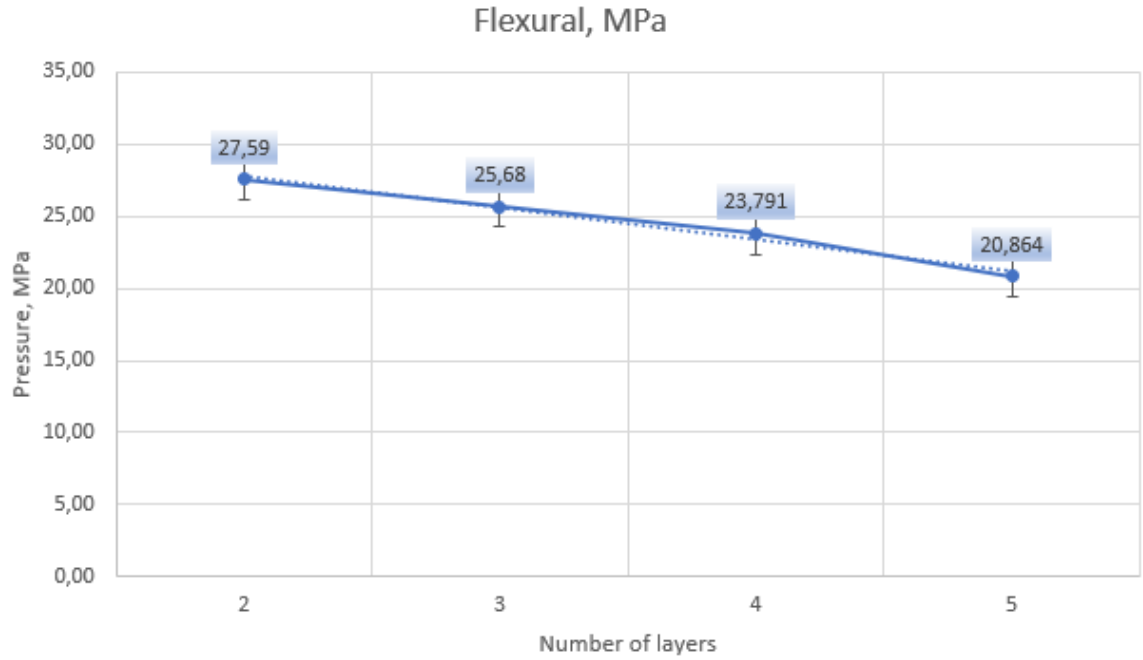


Figure 29: Flexural test diagram of microwaved geopolymer

On the contrary, specific microwave-treated samples have their bending strength decreasing gradually with a number of layers, which is not seen in the baseline (non-microwave-treated) samples. Indeed, it gives a much better and consistent performance at all the scales of variation. In this accomplished role, this performance showed its possible efficiency in both increases of material flexibility and enhancements in the overall structural integrity under bending loads. Where the latter offers immense business opportunities for training high-performance geopolymer structures.



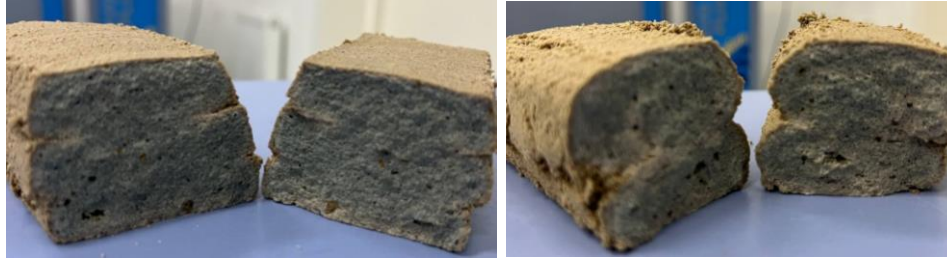


Figure 30: Microwaved samples after flexural tests

The shear strength enhancement served as a revealing factor by the process of microwaving and at the early-stage processing of the material to obtain a new type and properties of Geopolymer engineering material and customized fabrication of functional objects. In fact, the dawn of sophisticated material processing, which rapidly increases the characteristics of volatile material, in fact, governs the rebirth of components claiming high endurance and wild resistance, thereby proudly paving the way for the industrial revolution at lightning speed.

4.5. Comparison of results

The results of the compression test of the isotropic sample are compared with that of microwave-free and microwave-treated 3D-printed samples, finding key trends in material behavior. From the above results, correlation enlightens the data regarding the efficacy of microwave treatment for material property enhancement and its potential applications in additive manufacturing by Geopolymers.

