

STRUCTURAL BEHAVIOR OF GEOPOLYMER CONCRETE WITH GFRP BARS

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This thesis is dedicated to my family, whose unwavering support and encouragement have been my guiding light throughout this journey. To my beloved mother, Yeluri Lakshmi Devi, and Guntupalli Subbaratnama, and my father, Yeluri Venkateswarlu, and Guntupalli Chenchu Ramaiah, your love and sacrifices have been the foundation of my success. To my brothers, Yeluri Venkata Krishna and Yeluri Anka Babu, and my sister, Guntupalli Bhavitha Sree, your constant belief in me has been a source of strength. To my sister-in-law, Somepalli Lakshmi Thulasi, and my grandmother, Yeluri Jayamma, your prayers, and blessings have always been with me. I also extend my heartfelt gratitude to my supervisor, Dr. Karan Singh, Assistant Professor, School of Civil Engineering, Lovely Professional University, Phagwara, Punjab, India, and my co-supervisor, Dr. T.S. Ramesh Babu, Associate Professor, K.G. Reddy College of Engineering and Technology, Hyderabad, India. Your guidance, patience, and expertise have been invaluable in the completion of this work. To my friends, whose motivation and encouragement have been a constant source of inspiration, thank you for always believing in me. Thank you all for your unwavering support and encouragement.

DECLARATION

I, hereby declared that the presented work in the thesis entitled “Structural Behavior of Geopolymer Concrete with GFRP Bars” in fulfilment of degree of **Doctor of Philosophy (PhD)** is outcome of research work carried out by me under the supervision of Dr. Karan Singh, working as Assistant Professor, in the School of Civil Engineering of Lovely Professional University, Punjab, India. In keeping with general practice of reporting scientific observations, due acknowledgements have been made whenever work described here has been based on findings of other investigator. This work has not been submitted in part or full to any other University or Institute for the award of any degree.



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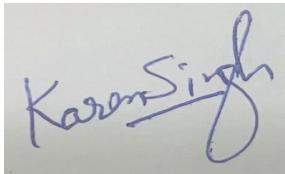
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CERTIFICATE

This is to certify that the work reported in the Ph. D. thesis entitled “Structural Behavior of Geopolymer Concrete with GFRP Bars” submitted in fulfillment of the requirement for the award of degree of **Doctor of Philosophy (Ph.D.)** in the School of Civil Engineering, is a research work carried out by Yeluri Sesha Choudary, 11816278, is bonafide record of his/her original work carried out under my supervision and that no part of thesis has been submitted for any other degree, diploma or equivalent course.



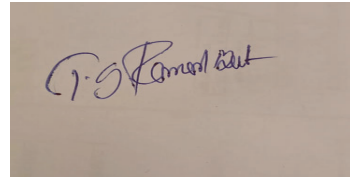
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ABSTRACT

In recent decades, geopolymer concrete (GPC) has become a viable substitute for traditional Portland cement concrete (PCC) in the construction industry. A lot of recent studies have been driven into utilizing geopolymer as a replacement for traditional concrete. GPC is characterized by its use of industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), which react with alkaline activators to form a binder. This innovative material offers several advantages, including high compressive strength, excellent durability, and superior resistance to fire and chemical attacks. Additionally, GPC significantly reduces carbon emissions and energy consumption compared to PCC, making it a more sustainable option. The increasing demand for sustainable construction materials has driven extensive research into the properties and applications of GPC. Studies have shown that GPC can achieve high early strength, making it suitable for precast applications and rapid construction projects. Its low shrinkage and thermal conductivity further enhance its performance in various environmental conditions. Despite these benefits, the widespread adoption of GPC faces challenges such as high initial costs, the need for specialized knowledge in its production, and the lack of standardized codes and specifications.

The increased demand for the usage of natural resources as construction materials due to rapid urbanization all over the world is observed. Furthermore, a massive amount of industrial waste is produced daily globally such as copper slag and rubber, and disposing of this waste material is a difficult task due to limited storage. The use of copper slag in concrete helps reduce the environmental pollution associated with the disposal of slag in landfills, which can lead to leaching of harmful substances into the soil and water bodies. By incorporating waste rubber into concrete, the volume of waste directed to landfills is reduced, alleviating the pressure on waste management systems. The incorporation of rubber and copper slag as aggregates in geopolymer concrete offers substantial environmental benefits. These include effective waste management and recycling, reduction in greenhouse gas emissions, conservation of natural resources, and minimization of environmental pollution. By leveraging these waste materials, the construction industry can move towards more sustainable and eco-friendly practices. Usually, steel is used as the reinforcement in concrete as the tensile material. However, the use of steel in environmental severe conditions leads to corrosion damage. The usage of steel limits to choose an alternative to it has been studied continuously. Fiber reinforcement polymers are the potential alternatives to steel as provided by the studies.

In response to these challenges, ongoing research is focused on optimizing the mix design of GPC to improve its workability, strength, and cost-effectiveness. The integration of agricultural by-products, such as rice husk ash and bagasse ash, into GPC formulations, has shown promising results in enhancing its mechanical and microstructural properties. Furthermore, the development of predictive models using artificial neural networks and other advanced techniques is aiding in the reliable estimation of GPC's performance. The potential of GPC to contribute to sustainable development in the construction industry is immense. By

reducing the reliance on natural resources and minimizing environmental impact, GPC aligns with the principles of green building and sustainable construction. Future research and collaboration among researchers, industry professionals, and policymakers are essential to overcome the existing barriers and promote the widespread adoption of GPC in construction projects worldwide.

This dissertation presents a thorough investigation into the optimization of fly ash-based geopolymer mortar and concrete through the variation of NaOH molarity, SS/SH ratio, and the substitution of conventional fine aggregates with industrial by-products such as copper slag and crumb rubber. The research aims to address the environmental concerns associated with the disposal of industrial waste and the sustainability challenges in the construction industry by developing eco-friendly construction materials without compromising on mechanical properties and durability. The study systematically explores the influence of alkali activator concentration, represented by NaOH molarity and SS/SH ratio, on the setting times, workability, compressive strength, flexural strength, and durability of geopolymer mortar and concrete. It was found that increasing NaOH molarity and SS/SH ratio significantly reduces the initial and final setting times, indicating a faster rate of geopolymerization. This acceleration in setting times was further enhanced with the addition of copper slag, suggesting its potential to act as a catalyst in the geopolymerization process. However, the incorporation of crumb rubber exhibited the opposite effect, extending the setting times, which was attributed to its hydrophobic nature and lower density compared to conventional aggregates.

Workability, as measured by flow values, decreased with higher NaOH molarity and SS/SH ratios, and further reductions were observed with the addition of copper slag and crumb rubber. This reduction in workability was linked to the increased viscosity of the geopolymer mix and the physical properties of the substitute materials. Despite the workability challenges, the compressive and flexural strengths of the geopolymer mortar and concrete were significantly improved with the addition of copper slag, highlighting its beneficial role in enhancing the mechanical properties of geopolymers. Conversely, crumb rubber reduced the compressive strength, although pre-treatment of rubber with NaOH was found to mitigate this effect to some extent.

Durability assessments, including sorptivity and rapid chloride permeability tests (RCPT), revealed that copper slag incorporation improves the resistance of geopolymer concrete to water and chloride ion penetration, thereby enhancing its durability. The addition of crumb rubber, on the other hand, increased the sorptivity values, indicating higher water absorption, but pre-treatment of rubber showed promising results in improving the durability characteristics. The microstructural properties of the concrete suggest that the GPC mix with copper slag consists of an aggregate, binder matrix, and an interfacial transition zone (ITZ). A strong pozzolanic-binder matrix forms due to an alkaline solution reaction with copper slag. A dense ITZ separates the aggregate and polymeric matrix, strengthened by alkaline solution dissolution. Rubber replacement increases void volume and crack size, while fly ash particles are rarely found. The bond properties of Glass fiber reinforced polymer (GFRP) based geopolymer concrete suggest that the bond strength of the GFRP reinforcement rubberized

slag-based geopolymer concrete shows better results compared to the GFRP and steel reinforcement in conventional geopolymer and traditional cement concrete.

This study contributes to the body of knowledge by providing a comprehensive understanding of the effects of alkali activator concentration and the substitution of fine aggregates with industrial by-products on the properties of fly ash-based geopolymer mortar and concrete. The findings underscore the potential of utilizing copper slag and crumb rubber, not only as sustainable alternatives to conventional aggregates but also as a means to enhance the mechanical properties and durability of geopolymer concrete. The potential use of GFRP bars as an alternative to steel has also been determined to analyze the structural performance of the concrete. This research opens new avenues for the development of eco-friendly and durable construction materials, paving the way for a more sustainable construction industry.

Keywords: *Geopolymer concrete, Copper slag, Crumb rubber, Rubber aggregates, GFRP bars, Mechanical properties, Durability properties, Bond properties.*

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Chapter 1

Introduction

1.1 Background:

Reinforced concrete is a significant substance in the field of construction, such as high-rise buildings, bridges, underground structures, and many more. It comprises essential constituents including steel, cement, aggregates, and water. The demand for concrete components is endless and projected to further increase in the foreseeable future. However, the utilization of these components is accompanied by a range of environmental concerns.

Notably, the cement industry has been recognized as the second-largest contributor to greenhouse gas emissions [1]. This can be attributed to the energy-intensive nature of its manufacturing process, which involves the calcination of limestone. According to estimates, the cement industry is responsible for approximately 8 % of carbon emissions on a global scale [2]. Furthermore, it is projected that cement production will reach a total of 4380 million tons by the year 2050 [3]. The production of one ton of cement results in the emission of approximately 0.85–1 ton of carbon dioxide (CO₂) [4].

The utilization of steel reinforcement in traditional concrete poses various challenges, such as the significant amount of energy required for steel production and its susceptibility to corrosion. The production of steel involves energy-intensive procedures that result in the substantial utilization of natural resources, thereby leading to carbon emissions. In addition, the corrosion of steel reinforcement within concrete structures gives rise to maintenance concerns and presents a potential risk to structural integrity, necessitating expensive repairs in the long run [5].

The extraction of natural aggregates, such as sand and gravel, has substantial environmental implications, encompassing habitat degradation, biodiversity reduction, and disturbance of riverine ecosystems. Furthermore, the transportation of aggregates over extended distances is a significant contributor to the release of greenhouse gases and the degradation of air quality [6]. The imperative to preserve the environment necessitates the reduction of natural aggregate consumption and the exploration of sustainable alternatives, given the increasing demand for construction materials. Thus, finding sustainable alternatives to natural aggregates has become crucial for preserving natural resources and mitigating environmental impacts. In response to the urgent need

for sustainable construction materials and practices, there is a growing interest in exploring alternative solutions to reduce the industry's ecological footprint. The substitution of conventional concrete with geopolymer concrete, steel bars with Glass Fiber Reinforced Polymer (GFRP) bars, and natural aggregates with waste materials exhibits the same performance.

1.2 Geo-polymer concrete:

In recent times, geopolymer concrete has emerged as a promising and innovative substitute for conventional Portland cement-based concrete owing to its distinctive composition and environmentally friendly characteristics [7]. Geopolymer concrete is a cement-like material that is made by combining alkaline activator solutions with industrial waste or naturally occurring materials that have silicon (Si) and aluminum (Al). The process of activation generates a network of geopolymeric bonds in three dimensions, leading to the formation of a binder that exhibits mechanical properties and durability that are comparable to, or even surpass, those of Ordinary Portland Cement (OPC) concrete. Depending on the material used in curing conditions to prepare the geopolymer concrete, the geopolymerization is different for those produced in the hydration of OPC [8]. The geopolymer binder is gaining popularity day by day due to its low CO₂ emissions, which have a low environmental impact in comparison to conventional cement-based binder [9]. In addition, geopolymer concrete demonstrates exceptional mechanical characteristics, such as notable compressive and flexural strengths, rendering it appropriate for a diverse array of structural implementations. The improved durability of concrete structures is attributed to its enhanced resistance to acid, sulphate, and chloride attacks, which effectively minimizes deterioration and extends the service life [10]. Thus, innovative substances have attracted considerable interest from scholars, engineers, and various sectors across the globe as they strive to mitigate the ecological consequences of construction activities and enhance the durability and efficacy of concrete infrastructure.

1.3 Applications of Geopolymer concrete:

Geopolymer concrete has exhibited considerable potential in diverse applications due to its exceptional mechanical properties, enhanced durability, and sustainable characteristics. The efficacy of this technology is evident in its application across

diverse infrastructure projects, including the development of road pavements, bridges, and tunnel linings. The notable characteristics of the subject in discussion, such as its high level of durability and its ability to resist chemical deterioration, offer significant advantages [11]. The utilization of geopolymer concrete is becoming more prevalent in the precast industry to produce various components such as beams, columns, and wall panels. The observed phenomenon can be attributed to the prompt hardening and notable initial strengthening characteristics of geopolymer concrete [12]. Furthermore, it has been observed that this technique has proven to be useful in the construction of mass concrete structures, including dams and retaining walls. The advantageous characteristics of this material, such as its low heat of hydration and reduced susceptibility to thermal cracking, make it highly suitable for large-scale placements that involve substantial volumes [13]. The material demonstrates exceptional durability and resistance to seawater, making it a viable option for marine structures such as offshore platforms, underwater foundations, and coastal protection works [14]. The chemical resistance of concrete has made it a highly promising option for the encapsulation and immobilization of nuclear waste materials. This quality ensures long-term stability and containment [15]. The application of geopolymer concrete offers a feasible remedy for the restoration and refurbishment of pre-existing concrete structures, as it offers enhanced durability and protection against potential deterioration [16]. The feasibility of incorporating geopolymer concrete has been examined as a potential solution for the implementation of environmentally friendly roof systems and permeable pavements. This can be primarily attributed to its ability to effectively reduce stormwater runoff and mitigate the negative effects of the urban heat island phenomenon [17].

1.4 Motivation:

The construction industry plays a pivotal role in influencing the progress of present-day societies. However, it also exerts a substantial influence on the environment by depleting natural resources and producing waste. In recent times, there has been an increasing concern regarding the ecological viability of conventional construction materials and methodologies. This concern has led researchers and engineers to investigate novel and environmentally sustainable alternatives that can effectively reduce ecological consequences while maintaining or even improving the performance

of structures. The motivation for this doctoral thesis develops from the imperative to address these environmental challenges and enhance overall sustainability in the construction field. The proposed research focuses on studying the structural behavior of Glass Fiber Reinforced Polymer (GFRP)-based reinforced geopolymer concrete made of copper slag and rubber as a viable alternative to conventional concrete with natural aggregates. This study aims to make an effort towards waste reduction and the preservation of natural resources by exploring the potential use of copper slag and rubber as alternative materials to replace natural aggregates.

The principal objective of this study is to investigate the mechanical and durability properties of geopolymer mortar and concrete that utilize fly ash as a primary component. Geopolymers have exhibited beneficial properties as a viable substitute for conventional concrete in construction, thereby offering potential for the advancement of sustainable construction methodologies. The comprehension of geopolymer behaviour will yield significant insights regarding its suitability and effectiveness in real-world construction scenarios. The secondary objective of this study is to investigate the mechanical and durability properties of geopolymer mortar and concrete incorporating copper slag. Incorporating copper slag as a fine aggregate in geopolymer mortar and concrete aligns with the broader goal of sustainable and eco-friendly construction practices. It provides a potential solution to both waste management challenges and the quest for more durable and resource-efficient construction materials. Another key objective of this study is to investigate the mechanical and durability properties of geopolymer mortar and concrete incorporating rubber aggregates. The utilization of rubber, obtained from discarded tires, as an aggregate substance possesses the capacity to not only mitigate waste but also enhance specific characteristics of the concrete. The investigation of the behaviour of these concrete mixtures will help advance structures that are both sustainable and resilient. Furthermore, this research seeks to explore the microstructural characteristics of geopolymer mortar and concrete. This microstructure study plays a vital role in defining the overall performance of concrete. This understanding will facilitate the optimization of their composition and enhance their suitability for various engineering applications. Lastly, the utilization of GFRP bars as reinforcement in geopolymer concrete is an important aspect of this research. The analysis of the structural behaviour using Abaqus, a powerful numerical simulation tool, will provide valuable data on the performance and safety of such

composites. If proven successful, this research could offer an alternative to traditional steel-reinforced concrete, reducing the carbon footprint associated with steel production and contributing to the overall sustainability of construction practices.

In summary, the motivation behind this Ph.D. thesis is to explore and promote the use of sustainable and environmentally friendly materials and practices in the construction industry. By studying the structural behaviour of GFRP-based reinforced geopolymer concrete made of copper slag and rubber, this research hopes to contribute to the development of eco-friendly building materials, cut down on waste, and possibly reduce the need for natural aggregates and traditional steel reinforcement. The findings from this research hold the potential to positively impact the construction industry and pave the way for a more sustainable and greener future.

1.5 Hypothesis:

The hypothesis of this thesis is as follows:

1. The mechanical properties and durability of Fly-ash based geopolymer mortar will demonstrate significant improvements compared to conventional cement-based mortar.
2. The use of copper slag and rubber as alternatives to aggregate geopolymer mortar and concrete will lead to enhanced mechanical properties and improved durability when compared to conventional concrete made with natural aggregates.
3. Geopolymer concrete made with rubber aggregates will exhibit comparable or improved mechanical properties and durability compared to conventional concrete made with natural aggregates.
4. The microstructural analysis of geopolymer mortar and concrete will reveal a denser and more homogeneous structure, which contributes to its enhanced mechanical properties and durability.
5. The use of Glass fiber-reinforced polymer (GFRP) as reinforcement leads to better bonding and bending properties compared to steel reinforcement.
6. The experimental and numerical analysis using Abaqus will confirm the structural behavior and performance of Geopolymer concrete reinforced with GFRP bars, highlighting its potential as a sustainable and durable construction material.

1.6 Research Objectives:

The thesis aims to study the structural behaviour of Glass Fiber Reinforced Polymer (GFRP) based reinforced geopolymer concrete made of copper slag and rubber as an alternative to natural aggregates. The use of waste materials as an alternative to natural aggregates and GFRP bars for the better durability of reinforcement concrete that is cured in ambient conditions to eliminate the heat curing requirement for geopolymerisation is the main goal of this research. The primary objectives of this research are as follows:

- To study the mechanical properties and durability properties of the Fly-ash based geopolymer mortar.
- To study the mechanical properties and durability properties of the geopolymer concrete made with rubber aggregates.
- To study the microstructural characteristics of geopolymer mortar and concrete.
- To analyse the experimental and numerical analysis of the structural behaviour of Geopolymer concrete made with GFRP bars using Abaqus/modelling techniques.

1.7 Outlines:

The thesis comprises six chapters, as outlined below:

Chapter 1 introduces the background, geopolymer concrete, applications of geopolymer concrete, motivation, hypothesis, and research objectives.

Chapter 2 presents a literature review of geopolymer concrete and its history, the use of alternatives, reinforced geopolymer concrete, glass fiber-reinforced polymers, and recent advancements.

Chapter 3 describes the materials used and their properties, the mix design of geopolymer paste, mortar, and concrete, the suitable tests conducted to determine the properties, and their procedures.

Chapter 4 presents the experimental study investigation of fresh properties, mechanical properties, durability properties, microstructural behavior, bond behavior, flexural behavior, and the cost analysis of geopolymer mortar, concrete, and reinforced concrete.

Chapter 5 presents conclusions, future aspects, and recommendations.

Chapter 2

Literature review

2.1 General:

The provision of infrastructure is a fundamental need in contemporary society. Nevertheless, the progress in infrastructure development is also linked to some adverse consequences for the global environment. This may be attributed to the use of certain materials in its construction that are not environmentally friendly, such as Portland cement concrete (PCC). Based on the findings of research, it has been determined that this activity is accountable for the release of dangerous carbon dioxide (CO₂) into the atmosphere, as well as the use of certain finite natural resources as its primary inputs. Hence, it is imperative that the global community transition towards using environmentally sustainable materials within the building sector. Geo-polymer concrete, a revolutionary eco-friendly material, has emerged as a promising solution with superior mechanical properties, a lower carbon footprint, and a reduced environmental impact. This chapter presents a thorough literature review that examines the extensive research conducted on geo-polymer concrete to analyze its properties, production methods, applications, and challenges.

2.2 History of Geo-polymer concrete:

The construction industry's significant contribution to economic growth and urban development cannot be overstated. However, it is also responsible for a substantial environmental impact, primarily due to the extensive use of traditional Portland cement as the principal binder in concrete production. Cement manufacturing is energy-intensive and produces a significant amount of carbon dioxide (CO₂) emissions, contributing to global greenhouse gas emissions and climate change. Additionally, the demand for concrete and cement is placing enormous pressure on the depletion of natural resources such as limestone and aggregates, further exacerbating environmental concerns.

In response to these challenges, researchers, engineers, and policymakers have been seeking sustainable alternatives to traditional cement-based concrete. Geo-polymer concrete has emerged as a promising eco-friendly material that offers the potential to address these environmental issues. Geo-polymer concretes have been found to exhibit excellent engineering properties such as higher compressive strength, better durability, and increased resistance to aggressive chemicals compared to conventional concrete [18]

The term "geopolymer" was coined by French materials scientist Joseph Davidovits in the 1970s. Davidovits pioneered research into geopolymers as an alternative to Portland cement, focusing on the synthesis of materials through a low-temperature chemical process [19]. Due to the large variety of formulations, geopolymer has a number of various names, including inorganic polymer and alkali-activated materials (AAM). Some claimed that the term "geopolymer" should instead apply to alkali-activated binders made from low-calcium precursors such as low-calcium fly ash (LCFA) and calcined clays [20]. One of the early instances of geopolymer concrete application was the construction of fire-resistant panels using geopolymers. In the late 1980s, the European Space Agency (ESA) collaborated with Davidovits to develop fire-resistant panels for spacecraft re-entry shields using geopolymers. These panels demonstrated the potential of geopolymers to provide exceptional fire resistance and thermal stability. Portland cement production contributes to a significant portion of global CO₂ emissions, approximately 5–7 %. As concerns over global warming intensified, the search for sustainable alternatives gained momentum. Geo-polymer concrete emerged as a promising candidate due to its potential for reduced greenhouse gas emissions [21].

Geopolymer concrete is an innovative cementitious material that derives its strength and durability from the geopolymerization process. The reaction of source materials rich in alumina and silica with alkaline activators produces geopolymers, which are amorphous aluminosilicate materials. Geopolymer concrete is a kind of concrete that may be manufactured by the polymerization process of aluminosilicates, comprising rice husk ash, fly ash, metakaolin, and slag [22]. This polymerization is accomplished by activating these materials using an alkaline solution. Unlike Portland cement, which relies on calcium silicate hydrate (C-S-H) gel as the binder, geopolymerization involves the reaction of aluminosilicate materials, such as fly ash, slag, or metakaolin, with alkaline activators, such as sodium hydroxide and sodium silicate. This process forms a three-dimensional amorphous network of geopolymeric gels, resulting in a hardened material with cementitious properties.

Apart from the precursor materials, a significant constituent of geopolymer formation is the alkali activator. These activators commonly encompass sodium or potassium hydroxides, silicates, carbonates, or their combinations, all of which exhibit solubility in water [23-24]. The successful development of the final geopolymer product hinges on the effective interaction between the precursor and the alkali activator. The choice of activator can markedly influence the performance of specific precursor materials, as their chemistry may lead to varying degrees of reactivity. For instance, ground granulated blast furnace slag (GGBFS) displays enhanced

activation when coupled with sodium silicate solution, which is attributed to its chemistry [25]. Similarly, sodium hydroxide emerges as a favorable activator for fly ash-based alkali activation [26]. In summary, the alkali activator, in conjunction with precursor materials, constitutes a fundamental aspect of geopolymer chemistry. The selection of the appropriate activator is crucial to ensuring optimal reactivity and performance of the resultant geopolymer product. Moreover, GPC, incorporating aggregates akin to OPC concrete, demonstrates remarkable mechanical properties and resistance to various environmental stresses, positioning it as a versatile and promising alternative in the realm of construction materials.

Researchers also focused on optimizing the mix design, curing conditions, and mechanical properties of geopolymer concrete to ensure its practical applicability in construction. Studies investigated the compressive strength, durability, and long-term performance of geopolymer concrete in comparison to traditional Portland cement-based concrete. While geopolymer concrete has shown promising properties and potential environmental benefits, its widespread adoption has been limited by factors such as cost, the availability of suitable source materials, and the need for standardized testing and design guidelines [27]. As of my knowledge, the cutoff date for research and development in the field of geopolymer concrete continues to progress, with ongoing efforts to address these challenges and promote its use as a sustainable alternative to conventional concrete.

2.3 Need of modifications:

The demand for modifications in geopolymer concrete is driven by the pressing need to enhance its overall performance, overcome existing limitations, and fully exploit its potential as a sustainable and innovative construction material. While geopolymer concrete presents itself as a promising alternative to traditional Portland cement-based concrete, there are several compelling reasons that underscore the imperative for continuous research and development to bring about substantive improvements.

Firstly, the versatility of geopolymer concrete is intimately linked to the availability of suitable source materials. The geographic variability of these materials presents a challenge that demands modifications in geopolymer formulations [28]. By adapting the instruction to encompass locally available resources, researchers can facilitate the widespread utilization of geopolymer concrete, fostering its applicability across diverse regions and reducing dependence on specific source materials [29]. Secondly, geopolymer concrete has demonstrated commendable mechanical properties; however, there remains room for

enhancement. Achieving consistent and robust early-age strengths is a priority [30]. The mechanical performance of geopolymer concrete must be optimized to match or exceed that of conventional concrete, especially in critical applications such as structural elements and load-bearing components [31]. By refining the mix design, composition, and curing methods, researchers seek to elevate the mechanical attributes of geopolymer concrete to meet the rigorous demands of modern construction. Thirdly, the durability of geopolymer concrete is a crucial aspect that warrants attention. While the material showcases favorable resistance to various forms of deterioration, further strides can be made to reinforce its long-term performance [32]. Specific challenges, such as resistance to freeze-thaw cycles, alkali-silica reactions, and chemical resistance, necessitate comprehensive solutions. Modification efforts target the optimization of material composition, curing techniques, and incorporation of additives to fortify the durability of geopolymer concrete, ensuring its resilience over extended service lives [33].

Moreover, optimizing the curing and setting times of geopolymer concrete is imperative for enhancing construction efficiency. Long curing periods have been a characteristic limitation of the material. Modifications aim to accelerate the curing process without compromising the final product's quality and performance. This innovation would streamline construction timelines, reduce project costs, and improve the feasibility of incorporating geopolymer concrete into time-sensitive projects. The financial feasibility of geopolymer concrete is also under scrutiny, necessitating modifications to ensure cost-effectiveness. Initial production expenses, often elevated due to activator costs and specialized manufacturing procedures, are a significant barrier to widespread adoption. Researchers are actively seeking ways to minimize production costs by exploring alternative activators, refining production techniques, and optimizing material usage, making geopolymer concrete a more economically viable option.