The compressive strength of the isotropic samples initially measured was 28.749 MPA. This reference value manifests the inherent strength of the material under ideal conditions. The samples printed without microwave exposure showed the same slight variation in compressive strength, measuring 25.687 MPA, against the isotropic benchmark. It was enough to adequately reflect the capability of the material in bearing compressive forces under standard production; however, it was not enough to reach the isotropy standard (Figure 31).

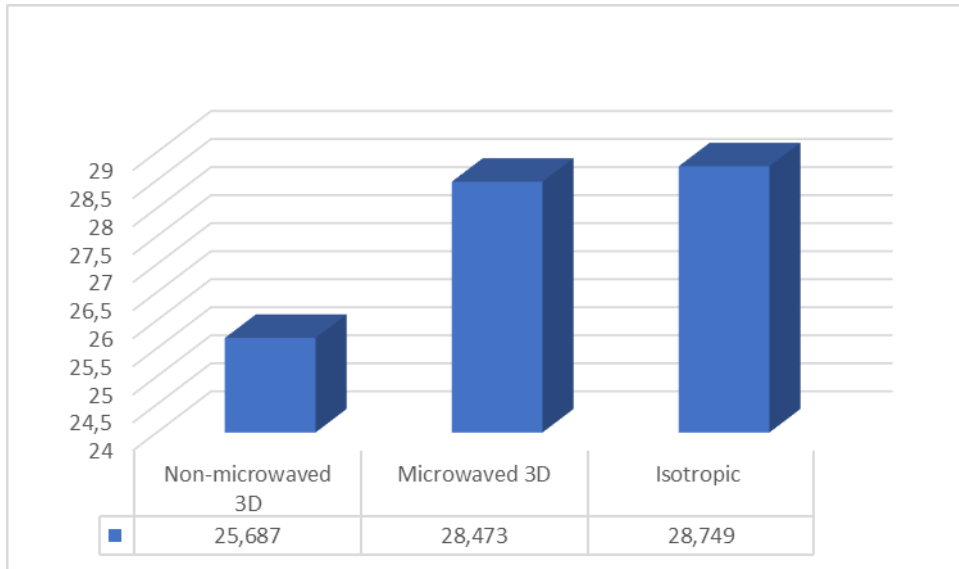


Figure 31: Bar chart for comparison of compression results

Microwave oven treatment, therefore, represents an innovative treatment intervention that brings forth enormous improvement in material performance throughout additive manufacturing. Sampled in this process, compressive strength treated with microwave irradiation showed a considerable improvement of up to 28.473 MPa, which is almost equal to isotropic samples. This result highlights the amazing impact of microwave heat in the intensification of strength and structural integrity of the material up to a point very close to equalling 3D-printed samples and isotropic benchmarks.



Figure 32: Some of the samples for isotropic compression tests

Therefore, the observed correlation of compressive strength values between microwave-treated samples and isotropic standards can lead to the suggestion that microwave-induced hardening in geopolymers may indeed bring a new way forward for the additive production of geopolymers. It will be able to cure printed samples effectively and fast, which gives a possibility to elaborate on designs of geopolymer with very high strength and elasticity. Thus, these results substantiate that microwave ovens as a tool for additive manufacturing hold great potential to become a disruption in the construction sector for an easy implementation sustainable built-environment solutions. The behavior of the Geopolymer material under bending stress is explained, and for this reason, the test results for bending tests on a few different types of samples are explained below.

These samples include isotropic samples, non-microwave 3D printed samples, and microwave-treated 3D printed samples. Much understanding of how the production parameters and post-processing techniques will ultimately decide the overall performance of the material can be concluded by this, analyzing and comparing test results from the two. In establishing a standard for the performance evaluation of 3D printed models, the bending strength of the isotropic sample was benchmarked at 22.56 MPa.

This crucial value reflects the material's ability to withstand bending stress under optimal conditions. Further tests went on to show that the samples printed without microwave exposure did have a noticeable increase in strength for a fixed bend of 24.5 MPa (Figure 33).