Furthermore, the lack of standardized testing methods and design guidelines for geopolymer concrete presents a formidable challenge [34]. To earn broader acceptance and facilitate confident implementation, modifications are being pursued to establish universally recognized protocols. These protocols encompass mix design, testing procedures, quality control mechanisms, and structural design guidelines, all of which contribute to consistency, reliability, and compatibility with existing construction practices [35]. The environmental footprint of construction materials is a growing concern, and geopolymer concrete's lower carbon emissions offer a promising solution [36]. However, further modifications are essential to maximize its sustainability. Researchers are exploring alternative sources for alkali

activators and optimizing production processes to reduce energy consumption and minimize greenhouse gas emissions, aligning geopolymer concrete with contemporary environmental objectives [37]. Lastly, architectural acceptance and aesthetic integration are critical for the widespread adoption of geopolymer concrete. While its mechanical and environmental attributes are compelling, its visual appeal must not be compromised. Modifications are underway to refine the surface finishes, colors, and textures of geopolymer concrete to align with architectural aesthetics, ensuring that it seamlessly integrates into diverse design contexts.

In conclusion, the need for modifications in geopolymer concrete is evident and multifaceted. The pursuit of enhanced mechanical properties, heightened durability, flexibility in source materials, optimized curing times, cost-effectiveness, standardized guidelines, environmental compatibility, and aesthetic refinement collectively underscores the imperative for ongoing research and development. The evolution of geopolymer concrete through systematic modifications not only addresses current challenges but also positions it as a transformative force in sustainable construction practices, promising a resilient and eco-friendly future for the built environment.

2.4 Reinforcement based Geopolymer concrete:

A crucial facet of geopolymer concrete's evolution is the integration of reinforcement techniques that enhance its structural performance, durability, and applicability across diverse engineering applications. This section explores the significance of reinforcement in geopolymer concrete, highlighting key aspects such as types of reinforcement, challenges, advancements, and future prospects.

Reinforcement in geopolymer concrete involves the incorporation of materials that enhance its tensile strength, ductility, and overall structural integrity. Common types of reinforcement include traditional steel reinforcement, glass fiber-reinforced polymer (GFRP) bars, and natural fibers [38]. Traditional steel reinforcement is widely used and well-studied, providing geopolymer concrete with increased strength and ductility. GFRP bars, on the other hand, address concerns related to corrosion and offer significant weight advantages, making them suitable for aggressive environments and lightweight structures. Natural fibers, such as jute and sisal, serve as sustainable alternatives to synthetic fibers, contributing to the eco-friendly nature of geopolymer concrete [39]. While the integration of reinforcement enhances geopolymer concrete's mechanical properties, it introduces challenges related to bond behavior, compatibility, and long-term performance. Ensuring an effective bond between reinforcement

and the geopolymer matrix is crucial to harnessing the full potential of reinforced geopolymer concrete. Researchers have focused on improving the interfacial bond through various techniques, including surface treatments and innovative fiber geometry [40].

Advancements in reinforcement techniques have led to the development of hybrid systems that combine different types of reinforcement to capitalize on their individual strengths. For instance, hybrid systems that merge steel reinforcement with GFRP bars capitalize on the high strength of steel and the corrosion resistance of GFRP, creating a balanced and versatile structural material [41]. Reinforced geopolymer concrete finds applications in a wide spectrum of structural elements, including beams, columns, and slabs. Research has demonstrated its effectiveness in enhancing the performance of flexural, shear, and axial-loaded members. Additionally, studies have explored the use of reinforced geopolymer concrete in seismic-resistant designs, showcasing its potential to contribute to resilient infrastructure [42]. The future prospects of reinforcement in geopolymer concrete hold promise for further refinement and optimization. Researchers are delving into the use of nanomaterials to enhance the bond between reinforcement and geopolymer matrix [43]. Additionally, advancements in 3D printing technology have opened avenues for the integration of reinforcement within intricate and complex geometries, expanding the possibilities for innovative architectural designs [44].

In conclusion, the integration of reinforcement in geopolymer concrete is a pivotal endeavor that contributes to its structural viability and long-term performance. The utilization of various reinforcement types, coupled with ongoing research and advancements, demonstrates the potential to unlock the full capabilities of geopolymer concrete as a sustainable and resilient construction material. By addressing challenges, embracing hybrid reinforcement systems, and exploring novel techniques, the construction industry stands poised to embrace reinforced geopolymer concrete as a key enabler of a sustainable built environment.

2.5 Use of modifiers:

The quest for environmentally friendly construction materials has amplified interest in geopolymer concrete (GPC). A vital area of study within GPC research focuses on its fresh properties, which include workability, setting time, and rheology, among others. This review encapsulates the fresh properties of GPC using various binders and aggregates based on key research studies.

The study conducted by Wilkinson et al. underscored the potential for achieving a slump of 193 mm in geopolymer concrete, a range that aligns with the criteria outlined in BS EN 1015-6, classifying it as plastic mortar [45]. Notably, the initial and final setting times were recorded as 150 min and 180 min, respectively, pointing to a degree of workability suitable for repair purposes. However, considerations arise when applying geopolymer concrete as a pothole replacement material, where swift setting times are crucial. The prolonged final setting time of 180 minutes presents a challenge, potentially hindering its immediate application in scenarios necessitating rapid deployment. Incorporating supplementary materials has emerged as a significant avenue for enhancing workability. Dave, Sahu, and Misra Anil [46] highlighted the influence of fly ash (FA) and silica fume (SF) on slump rates. Remarkably, a blend with 65 % GGBS and 35 % FA exhibited a substantial slump rate of 150 mm, attributed to the fine, spherical grains of FA, which contributed to heightened workability. Contrasting with GGBS alone, the inclusion of FA was found to enhance the workability of geopolymer concrete [30]. Additionally, the optimal water content and dosage of superplasticizer (SP) significantly impact workability and strength regulation [47-48]. The intricate balance between alkaline liquid content and its impact on both strength and workability has been investigated. Nath and Sarker [49] revealed that increasing alkaline liquid content could lower strength while enhancing workability due to altered liquid-solid ratios. A judicious mixture incorporating 5 % OPC content demonstrated favorable early-age strength, setting time, and workability for ambient-cured FA-based geopolymer concrete. Notably, the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio was identified as a pivotal parameter influencing the workability of FA-based geopolymer concrete [50]. Naphthalene-sulfonate-based SP also exerted a notable influence on workability. While SP enhanced workability in the fresh state, an excessive dosage led to a slight decline in the compressive strength of geopolymer concrete in the hardened state [51]. Furthermore, the addition of silica fume up to 10 % remarkably improved workability in the fresh state [52]. Particle size reduction demonstrated its potential to enhance workability [53], while the addition of fibers had a contrasting effect [54]. The effect of various mineral admixtures on workability was explored, with slag exhibiting enhanced workability due to its unique wetting characteristics [55-56]. Fine aggregates were found to fill voids and contribute to improved workability [57], while the selection of commercial SPs exhibited varying impacts [58]. It is noteworthy that the proportion of GGBS and silica fume may influence workability requirements [59]. Duxson et al. observed that fly ash-based GPC exhibited adequate workability, similar to Portland cement-based concrete. However, the setting time was slightly extended, depending on the alkaline activator's concentration [60]. Using slag as a binder,

Panias et al. revealed that GPCs tend to exhibit reduced workability due to the rapid setting nature of slag when activated with alkaline solutions [61]. Barbosa et al. demonstrated that GPCs with metakaolin exhibited quicker setting times and improved workability when synthesized using specific types of alkaline activators [62]. Fernandez et al. explored the synergistic effects of using both red mud and fly ash. They found that the combination produced a GPC with an optimal setting time and improved workability compared to using each binder individually [63]. GPC with natural aggregates like granite exhibited an increased demand for superplasticizers to achieve optimal workability due to the potentially high absorption of the aggregates [64]. Shirazian et al. studied GPC using recycled aggregates and observed a reduction in cohesiveness and workability due to the residual mortar on the recycled aggregates [65]. Ganesan et al. found that using quarry dust as a replacement for fine aggregates resulted in a slight reduction in workability due to the non-spherical shape and rough texture of the quarry dust particles [66]. Huseien et al. showed that using expanded glass as a lightweight aggregate in GPC resulted in a notable improvement in workability due to the spherical shape of the aggregate [67]. Singh et al. observed that the ratio of sodium silicate to sodium hydroxide in the activator solution plays a pivotal role in workability. A higher sodium silicate content led to increased workability [68]. Mustafa et al. emphasized the importance of superplasticizers in enhancing the workability of GPC, particularly for mixtures with binders or aggregates that are more demanding in terms of moisture [69]. Sathonsaowaphak et al. identified that the ambient temperature significantly affects the setting time of GPC, with higher temperatures accelerating the setting process [70]. Rattanasak et al. explored the introduction of glycerol in GPC, noting an extension in the setting time, which can be beneficial in certain construction scenarios [71]. Rahmani et al. highlighted that the incorporation of nanosilica in GPC enhanced its workability and decreased setting time due to the high reactivity of nanosilica [72]. Habert et al. investigated the effects of mechanical vibration on fresh GPC and found that adequate vibration can enhance the particle packing and overall cohesiveness of the mix [73]. Nematollahi et al. explored the influence of retarders on the setting time of GPC, noting that certain retarders can effectively extend the setting time without compromising the final strength [74]. Phair and Van Deventer found that GPCs with rice husk ash as a binder displayed varying workability based on the specific synthesis conditions and the age of the rice husk ash [75]. Alvarez-Ayuso et al. explored the fresh properties of GPCs using calcined clay and found that particle size played a significant role in determining workability [59]. Lignosulfonate, a waste by-product, was explored as an additive by Criado et al., revealing that it could act as a set retarder and workability enhancer for GPC [76]. Citric acid as an additive

was studied by Lancellotti et al., indicating that it could improve workability by acting as a dispersant, thus preventing premature setting [77]. Ahmaruzzaman et al. showcased the potential of desert sand as a fine aggregate in GPC, highlighting adequate workability and setting characteristics under optimized conditions [78]. The fresh properties of GPC are highly contingent on the binders, aggregates, and additives used. Varied research has been conducted to optimize these properties, ensuring GPC is viable for different construction needs. However, further research is essential to achieve more consistent results across different mix designs and applications.

An understanding of its mechanical properties, such as compressive strength, tensile strength, and modulus of elasticity, is essential. The compressive strength of concrete signifies its ultimate resistance against applied compressive loads before yielding. Geopolymer concrete exhibits a strength development trend similar to Portland cement, attributed to continuous polymerization and condensation of precursors, leading to increased strength over time [79]. Ternary precursors, including GGBS and SF alongside FA, accelerate strength gain [80]. GGBS and SF contribute to a dense microstructure and enhanced strength, with a strong bond between SF and GGBS resulting in improved strength [81]. Wilkinson et al. [82] demonstrated that all specimens exhibited 7-day compressive strengths of at least 89 % of the 28-day strengths. Geopolymer concrete compressive strength is influenced by factors such as wet-mixing time, curing conditions, temperature, particle size, and additives like $\text{Ca}(\text{OH})_2$, $\text{Al}(\text{OH})_3$, SF, nano- SiO_2 , nano- Al_2O_3 , and various superplasticizers [83-85]. The compressive strength of FA-based geopolymer concrete reduces at elevated temperatures and with excess water content, while calcination alters mineralogical composition and reduces strength [86]. The compressive strength of geopolymer concrete improves with the substitution of GGBS, RCA, and various additives [87-88]. Steel slag enhances the calcium oxide content and thus compressive strength, but its use can lead to drying shrinkage and carbonation [89]. Geopolymer concrete also demonstrates better durability performance, and resistance in aggressive environments [90]. Studies have highlighted the relationship between compressive strength and other properties of geopolymer concrete. Furthermore, the flexural capacity, ductility, shear strength, and strain capacity of geopolymer concrete have been explored [91-93]. Regarding shrinkage, mixtures activated with sodium silicate exhibit lower drying shrinkage at lower alkali modulus. GPC shows improved performance compared to OPC concrete under elevated temperature conditions [94-95]. Davidovits discussed fly ash-based GPC, indicating that, when properly cured, it could achieve compressive strengths surpassing

those of traditional Portland cement concrete [96]. Bernal et al. demonstrated that slag-based GPCs could attain high early strengths, depending on the type and concentration of the alkaline activator [97]. Van Jaarsveld et al. reported that GPCs incorporating metakaolin typically have higher tensile strengths due to the high reactivity of metakaolin with alkaline activators [98]. Zhang et al. concluded that rice husk ash, when used in combination with fly ash or slag, could enhance the compressive strength of GPC, attributing this to the synergistic effects of the binders [99]. Hardjito et al. explored combinations of binders and found that a fly ash-slag blend offers an optimal balance of workability and mechanical strength [100]. Nath and Sarker investigated GPCs using natural aggregates like granite, noting that the bond between the geopolymer matrix and natural aggregates plays a pivotal role in dictating overall strength [101]. Kong and Sanjayan studied the influence of recycled concrete aggregates in GPC, finding that the interfacial transition zone between the geopolymer matrix and recycled aggregates was crucial for strength development [102]. Sumajouw et al. found that using lightweight aggregates such as expanded perlite in GPC leads to a compromise between weight reduction and compressive strength [103]. Thangavel and Malathy evaluated the potential of quarry dust as a partial replacement for sand in GPC. The compressive strength increased initially but declined with higher replacement levels, indicating an optimal balance [104]. Olivia and Nikraz concluded that the type and concentration of the alkaline activator significantly affect the compressive strength, with higher concentrations leading to increased strengths [105]. Ribeiro et al. observed that an optimal curing temperature exists for each geopolymer mix, beyond which the mechanical properties could deteriorate [106]. Ranjbar et al. assessed the addition of steel fibers to GPC, noting a considerable improvement in tensile and flexural strengths [107]. Kumar et al. discussed the positive effects of incorporating silica fume into GPC, emphasizing enhanced compressive strength and durability [108]. Hassan et al. explored the impact of extended curing periods on GPC's mechanical properties, indicating that a prolonged curing duration often results in improved strength [109]. Kazemi-Kamyab et al. investigated the influence of chemical admixtures on GPC and concluded that certain admixtures could significantly modify the mechanical performance [110]. Memon evaluated the performance of GPC under aggressive conditions, such as acid attacks, finding that GPCs have commendable resistance and sustain their mechanical properties better than Portland cement concretes [111]. Sathonsaowaphak et al. assessed the impact resistance of GPC, reporting superior performance compared to traditional Portland cement concrete [112]. Bilim et al. investigated the flexural behavior of GPC, noting that the matrix-aggregate bond was a vital contributor to the observed performance [113]. Zhu and Zhang examined the toughness

of GPC, indicating a higher resistance to cracking and deformation than traditional concrete, largely attributed to the nature of the geopolymer matrix [114]. Rickard et al. studied the shrinkage characteristics of GPC, observing reduced shrinkage rates compared to traditional Portland cement concretes [115]. Rovnaník evaluated the shear strength of GPC, emphasizing the significance of the aggregate choice and matrix composition on the observed results [116]. Badar et al. focused on the tensile strength of GPC, revealing that the choice of alkaline activator and aggregate type plays a pivotal role in determining tensile performance [117]. Panias et al. examined the mechanical properties of GPC after exposure to high temperatures, noting an initial increase in strength followed by a decrease upon extended exposure [118]. Yunsheng et al. assessed the blasting resistance of GPC, indicating superior performance when compared to traditional concretes due to the inherent nature of the geopolymer matrix [119]. Shi et al. detailed the thermal performance of GPC, suggesting that the inherent low thermal conductivity makes GPC an excellent choice for thermally efficient structures [120].

The durability properties of GPC depend on the type of binder and aggregates used. Fly ash, a by-product from coal-fired power plants, is the most commonly used source material for geopolymers. It's rich in silicon and aluminium oxides, making it an ideal raw material for geopolymerization. Studies have shown that fly ash-based GPC exhibits excellent resistance to acid attack, sulfate attack, and elevated temperatures [121]. However, its resistance to chloride ion penetration is comparable to ordinary Portland cement (OPC) concrete [122]. Ground granulated blast furnace slag (GGBFS), a by-product from the steel industry, has also been used as a primary source material for geopolymers. Slag-based GPC has demonstrated superior resistance against chloride ion penetration and alkali-silica reaction (ASR) as compared to OPC [123]. Metakaolin, derived from the calcination of kaolinite clay, is a pozzolanic material that's been extensively researched as a binder for geopolymers. Zhang et al. found that metakaolin-based GPC exhibits impressive resistance to sulfate attack and reduced permeability, contributing to its overall durability [124]. Another alternative binder studied is rice husk ash (RHA). RHA, when properly processed, can act as a supplementary binder in geopolymers. Phair and Van Deventer found that RHA-based geopolymers display good resistance against acidic environments [125]. Conventional natural aggregates like granite and limestone have been used in GPC. These GPCs have shown good durability properties, with resistance to freezing and thawing and a significant reduction in shrinkage as compared to OPC [126]. To further enhance sustainability, recycled aggregates (from demolished concrete) have been used in GPC. These concretes, while sustainable, tend to have slightly reduced durability properties

due to the inherent characteristics of the recycled aggregates. However, with appropriate mix design and curing, these GPCs can achieve durability close to that of natural aggregate GPC [127]. Kumar et al. researched the properties of GPC using basalt, a volcanic rock, as the aggregate. The study confirmed that basalt aggregate GPCs possess enhanced fire resistance and thermal stability compared to those made with conventional aggregates [128]. Rovnaník's study on using expanded perlite as lightweight aggregate in geopolymer concretes indicated a significant reduction in thermal conductivity, making them suitable for thermal insulation applications [129]. Research by Singhal et al. unveiled that GPCs with quarry dust as fine aggregate have promising durability, especially regarding resistance to water absorption and sulfate resistance [130]. Fibers have been added to GPCs to enhance their toughness and durability. Ranjbar et al. established that the inclusion of polypropylene fibers significantly improved the impact resistance of GPCs [131]. Nano-silica's addition to GPC can remarkably improve its microstructure. Shaikh reported enhanced compressive strength and improved durability when nano-silica was incorporated into the GPC mix [132]. Alkaline residues from industries have been used in GPC, helping in waste utilization. Temuujin et al. found that GPC with alkaline residues showed resistance to acid attack [133]. Carbon nanotubes (CNTs) have been used to enhance various properties of GPC. Nazari et al. discovered that incorporating CNTs not only increased strength but also improved durability against freeze-thaw cycles [134]. Red mud, a by-product of the aluminium industry, has also been considered a binder. Silva et al. found that red mud GPCs displayed low water absorption and good resistance against aggressive environments [135].

Understanding the microstructural properties of geopolymer concrete (GPC) is paramount to unlocking its potential as an alternative to conventional Portland cement-based concrete. Several research studies have examined the microstructural characteristics of GPC, considering its binder and aggregate constituents. In a study by Provis et al., scanning electron microscopy (SEM) was used to examine the microstructure of fly ash-based GPC. They observed a dense matrix with a predominantly gel-like phase, illustrating the crucial role of the fly ash's reactive silica and alumina content [136]. Duxson et al. conducted a detailed microstructural analysis of slag-based GPC. Their findings pointed towards the formation of a C-A-S-H (calcium-aluminium-silicate-hydrate) gel structure that binds the aggregates, providing evidence for the high mechanical strength of this geopolymer type [137]. Barbosa et al. examined the microstructure of metakaolin-based GPC using X-ray diffraction (XRD) and SEM techniques. They discovered the presence of an amorphous alumino-silicate gel, reinforcing the importance

of metakaolin's high reactivity in geopolymerization [138]. Komnitsas et al. researched the microstructure of GPCs using natural aggregates like granite. Their findings indicated that the geopolymer matrix formed a tight bond with these aggregates, with negligible voids and reduced microcracking [139]. Kong and Sanjayan, through their research, underscored the significance of the interfacial transition zone between the geopolymer matrix and recycled aggregates. The optimal particle distribution and surface texture of the recycled aggregates ensured a cohesive bond, with the matrix enveloping even minute particles [140]. Sakkas et al. investigated lightweight aggregate GPC, showing that while the geopolymer matrix was consistent, the bond with lightweight aggregates was characterized by a more porous interfacial transition zone, impacting the mechanical properties [141]. Zhang et al. explored the microstructural evolution of GPC with added nanomaterials. The incorporation of nanosilica was observed to refine the pore structure, enhance the matrix's compactness, and subsequently improve the concrete's overall durability [142]. The research by Temuujin et al. focused on the nanoindentation technique for GPC microstructural analysis. The method allowed for a deeper understanding of the material's hardness and modulus at the nanoscale, providing insights into the matrix-aggregate bond and the effect of varied curing temperatures [143]. The microstructural analysis of geopolymer concrete, considering both binders and aggregates, presents a deep understanding of its behavior and performance. As research techniques advance, the knowledge of GPC microstructure will undoubtedly refine, aiding in its broader application in sustainable construction.

2.6 GFRP based Geo-Polymer:

Fiber-reinforced Polymer (FRP) bars are increasingly being used as a substitute for conventional steel reinforcement in concrete constructions because of their resistance to corrosion, high strength-to-weight ratio, and electromagnetic neutrality. When geopolymer concrete (GPC) is blended with conventional Portland cement concrete, it creates a composite that has improved structural and durability characteristics. GPC is a sustainable alternative to ordinary Portland cement concrete. In a pioneering study, Al-Mahaidi et al. found that FRP bars could be effectively used as a reinforcing material for GPC beams. The beams displayed satisfactory flexural performance, and it was inferred that the bond between FRP and the geopolymer matrix was comparable to that in Portland cement concrete [144]. Shaikh conducted experiments focusing on the bond behavior of FRP bars in fly ash-based GPC. The findings suggested that the bond strength of GPC with FRP was influenced by the type of FRP used and the curing process. Interestingly, higher bond strengths were observed in GPC than

in Portland cement concrete [145]. A notable study by Ariffin et al. observed the durability of GPC beams reinforced with FRP bars under accelerated aging conditions. It was found that such beams displayed better durability properties than their Portland cement counterparts, especially in aggressive environments [146]. In research led by Patil, the shear behavior of GPC beams reinforced with FRP bars and stirrups was investigated. The outcomes revealed that shear strength was predominantly dependent on the quality of the bond between the GPC matrix and the FRP reinforcement [147]. Nematollahi et al. assessed the fatigue performance of FRP-reinforced GPC beams. It was found that the beams exhibited satisfactory performance under repeated loading, with the GPC matrix providing adequate support to the FRP reinforcement [148]. A study by Sumajouw et al. explored the impact resistance of FRP-reinforced GPC slabs. The results indicated enhanced impact resistance as compared to traditional concrete, underlining the benefit of merging GPC with FRP [149]. Chen and Kumar investigated the tensile behavior of GPC cylinders reinforced with FRP wraps. They found that FRP wraps provided substantial confinement to the GPC, enhancing its axial tensile strength and ductility [150]. Sajedi and Nazari highlighted the efficacy of using FRP sheets for externally strengthening GPC columns. This approach was found to enhance the load-carrying capacity and ductility of the columns considerably [151]. Kodur et al. focused on the seismic performance of FRP-reinforced GPC frames. They reported enhanced energy absorption, reduced vulnerability to cyclic loading, and better overall seismic behavior for such frames [152]. Dias et al. examined the thermal behavior of FRP-reinforced GPC walls. The results indicated that GPC, when combined with FRP, offered enhanced fire resistance, with the GPC acting as an insulator for the FRP bars [153]. The amalgamation of geopolymer concrete and FRP reinforcement offers several benefits, such as enhanced durability, mechanical strength, and fire resistance. As research progresses in this domain, more insights and innovative applications will likely emerge, promoting the sustainable and resilient infrastructure of the future.

2.7 Recent advancements:

In an era where sustainability and innovation are paramount in the construction industry, reinforced geopolymer concrete has emerged as a dynamic area of research and development. Recent advancements in reinforced geopolymer concrete have propelled its evolution, enabling its integration into diverse engineering applications. The quest for sustainable construction practices has driven innovative developments in binder materials and the replacement of

traditional aggregates and various types of reinforcements in geopolymer concrete. These advancements are reshaping the landscape of construction materials by offering improved performance and reduced environmental impact. This section explores some of these noteworthy advancements, emphasizing their significance and potential.

Researchers have been investigating the incorporation of various industrial by-products and waste materials to create blended binder systems. Innovative binder materials contribute to the development of geopolymer concrete with exceptional mechanical properties. These include materials such as fly ash, ground granulated blast furnace slag (GGBFS), and silica fume. These by-products not only serve as sustainable alternatives but also enhance the overall performance of geopolymer concrete by improving its strength, durability, and chemical resistance. The incorporation of fly ash, blast furnace slag, and metakaolin as supplementary materials in geopolymer formulations results in improved workability, strength, and long-term durability [154]. The concept of blended binder systems has gained prominence, where geopolymer concrete incorporates various supplementary materials. Blended systems often include fly ash, slag, and metakaolin as components alongside the primary binder source. These blended binders exhibit improved workability, strength development, and durability, thus broadening the application range of geopolymer concrete. Blended binder systems foster higher compressive and flexural strengths, rendering geopolymer structures suitable for a diverse array of load-bearing applications [155]. Researchers have investigated the incorporation of waste materials such as fly ash and slag as supplementary cementitious materials [156]. This not only enhances the sustainability of the material but also contributes to the overall mechanical properties of the concrete. Nanotechnology has paved the way for the development of nano-enhanced binder materials. Nanomaterials such as nano-silica and nano-alumina are being added to geopolymer mixtures to enhance mechanical properties and mitigate issues related to shrinkage and cracking, thereby optimizing the overall performance of geopolymer concrete [157]. The incorporation of nano-engineered binders enhances the durability and resistance of geopolymer concrete. Nano-additives mitigate microcracking and improve resistance to chemical attacks, ensuring the longevity of structures and minimizing maintenance requirements [158]. The recent advancements in binder materials for geopolymer concrete carry immense potential for the construction industry and the environment. These innovations offer multifaceted benefits that reverberate across sustainability, mechanical performance, and long-term durability. The trajectory of binder material advancements in geopolymer concrete holds exciting prospects for the future of sustainable construction.

Continued research and development in this field are poised to unlock further potential, yielding innovations that redefine the possibilities of geopolymer concrete. The integration of innovative binder materials with emerging construction technologies, such as 3D printing and additive manufacturing, offers the potential to revolutionize construction methodologies and realize intricate and sustainable architectural designs. Future research endeavors can delve into comprehensive life cycle assessments of geopolymer concrete with varying binder formulations. This holistic approach will provide a deeper understanding of the overall environmental impact and sustainability of geopolymer structures.