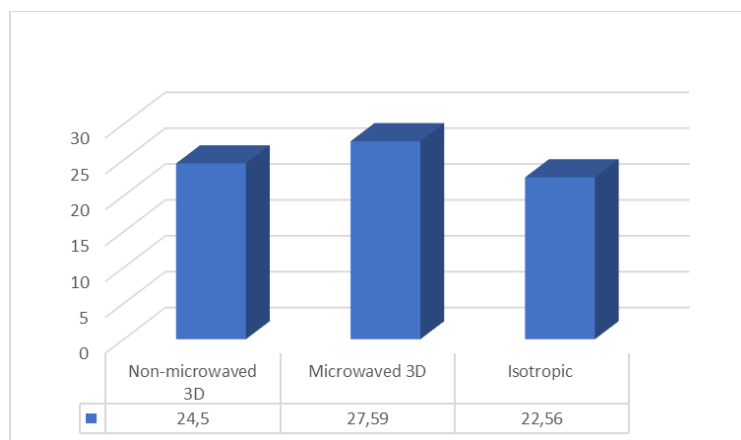


Figure 33: Bar chart for comparison of flexural results

Quality-wise, as mentioned, these features were of not the best quality but were generally improved due to the layered manufacturing process of 3D printing. The use of microwave-induced treatment is interventionism in the process of additive manufacture, revolutionizing the process with apparent productivity improvement in bending. On the other hand, the bending strength for microwave-treated samples showed marked improvement and read 27.59 MPA, which is the same as isotropic sample bending strength.



Figure 34: Some of the samples for isotropic flexural tests

This outstanding finding seems to unveil the significant effectiveness of microwave heating on the enhancement of elasticity and structural integrity of the material, which also eliminated the gap between 3D printed samples and isotropic standards. The values of bending strength for the 3D printed samples treated in the microwave respect isotropic standards and refer to excellent mechanical properties. An inherent, layered production process of 3D printing gives important benefits that will increase structural consistency and strength in a way to allow better productivity in the process of bending. These results come to confirm that the 3D printed samples are above the isotropic tests and likely able to influence the success of the additive manufacturing technologies in changing the game for the mechanical engineering industry.

Chapter 5 – Conclusion and Future work

5.1. Conclusion

Summing up, in this chapter, a comprehensive review has been conducted both of the examination of geopolymer materials and the development of experimental methods and setup that may establish a base to investigate the effect of microwave heating on 3D structure printing using geopolymers. Final selection of raw material, especially kaolins obtained from Kokshetau and the ordered development of geopolymer compositions, is of great importance to understand intricacies in material composition. The additives like Fly Ash and Ground Granulated Blast Furnace Slag, beside improving polymerization, improve by addition the factors affecting important factors reacting to chemical and mechanical factors. This journey looking at materials will pave the ground for a thorough exploration in the ensuing sections, which will dwell on the interactive framework of elements within the geopolymer matrix.

A meticulously planned technique during the whole study served as a vital link between material selection and experimental design. This is of special importance to the course of metakaolin extraction from the Kokshetau kaolin, because it indicates significant changes, which were set in during the geopolymerization. The experimental setup represents the three-dimensional building printer, which is very specialized, like a microwave oven and an apparatus for stress-strain tests in the given types, all new words in their respective fields. It could be pointed out that the use of silicon molds is a methodically focused process of using shields during the setup of the microwave with the aim of assuring safety and precision. That approach and the experimental setup of the experiments postulate solid grounds in favor of a controlled and reproducible investigation, placing this investigation at the cutting-edge frontier line of the research for the transformative potentials of microwave-induced curing in geopolymer-based 3D structure printing. A detailed analysis of the compression and bending tests clearly shows the very high influence that additive manufacturing technologies have on the evolution of the building material industry.

Thus, these results establish important insights into the mechanical performance of 3D-printed specimens both under compression and bending loads from careful experimentation and analysis with the action of microwaves. The comparison of the compression test result showed remarkable strength of the material after microwave treatment.

The compressive strength of the microwave-treated samples was on par with that of the Isotropic samples, which was effectively proven for material strength and structural integrity improvement by the microwave treatment. By this success, a way was open for further development related to geopolymer structures that had remarkable strength and flexibility. Comparatively, and compared with bending test results, microwave and non-3D printed samples exhibited excellent mechanical properties relative to isotropic standards.

3D printing, because of its layered production approach, has an in-built advantage to the structural consistency and strength; hence, it enhances productivity during bending. In summary, the findings presented in this study highlight the game-changer opportunities that arise from the incorporation of cutting-edge production technologies, particularly 3D printing with geopolymer materials, into the construction industry. It could open a way for the utilization of advanced manufacturing and post-processing techniques such as microwave hardening to develop geopolymer structures of very high durability, strength, and ductility. These results would be significant for sustainable infrastructure solutions with new exciting horizons for the construction industry.