One significant advancement in geopolymer concrete technology involves the exploration of alternative alkali activators. Traditional activators like sodium hydroxide and sodium silicate have been supplemented with innovative options such as potassium hydroxide and potassium silicate [159]. These alternative activators not only contribute to the development of geopolymer bonds but also offer enhanced resistance to chemical attacks and improved mechanical properties. Further exploration of alternative alkali activators and binder materials allows for the customization of geopolymer concrete properties to suit specific applications. This adaptability enables engineers to create tailored solutions for varying structural requirements. By exploring alternative alkali activators and supplementary binder materials, geopolymer concrete reinforces its commitment to sustainability.

Another significant advancement is the utilization of various industrial by-products as aggregates. Incorporating waste materials such as recycled concrete aggregate, slag, and fly ash as replacements for natural aggregates not only diverts waste from landfills but also enhances the sustainability of geopolymer concrete [160]. The integration of innovative aggregates contributes to the development of geopolymer concrete with improved mechanical properties. Enhanced compressive strength, flexural strength, and abrasion resistance empower geopolymer structures to withstand diverse loading conditions [161]. Researchers are exploring the use of lightweight aggregates such as glass beads, clay, and polystyrene beads as replacements for traditional coarse aggregates. This substitution results in reduced structural weight, improved thermal insulation, overall material consumption, and increased fire resistance while maintaining adequate mechanical strength [162]. An intriguing advancement in geopolymer concrete technology is the use of recycled concrete aggregates (RCA). This sustainable approach involves reusing crushed concrete from demolished structures as a replacement for natural aggregates. Research has shown that incorporating RCA can lead to comparable mechanical properties and improved sustainability while addressing the challenge

of construction waste [163]. The use of industrial by-products and recycled aggregates in geopolymer concrete results in significantly lower embodied carbon compared to conventional concrete. This reduction in carbon emissions contributes to the mitigation of climate change impacts [164]. The trajectory of aggregate advancements in geopolymer concrete holds promising prospects for future construction practices. Further research and development in this domain can unlock untapped potential, leading to innovations that revolutionize the landscape of sustainable construction. Future research can delve into tailoring aggregate formulations to meet specific structural requirements. By optimizing aggregate combinations, geopolymer concrete can be engineered to excel in various applications, ranging from structural elements to architectural finishes. In-depth studies on the long-term durability and performance of geopolymer concrete with various aggregate types will provide valuable insights into their resistance to aggressive environments, chemical attacks, and structural integrity over time. As innovative aggregate materials continue to emerge, the development of standardized guidelines and codes of practice for incorporating these aggregates into geopolymer concrete will facilitate widespread adoption in construction projects. In conclusion, recent advancements in various types of aggregates for geopolymer concrete exemplify the dynamic evolution of sustainable construction.

In addition to binder materials and aggregates, advancements in geopolymer concrete have extended to the use of natural fibers as reinforcement. Natural fibers like jute, sisal, and coconut fibers are being incorporated to enhance the tensile strength and toughness of geopolymer concrete while also contributing to a more sustainable construction approach [165]. Advancements in sustainable construction have led to the exploration of natural fibers as reinforcements in geopolymer concrete. Fibers derived from sources such as jute, coconut husk, and bamboo are being incorporated to improve the tensile behavior and toughness of geopolymer concrete while contributing to a more environmentally friendly construction approach [166]. A notable advancement in geopolymer concrete technology involves the use of fiber-reinforced polymers (FRP) as reinforcements. FRP composites, comprising high-strength fibers embedded in a polymer matrix, have emerged as a viable alternative to conventional steel reinforcement. Their lightweight nature, corrosion resistance, and high tensile strength contribute to improved structural performance and durability [167]. Steel fibers, commonly used in conventional concrete, are also being adopted in geopolymer concrete. Recent research has focused on optimizing fiber geometry and content to enhance flexural and tensile properties, crack control, and impact resistance [168]. The recent

advancements in various types of reinforcements for geopolymer concrete hold substantial potential, both for the construction industry and the environment. These innovations offer multifaceted benefits that encompass structural integrity, sustainability, and material optimization. The integration of innovative reinforcement materials contributes to superior structural performance in geopolymer concrete. FRP reinforcements offer excellent strength-to-weight ratios and enhanced crack resistance, while steel fibers and natural fibers enhance ductility and toughness. Reinforcement materials such as FRP and natural fibers address concerns related to corrosion, a critical issue in conventional steel-reinforced concrete. This enhanced durability extends the service life of geopolymer concrete structures, reducing maintenance requirements and life cycle costs. The adoption of natural fibers aligns with the drive for sustainable construction. Utilizing renewable and biodegradable materials reduces the environmental footprint of geopolymer concrete and contributes to the reduction of non-renewable resource consumption. The trajectory of reinforcement advancements in geopolymer concrete holds tremendous promise for shaping the future of sustainable construction. Continued research and innovation in this domain can unlock unexplored potential, leading to transformative solutions and sustainable structural designs. Future research endeavors can focus on the development of hybrid reinforcement systems that combine various types of reinforcement. Combining the advantages of FRP, steel fibers, and natural fibers can create tailored reinforcement strategies for specific applications [169]. In-depth studies on the long-term behavior of reinforced geopolymer concrete structures, considering factors such as creep, shrinkage, and cyclic loading, will provide valuable insights into the durability and resilience of these innovative materials. The development of comprehensive design guidelines and codes of practice for reinforced geopolymer concrete structures will facilitate their integration into mainstream construction practices. In conclusion, recent advancements in various types of reinforcements for geopolymer concrete underscore the transformative potential of sustainable construction practices. By embracing innovative materials such as FRP, steel fibers, and natural fibers, geopolymer concrete not only enhances its structural performance but also reduces its environmental impact and extends its service life. These advancements reinforce geopolymer concrete's position as a pioneering and eco-friendly construction material, poised to revolutionize the field of sustainable structural engineering. One notable stride in reinforced geopolymer concrete involves the exploration of innovative reinforcement materials. Additionally, advanced materials like carbon nanotubes and graphene are being integrated into the matrix to further enhance its tensile strength and durability [170]. These innovative reinforcements not only offer superior properties but also

support the sustainable ethos of modern construction. Advancements in reinforced geopolymer concrete have also led to the development of hybrid reinforcement systems that combine different types of reinforcement to optimize performance. Hybrid systems, such as steel and polymeric fibers, are being investigated to synergistically leverage the strengths of each material [171]. This approach results in a well-balanced material that exhibits improved crack control, ductility, and load-bearing capacity, catering to a wide range of structural applications. Ensuring a robust bond between reinforcement and the geopolymer matrix is crucial for the effective utilization of reinforced geopolymer concrete. Recent research has focused on modifying the surface characteristics of reinforcement materials to improve their interfacial bond with the matrix [172]. Techniques such as surface treatments and coatings have been explored to enhance adhesion and prevent debonding, ultimately enhancing the load transfer mechanism and overall structural integrity. Advancements in reinforced geopolymer concrete also address the critical aspect of durability. Researchers are focusing on enhancing the corrosion resistance of reinforcement materials, particularly in aggressive environments. The incorporation of non-corrosive reinforcement materials like glass fiber-reinforced polymer (GFRP) bars and basalt fibers has shown promising results in terms of extending the service life of structures and reducing maintenance costs [170]. Reinforced geopolymer concrete has shown potential in seismic-resistant designs. Recent studies have explored the seismic behavior of reinforced geopolymer concrete members under various loading conditions, leading to the development of design guidelines for earthquake-resistant structures [172]. The enhanced ductility and crack resistance of geopolymer concrete, combined with effective reinforcement strategies, contribute to improved seismic performance and overall resilience.

Advancements in computational modeling and simulation techniques have revolutionized the design and analysis of reinforced geopolymer concrete structures. Finite element analysis (FEA) and advanced modeling tools enable engineers to predict structural responses, optimize reinforcement layouts, and assess the effects of different design parameters [173]. This computational approach expedites the design process and provides insights into the behavior of complex structural configurations. Recent advancements have extended beyond material enhancements to incorporate sustainable construction techniques. Additive manufacturing and 3D printing have been employed to fabricate intricate reinforcement layouts, allowing for customized and optimized reinforcement distribution [168]. These techniques not only enhance structural performance but also minimize material waste and energy consumption. In conclusion, recent advancements in various reinforced geopolymer concrete technologies have

redefined the possibilities of sustainable construction. From innovative reinforcement materials to hybrid systems, enhanced bond behavior, improved durability, seismic resilience, computational modeling, and cutting-edge construction techniques, these advancements collectively contribute to the evolution of reinforced geopolymer concrete as a transformative construction material. The integration of these advancements not only addresses traditional construction challenges but also aligns with the global drive for environmentally responsible and resilient infrastructure.

Chapter 3

Materials and Methodology

3.1 Overview:

Geopolymer concrete has emerged as a viable alternative, demonstrating the potential to contribute to a future characterized by enhanced environmental sustainability and optimized resource use. This chapter provides a comprehensive overview of the materials used in this study. The physical and chemical characteristics of the source materials and solutions used in the investigation have been provided in a tabular form. The mix of proportion of the geopolymer is discussed in later sections of this chapter. This chapter presents a concise overview of the process involved in preparing an alkaline solution, as well as the subsequent steps of mixing, casting, curing, and testing concrete. A comprehensive understanding of the constituents and their mixtures is crucial to harness the exceptional mechanical properties and sustainable attributes inherent in this novel construction material.

According to the findings presented in the literature study, it has been shown that the presence of SiO_2 and Al_2O_3 in a material is conducive to the development of geopolymer concrete. In this study the potential use of several materials, including fly ash, GGBS (Ground Granulated Blast Furnace Slag), and rice husk ash, for the development of geopolymer concrete were considered. The preliminary findings indicated favorable outcomes for the use of fly ash and GGBS, however the utilization of other materials did not provide similar results. The rice husk ash exhibited a silica content of 90 %, leading to the formation binder but the mortar and concrete retained their soft consistency for a duration of many weeks, without undergoing any solidification under any given environmental conditions. Therefore, materials with a SiO_2 / Al_2O_3 ratio ranging from 1.5 to 3 were used for this study. Subsequently, a decision was made to concentrate the investigation on the use of fly ash as the binding agent.

3.2 Materials used:

In this study, fly ash is used as source material for binder in geopolymer. The alkaline liquid used to activate the reaction was a mixture of NaOH and Na_2SiO_3 solutions. Water, fine aggregates, and coarse aggregates were also used similar to OPC concrete. Copper slag and crumb rubber is used as a partial replacement of fine aggregates whereas rubber aggregates of size 10-15 mm used as partial replacement of coarse aggregate.

3.2.1 Fly Ash:

IS 3812 categorizes fly ash into two categories, namely class C and class F, based on its CaO concentration. Class C fly ash contains a CaO content of more than 10 %, whereas Class F fly ash has a low CaO content. This difference in CaO content leads to improved binding of concrete. The current experimental study utilizes low calcium, Class F dry fly ash sourced from the Rayalaseema Thermal Power Plant in India as the primary component material is shown in **Fig 3.1**. The physical and chemical parameters conformed to the specified limitations outlined in IS 3812. The reference "IS 3812, 2013" is being mentioned. The fly ash used has a fineness of 325 m²/kg and a specific gravity of 2.20. The SiO₂/Al₂O₃ ratio in fly ash was determined to be 1.62. The chemical properties of the material were determined by the utilization of X-ray fluorescence, as demonstrated in **Table 3.1**.



Fig 3.1: Fly ash

Table 3.1 : Chemical Composition of Class F-Fly ash

Component	% Fly ash
SiO ₂	49.52
Al ₂ O ₃	29.83
Fe ₂ O ₃	10.76
CaO	3.58
MgO	1.6
Na ₂ O	0.32

TiO₂	1.89
P₂O₅	0.48
Mn₂O₃	0.2
SO₃	0.35
K₂O	-
Cu	-
LOI	1.5

3.2.2 Alkali-activated solution:

The alkaline solution utilized in this investigation included a mixture of NaOH solution and Na₂SiO₃ solution. As previously stated, fly ash is activated by the addition of an alkali-activated solution. Sodium hydroxide, commonly known as caustic soda, is extensively utilized in the paper, textile, soap, and detergent sectors. The substance is accessible in the forms of flakes, granules, pellets, or as a solution that is 50 % saturated. The NaOH pellets used in this study were acquired from P.K. Chemicals, located in Jalandhar. The **Fig 3.2** shows the NaOH pellets and alkali activator solution used in this study. The flakes were kept in a hermetically sealed container to prevent any exposure to atmospheric moisture. The NaOH solution was made by dissolving the flakes in a predetermined quantity of water. The dissolution of NaOH was a highly exothermic reaction, and great caution was exercised throughout the preparation of the solution to prevent any mishaps. The distributor has supplied specific information on the chemical composition of NaOH flakes, which is described in **Table 3.2**. In this study, the concentration of 8, 10, and 12 M of NaOH are used. The concentration of NaOH is determined by multiplying the molarity with molecular weight of the NaOH. For example, for 8 M concentration the mass of NaOH pellets used are $8 \times 40 = 320$ grams for 1 liter of iced tap water. Na₂SiO₃, often referred to as sodium silicate, is a substance that may be found in both clear and viscous liquid states, often known as water glass or liquid glass. This substance exhibits adhesive characteristics and has fire-resistant capabilities, it is often used in detergent manufacturing, glass production, paper production, and textile printing. It is obtained from the local dealer S.S. Chemical and minerals, Jalandhar. The chemical composition of the Na₂SiO₃ solution, which may be found in **Table 3.3**.

Table 3.2: Chemical Composition of NaOH pellets

Chemical Composition	Proportion
NaOH	98.3
Chloride	1.5
Carbonate (CO_3)	0.01
Silicates (SiO_2)	0.01
Nitrate (NO_3)	< 0.005



Fig 3.2: NaOH and Alkali activator solution

Table 3.3 : Chemical Composition of sodium silicate solution

Chemical Composition	Proportion
SiO ₂	30.5
Na ₂ O	9.6
H ₂ O	59.9
SiO ₂ / Na ₂ O	3.17

3.2.3 Aggregate:

The aggregates utilized in this investigation were acquired from a nearby source of concrete materials at the RMC facility in Jalandhar. The coarse and fine aggregates were obtained in a saturated surface dry (SSD) state, following the guidelines of IS 383-1970. Sand is a naturally occurring substance composed of finely split particles of rock and minerals. Silica, also known as Silicon dioxide (SiO₂), is the primary constituent of sand found in both inland continental habitats and non-tropical coastal areas. Quartz, the most abundant form of silica, is highly resistant to chemicals and has a high level of hardness, making it the most durable stone against weathering. It is frequently employed as a high-quality component in concrete. The river sand that was locally accessible and had a particle size less than 4.75 mm was utilized for this experimental study. The parameters of fine aggregates were determined according to the IS: 2386-1963 standard and are listed in **Table 3.4**. The results of the sieve analysis are shown in **Table 3.5**. **Figure 3.3** displays the gradation curve for the fine aggregate.

Table 3.4: Fine Aggregates Physical properties

Properties	Value
Water Absorption	0.6 %
Specific Gravity (G)	2.65

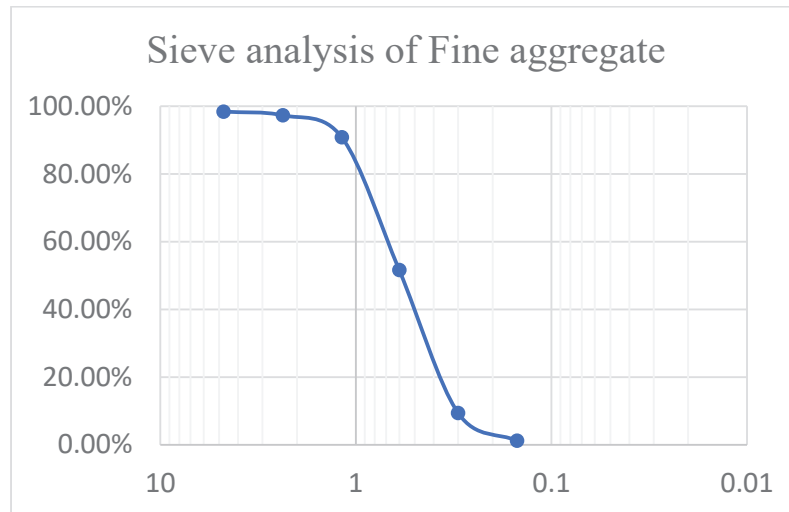


Fig 3.3 : Sieve Analysis of sand

Table 3.5: Sieve Analysis of sand

Sieve size(mm)	Weight Retained (gm)	% Passing
4.75	16	98.4
2.36	11	97.3
1.18	65	90.8
0.6	391	51.6
0.3	420	9.4
0.15microns	82	1.2
Total	1000	-

In most cases, the stone must be crushed before it can be used as coarse aggregate. In the course of our research, we determined that the maximum size of coarse aggregate available in the area should be between 10 and 20 mm. Locally available crushed granite stone aggregate of 20 mm maximum size was used as coarse aggregate. The coarse aggregate passing through 20mm and

retaining 4.75mm was used for experimental work. The following properties of coarse aggregates were determined as per IS: 383-1970 and given in Table 3.6 and sieve analysis were presented in a Table 3.7.

Table 3.6: Coarse Aggregates Physical properties

Properties	Value
Water Absorption (WA)	0.68
Specific Gravity (G)	2.76
Fineness Modules	6.76

Table 3.7: Sieve Analysis of Coarse Aggregate

S. No.	Size of Sieve (mm)	Retained Weight (g)	Retained Cumulative weight (g)	Retained Cumulative Percentage
1.	20	0.0	0.0	0.0
2.	10	2300	2300	76.6
3.	4.75	700	3000	100
4.	2.36	0	3000	100
5.	1.18	0	3000	100
6.	0.6	0	3000	100
7.	0.3	0	3000	100
8.	0.15	0	3000	100
		SUM	=	676.6

3.2.4 Copper Slag:

Copper slag is obtained as a secondary product in the course of copper smelting and refining. Currently, this slag is being utilized for the creation of abrasive powder, as well as for grit blasting, surface blast cleaning, and land filling purposes. Concrete particles have sizes that are similar to sand particles, which makes them appropriate for use as fine aggregate. The study

utilized sand obtained from Kalyan Industries, which is situated in Bhavnagar, India, as a substitute for a portion of the sand as shown in **Fig 3.4**. The manufacturer provides the chemical composition of copper slag, which is characterized by a significant concentration of iron, silica, and calcium as indicated in **Table 3.8**.

Table 3.8: Chemical Composition of Copper Slag

Component	% Copper slag
SiO₂	35.00
Al₂O₃	3.01
Fe₂O₃	55.00
CaO	0.20
MgO	0.90
Na₂O	0.95
TiO₂	0.60
P₂O₅	-
Mn₂O₃	-
SO₃	-
K₂O	1.02
Cu	0.42
LOI	-



Fig 3.4: Copper slag

3.2.5 Rubber:

The crumb rubber used in this study was sourced from a local rubber recycling facility in Jalandhar, India. The rubber was produced by crushing waste tire rubber. In order to get the necessary size of rubber, the crumb rubber is then filtered using a 4.75 mm sieve as shown in **Fig 3.5**.



Fig 3.5: Rubber aggregate

3.2.6 Pre-treatment of Crumb rubber with NaOH:

In accordance with prior research [19], crumb rubber was subjected to a 10 M NaOH solution for durations of 1 and 24 hours. Initially, the rubber is subjected to a thorough washing process under high pressure to effectively eliminate dirt and other extraneous substances, hence

enhancing the adhesion between rubber particles. Furthermore, the rubber is submerged in a NaOH solution with a pH level of 13 for the duration of the treatment. Ultimately, the rubber is extracted from the alkaline solution and rinsed with regular water in order to lower the pH level to a neutral state. This is done to mitigate the negative impact of the excessive alkaline solution on the characteristics of the mortar. The pre-treatment process effectively eliminates dirt and pollution from the outer surface of the rubber, resulting in the exposure of surface pores. The newly prepared adhesive paste has the ability to occupy these tiny openings, leading to enhanced adhesion and increased resistance to sliding for the rubber substance. Extended immersion of the rubber in a concentrated NaOH solution results in the elimination of the outer layer, which acts as a barrier between the rubber and binder, hence enhancing the adhesion between the aggregates and binder.

3.2.6 Glass fiber reinforced polymer (GFRP):

The glass fiber reinforced polymer (GFRP) bars are extensively used and acknowledged within the range of accessible fiber reinforced polymer (FRP) reinforcements. This is primarily due to their advantageous cost-to-performance ratio and their proven efficacy in diverse concrete constructions such as bridge deck slabs, barrier walls, parking garages, continuous pavement, and others. The GFRP bars used as reinforcement in the geopolymer concrete are sourced from Sanfield Limited, located near Bhopal, India as **Fig 3.6**. These bars are created by the pultrusion method, including the embedding of E-glass fibers with modified vinyl ester resin. This study used high-modulus glass fiber-reinforced polymer (GFRP) bars with a straight sand-coated surface. These bars have a nominal diameter of 12 and 16 mm. The bars in question are strengthened by the incorporation of continuous E-glass fibers, ensuring a minimum volume fraction of 65 %. The binding substance used is a modified vinyl ester, with a maximum volume fraction of 35 %. The qualities of the bars are primarily influenced by the features, quantities, and bonding interaction between the fibers and matrices. The bar's diameter, tensile strength, elastic modulus, and failure strain were assessed in accordance with the guidelines outlined in ACI 440.3R-04 (ACI 2004). **Table 3.9** provides a summary of the mechanical and physical parameters of the bar.



Fig 3.6: GFRP's bars

Table 3.9: Physical and mechanical parameters of the bar

Property	Type-1	Type-2
Diameter of the bar (mm)	12	16
Cross sectional area of the bar (mm ²)	113.1	201.06
Tensile strength (MPa)	1523.6	1234.10
Elastic modulus of the bar (GPa)	63.4	58.2
Tensile strain at failure (%)	2.4	2.12

3.3 Mix Design:

The current investigation involved substituting a portion of natural sand with copper slag and crumb rubber, and examining the impact of varied treatment durations of crumb rubber on the performance of mortar and concrete mixtures. The copper slag was partially substituted with crumbed rubber at varying percentages: 0, 10, 20, 30, 40, and 50 %. Additionally, the crumbed rubber was replaced at percentages of 5, 10, and 15 %. Multiple studies indicate that using more than 15 % rubber as a substitute in mortar results in a rigid and difficult to work with mixture, which is unable to attain the necessary strength for structural purposes. The pre-treatment of rubber for durations of 1 and 24 hours was selected due to the absence of any notable disparity in mortar performance when treated for 1 hour. However, extending the treatment period beyond 24 hours has a detrimental impact on the bond, as it increases the

porosity of the rubber aggregates. Hence, we will examine three classifications of crumb rubber: raw, treated for 1 hour, and treated for 24 hours. A variety of mixtures were created using different molarities of NaOH. Different SS/SH ratios were measured to get the appropriate fluidity and solidification time of the aggregates and binder.

The choice of mixture proportion involves a thorough assessment of various parameters. The primary objective of the mixture design is to achieve significant strength and durability in the final product. However, the selection of materials is also influenced by considerations of economics and sustainability. There is no specific code recommendation for the mix design of geopolymer mixture unlike OPC. This is primarily due to the lack of enough data to construct a reliable trend chart for the variation of several affecting components. Certain pre-made mixtures were formulated according to methods outlined in the existing literature to achieve a better understanding of their properties and strength. Utilizing both the information found in the literature and the results obtained from laboratory experiments, the following procedure was employed to determine the appropriate material proportions. The objective was to formulate a geopolymer concrete blend with a targeted average compressive strength of 35 N/mm². To accomplish this, the procedural steps outlined in **Table 3.10** were thoroughly observed during the trial phase.

Table 3.10: Mixture proportions of geopolymer mortar and concrete

Components (kg/m³)	Mortar	Concrete
Unit weight	2200	2500
Mass of the binder	1/3 of the unit weight = 733.33	400
Mass of alkaline solution	40 % of total binder = 294	40 % of total binder = 160
Mass of total aggregate	Unit weight – Mass of binder and alkaline solution = 2200 – 735 – 300 = 1165	Unit weight – Mass of binder and alkaline solution = 2500 – 400 – 160 = 1940

Mass of fine aggregate	1165	35 % of total aggregate = 675
Mass of coarse aggregate	Not applicable	= Mass of total aggregate – mass of fine aggregate = 1940 – 675 = 1265

Firstly, in the mechanical mixer, fly ash is mixed with aggregates, copper slag, and rubber in the dry state for 2 minutes, and then alkali activator solution is added to the mixer along with excess water needed for the mix and thoroughly mixed for 5 minutes. After obtaining the homogenous mix, the mixture is transferred to moulds and properly compacted. The specimens are demoulded after one day and placed for curing under ambient conditions for a desirable period. Previous research shows that heat curing results in high performance in geopolymer specimens, but ambient curing is preferred because of less shrinkage, energy efficiency, and fewer surface cracks.

The following methodology was employed to give the designations for various mixture proportions such as

For mortar sample : GMCxCrYSHz

Where GM: Geopolymer mortar,

Cx: Various proportions of Copper slag,

CRy: Various proportions crumb rubber,

SHz: Ratio of Sodium silicate to Sodium hydroxide.

For concrete sample: GCCxCrYSHz

Where GC: Geopolymer concrete,

Cx: Various proportions of Copper slag,

CRy: Various proportions rubber,

SHz: Ratio of Sodium silicate to Sodium hydroxide.