5.2. Contribution to Knowledge

This The research adopts new frontiers in the area of building materials and additive manufacturing by the exploitation of untapped potential of microwave heat in the development of geopolymer additive manufacturing. The effect of geopolymer-based design on 3D printing, in the context of the described scrutiny, was further developed. This study elaborates on another great advantage of novel technologies in the fabrication of geopolymer additives. Therefore, the use of microwave curing for opening new prospects in the enhancement of material properties and structural integrity could be very helpful in the development of highly efficient geopolymer structures.

Care and attention have been taken in the experiments carried out and their analysis since there is an intricate relationship between the production parameters, post-processing techniques, and the mechanical properties of 3D-printed geopolymer samples. The information coming from these findings will be of great importance, for they are likely to guide on optimization in printing parameters and approaches in treatment in the production of robust structural components with augmented mechanical strengths.

Such a very significant improvement in compressive and bending strength that microwave processing could bring indicates substantial changes this technology could introduce in increasing elasticity and material strength. Microwave heating is thus bridging between 3D-printed samples and isotropic standards, throwing a ground for exceptionally effective geopolymer structures that can fulfill practical application's low-tolerance demands.

The possibility of using geopolymer materials in construction would thus be labeled as sustainable development. There would be less dependency on the use of traditional building materials, which in the end means less environmental impact. In so doing, this research not only proves the efficacy of microwave treatment but also serves to establish the compatibility of geopolymer-based 3D printing with microwave treatment and contributes to the validation in the literature and establishment of compatibility between sustainable construction and an environmentally acceptable building material.

Indeed, the result of this research finds the bodies of knowledge over the geopolymer production mixture and paves the way for innovative, novel solutions in the construction sector. Because of its interdisciplinary, intertwining character of materials science, engineering, and state-of-the-art manufacturing technologies, this approach sounds very sound and will provide a solid base for future efforts in the field of development of sustainable infrastructure.

5.3. Future work

It is on these bases that future research, focusing on a number of critical areas, may precipitate significant advancement in the field of Geopolymer printing. Developing the geometry of the nozzle to minimize deformation of the printed object is a logical way to follow. This would be to systematically change dimensions and ratios of the rectangular nozzles in such a way that they find the most critical geometry, which will ensure that the structural distortions are at a minimum while deposition of material is uniform. This research, therefore, seeks to lend a hand in not only advancing printing technologies but also in aiding improvements in the precision of measurement for structures based on geopolymers.

The strength and mechanical properties developed by the printed objects can further be improved if the Geopolymer mixture solution formula is improved. Only with high precision in selecting composition and proportion of raw material, hardening kinetics and material qualities can be controlled. This would provide a much stronger and resilient structure to the print, while at

the same time paving the way to the development of elastic material based on geopolymers that is environmentally friendly.

Along with that, the advancement of geopolymers of the nozzle includes the exploration of other shapes of the nozzle. While most of the nozzles will be rectangular, the others will include conical, cylindrical, and specially designed ones that really open new aspects of versatile printing. Such analyses would lead to the best set-up of different nozzle shapes and their different effects on material application, layer adhesion, and quality, leading to defined tasks of printing and material characteristics. To have such a comparative analysis would definitely lead to bringing out some enlightening information, which would help make an optimized decision for outcomes related to printing.

It seems to be very promising in the relative performance, durability, and stability of geopolymers compared to conventional building materials. This paper will detail the strengths, potential limitations of geopolymer-based structures with the use of traditional materialistic tools like concrete, steel, and wood. The paper will include life-cycle assessments and mechanical testing, giving details on the strengths and potential limitations of geopolymer-based structures with the use of traditional materialistic tools such as concrete. This level of detail in the assessment is paramount in building firm grounds towards informed decision-making in regard to construction projects, supporting if not encouraging, the broad adoption of geopolymer solutions across many applications.

In the future, critical areas will remain to be researched with regard to the use of geopolymers in additive manufacturing. This would have definitely optimized printing parameters in attaining quality and efficiency with printed structures. Understanding features of geopolymer mix may influence and enhance mechanical properties and durability of the printing product; probably, the invention of an alternative printing nozzle might influence better printing accuracy and leave over less amount of material. Moreover, the presented comparison with traditional structural material would be able to highlight the benefit and potential of geopolymers in modern construction.

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