Table 3.11 Mix proportions of various geopolymers mixes with acronym

S.No	Composition	Acronym
	GM: Geopolymer mortar	
1	Copper slag 0%, SS/SH ratio 1.	GMC0SH1
2	Copper slag 0%, SS/SH ratio 2.	GMC0SH2
3	Copper slag 0%, SS/SH ratio 3.	GMC0SH3
4	Copper slag 10%, SS/SH ratio 1.	GMC10SH1
5	Copper slag 20%, SS/SH ratio 1.	GMC20SH1
6	Copper slag 30%, SS/SH ratio 1.	GMC30SH1
7	Copper slag 40%, SS/SH ratio 1.	GMC40SH1
8	Copper slag 50%, SS/SH ratio 1.	GMC50SH1
9	Copper slag 10%, SS/SH ratio 2.	GMC10SH2
10	Copper slag 20%, SS/SH ratio 2.	GMC20SH2
11	Copper slag 30%, SS/SH ratio 2.	GMC30SH2
12	Copper slag 40%, SS/SH ratio 2.	GMC40SH2
13	Copper slag 50%, SS/SH ratio 2.	GMC50SH2
14	Copper slag 10%, SS/SH ratio 3.	GMC10SH3
15	Copper slag 20%, SS/SH ratio 3.	GMC20SH3
16	Copper slag 30%, SS/SH ratio 3.	GMC30SH3
17	Copper slag 40%, SS/SH ratio 3.	GMC40SH3
18	Copper slag 50%, SS/SH ratio 3.	GMC50SH3
19	Copper slag 0%, Crumb rubber 5%, SS/SH ratio 2.	GMC0CR5SH2
20	Copper slag 0%, Crumb rubber 10%, SS/SH ratio 2.	GMC0CR10SH2
21	Copper slag 0%, Crumb rubber 15%, SS/SH ratio 2.	GMC0CR15SH2
22	Copper slag 30%, Crumb rubber 5%, SS/SH ratio 2.	GMC30CR5SH2
23	Copper slag 30%, Crumb rubber 10%, SS/SH ratio 2.	GMC30CR10SH2
24	Copper slag 30%, Crumb rubber 15%, SS/SH ratio 2.	GMC30CR15SH2
25	Copper slag 40%, Crumb rubber 5%, SS/SH ratio 2.	GMC40CR5SH2
26	Copper slag 40%, Crumb rubber 10%, SS/SH ratio 2.	GMC40CR10SH2
27	Copper slag 40%, Crumb rubber 15%, SS/SH ratio 2.	GMC40CR15SH2
28	Copper slag 50%, Crumb rubber 5%, SS/SH ratio 2.	GMC50CR5SH2
29	Copper slag 50%, Crumb rubber 10%, SS/SH ratio 2.	GMC50CR10SH2
30	Copper slag 50%, Crumb rubber 15%, SS/SH ratio 2.	GMC50CR15SH2
	GC: Geopolymer concrete	
31	Copper slag 0%, SS/SH ratio 1.	GCC0SH1
32	Copper slag 0%, SS/SH ratio 2.	GCC0SH2
33	Copper slag 0%, SS/SH ratio 3.	GCC0SH3
34	Copper slag 10%, SS/SH ratio 1.	GCC10SH1
35	Copper slag 20%, SS/SH ratio 1.	GCC20SH1
36	Copper slag 30%, SS/SH ratio 1.	GCC30SH1
37	Copper slag 40%, SS/SH ratio 1.	GCC40SH1
38	Copper slag 50%, SS/SH ratio 1.	GCC50SH1
39	Copper slag 10%, SS/SH ratio 2.	GCC10SH2
40	Copper slag 20%, SS/SH ratio 2.	GCC20SH2
41	Copper slag 30%, SS/SH ratio 2.	GCC30SH2
42	Copper slag 40%, SS/SH ratio 2.	GCC40SH2
43	Copper slag 50%, SS/SH ratio 2.	GCC50SH2

44	Copper slag 10%, SS/SH ratio 3.	GCC10SH3
45	Copper slag 20%, SS/SH ratio 3.	GCC20SH3
46	Copper slag 30%, SS/SH ratio 3.	GCC30SH3
47	Copper slag 40%, SS/SH ratio 3.	GCC40SH3
48	Copper slag 50%, SS/SH ratio 3.	GCC50SH3
49	Copper slag 0%, Crumb rubber 5%, SS/SH ratio 2.	GCC0CR5SH2
50	Copper slag 0%, Crumb rubber 10%, SS/SH ratio 2.	GCC0CR10SH2
51	Copper slag 0%, Crumb rubber 15%, SS/SH ratio 2.	GCC0CR15SH2
52	Copper slag 30%, Crumb rubber 5%, SS/SH ratio 2.	GCC30CR5SH2
53	Copper slag 30%, Crumb rubber 10%, SS/SH ratio 2.	GCC30CR10SH2
54	Copper slag 30%, Crumb rubber 15%, SS/SH ratio 2.	GCC30CR15SH2
55	Copper slag 40%, Crumb rubber 5%, SS/SH ratio 2.	GCC40CR5SH2
56	Copper slag 40%, Crumb rubber 10%, SS/SH ratio 2.	GCC40CR10SH2
57	Copper slag 40%, Crumb rubber 15%, SS/SH ratio 2.	GCC40CR15SH2
58	Copper slag 50%, Crumb rubber 5%, SS/SH ratio 2.	GCC50CR5SH2
59	Copper slag 50%, Crumb rubber 10%, SS/SH ratio 2.	GCC50CR10SH2
60	Copper slag 50%, Crumb rubber 15%, SS/SH ratio 2.	GCC50CR15SH2

3.4 Tests:

3.4.1 Fresh Properties:

3.4.1.1 Flow value test: In accordance with ASTM C1437, a flow table test was performed to assess the workability of the new mortar. A newly mixed mortar is poured into a mold fashioned like a cone, which is placed on top of a table designed to measure the flow of materials. Subsequently, the mould is elevated to enable the uninterrupted flow of mortar. The flow table is elevated to a height of 13 mm and thereafter released 25 times within a duration of 15 seconds. The spread mortar diameter (d) is the average of two fully spread mortar diameters that are perpendicular to each other as shown in **Fig 3.7**. The flow value is equal to the difference between the diameter (d) and the base diameter of the cone.

3.4.1.2 Initial and Final setting time: According to ASTM C191, the setup was altered to enable the measurement of setting time using a Vicat needle. The needle's diameter used was 1.00 ± 0.05 mm.

3.4.1.3 Density: ASTM C642 specifies that density is determined by oven drying the sample for 1 day at a temperature of 110 ± 5 °C, allowing it to cool down, and then measuring its weight. This process is carried out for a curing duration of 28 days.

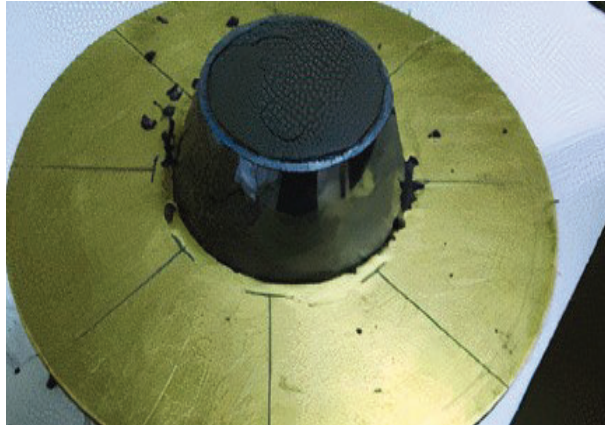


Fig 3.7: Flow table test

3.4.1.4 Water absorption: In order to evaluate the durability of the mortar sample, we examine both its initial and ultimate water absorption. After a 28-day curing period, the water absorption is determined according to ASTM C642 by immersing the sample in water for 0.5 and 48 hours, respectively.

3.4.2 Mechanical Properties:

3.4.2.1 For mortar: The cube-shaped molds with dimensions of 50 mm were used to assess the compressive strength of Geopolymer mortars (GPMs). The measurement was conducted according to the ASTM C109/109M standard. The control mortar strengths were utilized to assess and examine the strengths of the GPM sample as shown in **Table 3.8**. The sample's compressive strength was evaluated at 7, 28, and 90-day intervals. The results are provided following the computation of three distinct means on the samples.

3.4.2.2 For concrete:

The geopolymer concrete was tested for compressive strength of cubes of size 150*150*150 mm, split tensile strength of size 150 mm diameter and 300 mm cylinder specimens, flexural strength of size 100*100*500 mm beam specimens are used in this study as per Indian standard IS:516- 1959. The compressive strength of the sample was tested for 7, 28, and 90 days curing whereas split tensile and flexural strength was tested for 28 days curing. The findings are presented after calculating three separate averages on the samples. Fig 3.9 shows the concrete samples used for this study.

3.4.3 Durability properties:

3.4.3.1 Sorptivity test: According to ASTM C1585- 04, the sorptivity test was conducted. The capillary force that the pore structure of the concrete utilizes to suck fluids into the concrete's core is known as sorptivity. The test was conducted using concrete slices that were 50 mm thick and 100 mm in diameter. The original mass of the specimen was collected after the sides were waxed and sealed with a plastic sheet. After that, the specimen was stored in a tray with 2 to 5 mm of its depth submerged in water. After removing and blotting off the extra surface water, the specimen's mass was then measured after one minute, five minutes, ten minutes, twenty minutes, thirty minutes, one hour, two hours, three hours, four hours, five hours, and six hours. The sorptivity value was calculated using the equation $s = I/t^{1/2}$, where s is the sorptivity in mm/min, t is the elapsed time in min, and I is the cumulative absorption determined by $I = m/Ad$, where m is the increase in mass, A is the specimen surface area through which water penetrates, and d is the density of the medium, i.e. water. The cumulative absorption values were plotted against the square root of time, and the slope of the plot's best-fitting line was used to determine the sorptivity.

3.4.3.2 Rapid chloride permeability test: According to ASTM C1202-97, the Rapid Chloride Permeability Test (RCPT) was carried out. This test quickly measures the concrete's electrical conductivity in relation to how well it resists chloride ion penetration. After 28 days from the date of casting, cylindrical specimens of 100 mm in diameter and 50 mm in thickness were employed for this test. Across the ends of the specimen, a potential difference of 60 V persisted for around 6 hours. The device had two ends, one attached to a cell holding a 0.3 N sodium hydroxide solution and the other to a cell containing a 3 % sodium chloride solution. For up to six hours, the specimen's current flow was monitored every 30 minutes. Temperature and chloride contamination were both observed. The total charge transmitted through the specimens was computed in coulombs using the current and time readings and was correlated to the specimen's resistance to chloride ion penetration. The permeability of the specimen increases with the total charge transmitted.

3.5 Bond properties:

Various tests are employed to examine the bond behavior between reinforcing bars and concrete, including pullout tests, beam-end tests, beam anchorage, and splice tests. In this study, the pullout test was selected due to its straightforward fabrication, repeatability, and effectiveness for comparative analysis. This test is primarily utilized to assess the bond strength

of different materials under consistent conditions. It involves a reinforcement bar centrally positioned on vertical direction within a concrete. Each bar, measuring 1,000 mm in length with specialized anchorage at one end to prevent premature failure, was embedded in a 150*150*150 mm concrete cube. The embedment lengths varied as three, six, and nine times the diameter of the bar. For each embedment length, three nominally identical specimens were tested using a universal testing machine. The GFRP bar was embedded to a depth of 100 mm, providing a 50 mm cover of geopolymer concrete. A connector plate was affixed to the end of the bar to facilitate attachment to the testing apparatus. The bond properties of the reinforced concrete were evaluated after a curing period of 28 days.



Fig 3.10 Bond properties of concrete

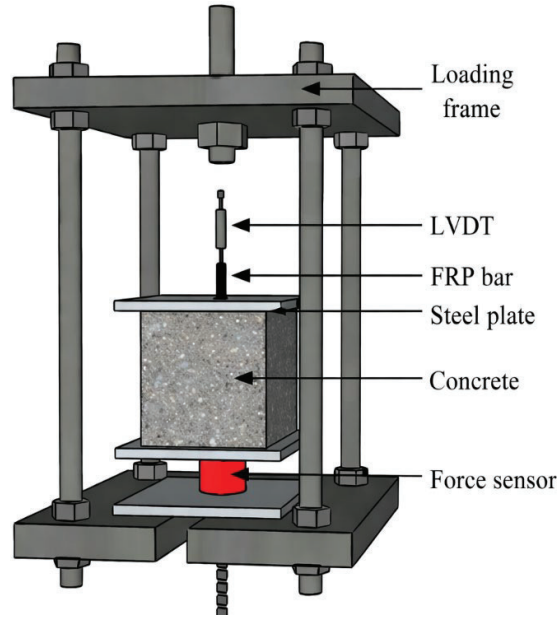


Fig 3.11 Test setup for bond strength

The average bond strength is defined as the shear force exerted per unit surface area of the bar. In this analysis, the average bond strength, derived from the peak pullout load, is considered to represent the ultimate bond strength between the two materials. This definition and calculation method for average bond strength are consistently applied throughout the analysis.

$$\tau = \frac{P}{\pi L_b d_b} \quad (3.1)$$

where τ = average bond strength, in megapascals; P = applied maximum pullout load, in Newtons; d_b = nominal diameter of the bar, in millimeters; and L_b = bonded/embedded length, in millimeters.

Chapter 4

Results and Discussion

4.1 Overview:

This chapter provides the detail discussion on the performance of geopolymer mortar and concrete for various mix proportions in term of physical, mechanical and chemical strength using experimental findings.

In this investigation natural materials (aggregates) are substituted by waste materials (copper slag and rubber) individually and combinedly in creating the concrete mix to analyse the optimum mix design of the geopolymer. The physical characteristics of the materials are discussed in chapter 3. The fresh, mechanical, durable, microstructural and bond properties along with cost analysis are discussed in this chapter. The assessment of the mentioned properties through various tests such as setting time, workability, compressive strength, split tensile strength, flexural strength, sorptivity, and rapid chloride ion penetration are presented. The bond strength characteristics of the geopolymer concrete with steel and GFRP's are also studied. The application of GFRP as replacement to steel in concrete is validated by modeling techniques and the results are discussed.

4.2 Fresh properties:

4.2.1 Setting time of mortar sample:

Setting times of geopolymer mortar are studied in research to understand the material's workability and the time required for transport, placing, and compacting, which are critical for ensuring efficient construction processes and achieving desired structural properties. Additionally, these studies help in optimizing the mix design by adjusting factors such as the proportions of binder materials and the molarity of the alkaline solution, which influence the setting behavior and final strength of the geopolymer mortar. **Table 4.1** provides a thorough analysis of how varied ratios of sodium silicate to sodium hydroxide (SS/SH) and variable molarities of NaOH affect the setting times of standard geopolymer mortar. The mortar sample, which has an SS/SH ratio of 1 and a NaOH molarity of 8 M, exhibits initial and final setting times of 425 and 670 minutes, respectively. As the SS/SH ratio improves, there is a clear decrease in both the time it takes for the material to initial set and the time it takes for it to finally set. More precisely, the time it takes for the first setting of the material is lowered to

335 minutes when the SS/SH ratio is 2, and to 215 minutes when the ratio is 3. Similarly, the time it takes for the final setting decreases to 486 minutes and 442 minutes for the same ratios. The decrease in setting time is mainly due to the higher concentration of soluble silica, which improves the alkali activation process and accelerates the rate of hardening of the material. In addition, increasing the concentration of NaOH also reduces both the initial and final setting times. When the concentration of NaOH is increased from 10 M to 12 M, the initial setting time decreases from 356 minutes to 305 minutes, and the final setting time decreases from 498 minutes to 456 minutes. These changes occur when the SS/SH ratio is 1. With an SS/SH ratio of 2, the initial setting times reduce to 298 minutes and 265 minutes, while the final setting times decrease to 416 minutes and 378 minutes. With an SS/SH ratio of 3, the initial setting times are decreased to 196 minutes and 174 minutes, and the final setting times are decreased to 351 minutes and 327 minutes, as shown in **Fig 4.1 and 4.2**. The increase in setting times can be attributed to the elevated alkalinity resulting from a greater concentration of NaOH, which enhances the dissolving of aluminosilicate components in fly ash. The process of dissolution releases alumina and silica ions into the mixture, hence improving the geopolymerization process. As the concentration of these ions rises, the rate of geopolymerization intensifies, resulting in accelerated solidification of the mortar. Moreover, the elevated concentration of hydroxide ions (OH^-) resulting with greater NaOH molarity accelerates the polymerization process of the dissolved silica and alumina, hence contributing in the formation of the geopolymer matrix. The presence of this matrix has significance for accelerating the process of both the hardening and strengthening of the mortar, leading to a substantial decrease in the time required for the mortar to set.

Table 4.1: Initial setting time of conventional geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1,2 and 3.

Mixes	Initial setting time (min)			Final setting time (min)		
	8 M	10 M	12 M	8 M	10 M	12 M
GMC0SH1	425	356	305	670	498	456
GMC0SH2	335	298	265	486	416	378
GMC0SH3	215	196	174	442	351	327

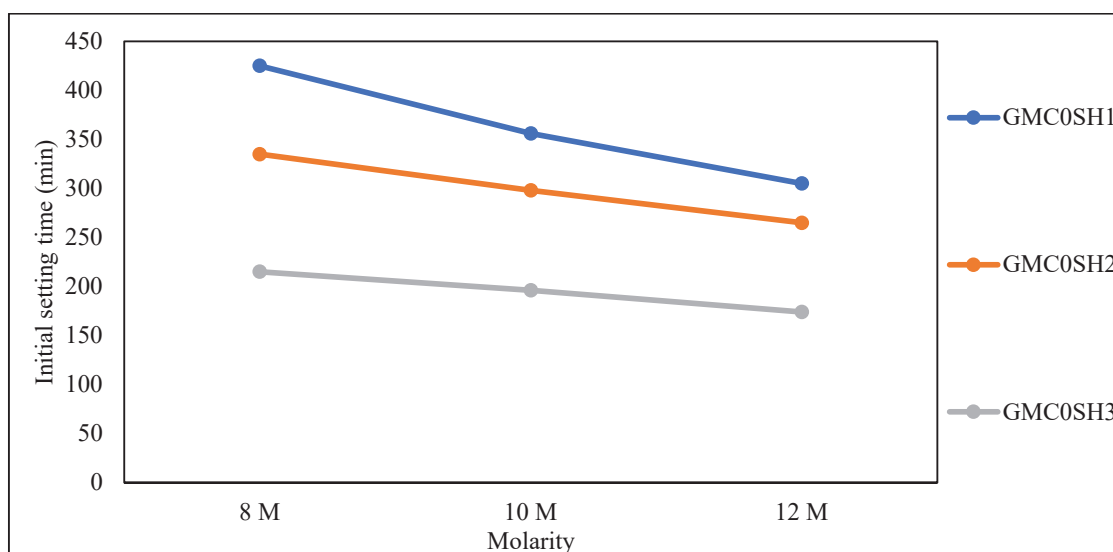


Fig 4.1: Initial setting time of conventional geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1,2 and 3.

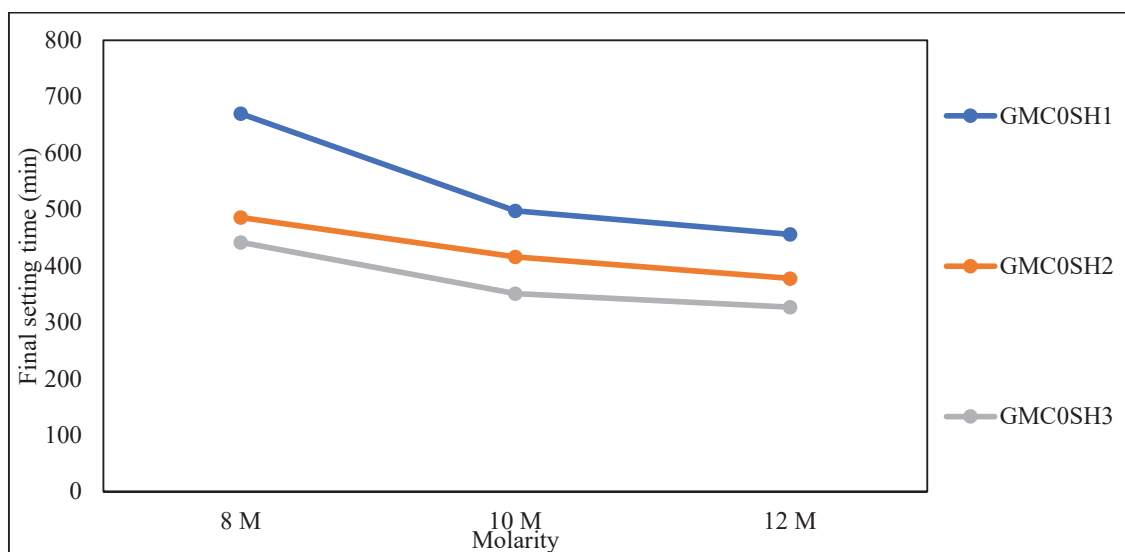


Fig 4.2: Final setting time of conventional geopolymer mortar with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 1, 2 and 3.

The setting times of geopolymer mortar, with the substitution of fine aggregates by copper slag in increments of 10, 20, 30, 40, and 50 %, were thoroughly assessed. **Table 4.2** provides a thorough analysis of how varied ratios of sodium silicate to sodium hydroxide (SS/SH) and

variable molarities of NaOH affect the initial and final setting times of copper slag-based geopolymer mortar.

Observations showed that the initial setting times of a geopolymer mortar with an SS/SH ratio of 1 decreased as the copper slag concentration and NaOH molarity increased. More precisely, when the molarity of NaOH was 8 M, the initial setting time decreased from 382 minutes when 10 % copper slag was added to 309 minutes when 50 % copper slag was added. For a 10 M NaOH concentration, the initial setting times varied between 315 minutes when adding 10 % copper slag and 234 minutes when adding 50 % slag. In addition, when the molarity of NaOH was increased to 12 M, the initial setting times decreased from 210 minutes for a 10 % addition to 172 minutes for a 50 % addition. The final setting times showed a similar pattern. When the molarity of NaOH was increased to 8 M, the final setting times decreased from 548 minutes when adding 10 % copper slag to 472 minutes while adding 50 % slag. The final setting times varied from 371 minutes for a 10 % addition to 285 minutes for a 50 % addition, using a NaOH solution with a molarity of 10 M. When the molarity of NaOH was increased to 12 M, the final setting times decreased from 311 minutes for a 10 % addition to 252 minutes for a 50 % addition, as shown in **Fig 4.3 and 4.4**.

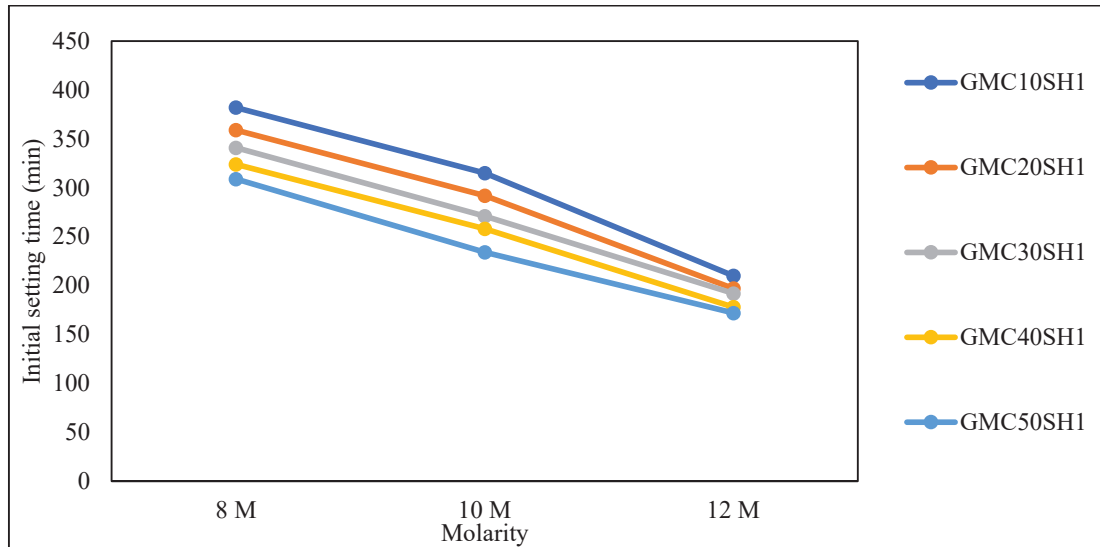


Fig 4.3: Initial setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1.

Table 4.2: Initial and final setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1, 2 and 3.

Mixes	Initial setting time (min)			Final setting time (min)		
	8 M	10 M	12 M	8 M	10 M	12 M
GMC10SH1	382	315	210	548	371	311
GMC20SH1	359	292	197	534	354	303
GMC30SH1	341	271	192	512	327	292
GMC40SH1	324	258	178	498	304	287
GMC50SH1	309	234	172	472	285	252
GMC10SH2	291	228	153	338	282	229
GMC20SH2	263	209	142	321	257	210
GMC30SH2	247	197	138	304	235	192
GMC40SH2	229	173	124	294	212	159
GMC50SH2	217	159	123	271	182	145
GMC10SH3	183	157	102	312	252	218
GMC20SH3	167	139	96	292	247	182
GMC30SH3	142	119	82	267	227	157
GMC40SH3	127	105	78	254	174	149
GMC50SH3	110	92	63	235	157	132

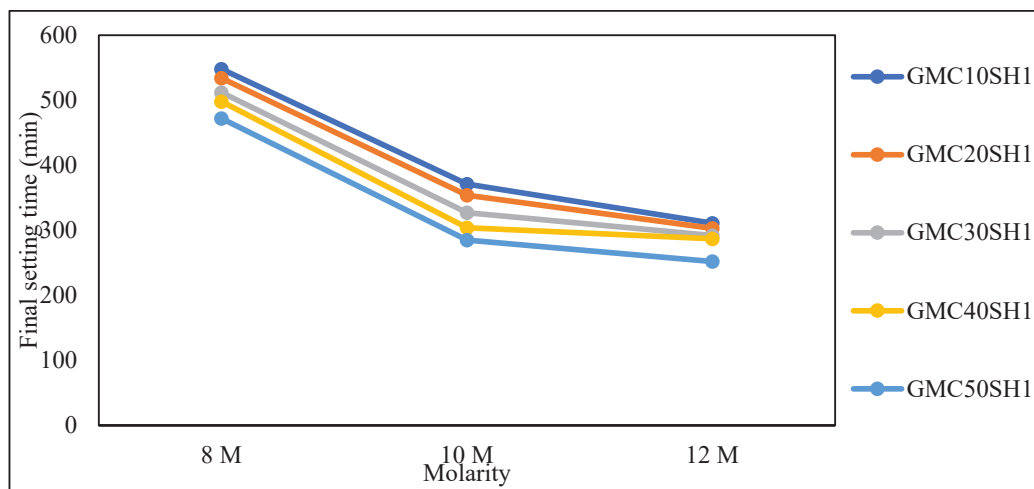


Fig 4.4: Final setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1.

The initial setting times of a geopolymer mortar with an SS/SH ratio of 2 were found to vary based on the molarity of NaOH and the quantity of copper slag provided. At a molarity of 8 M NaOH, the initial setting times decreased from 291 minutes when 10 % copper slag was added to 217 minutes when 50 % copper slag was added. At a molarity of 10 M NaOH, the durations varied from 228 minutes for a 10 % addition to 159 minutes for a 50 % addition. In addition, when the molarity of NaOH was 12 M, the initially setting times were further decreased. The initial setting time was 153 minutes for a 10 % addition and decreased to 123 minutes for a 50 % addition. The final duration of the settings adhered to a comparable trend. When the molarity of NaOH was increased to 8 M, the final setting times decreased from 338 minutes when adding 10% copper slag to 271 minutes while adding 50 % slag. The final setting times varied from 282 minutes for a 10 % addition to 182 minutes for a 50 % addition, using a NaOH solution with a molarity of 10 M. The final setting times decreased from 229 minutes to 145 minutes when the molarity of NaOH was increased from 10 to 50 %, as shown in **Fig 4.5 and 4.6**.

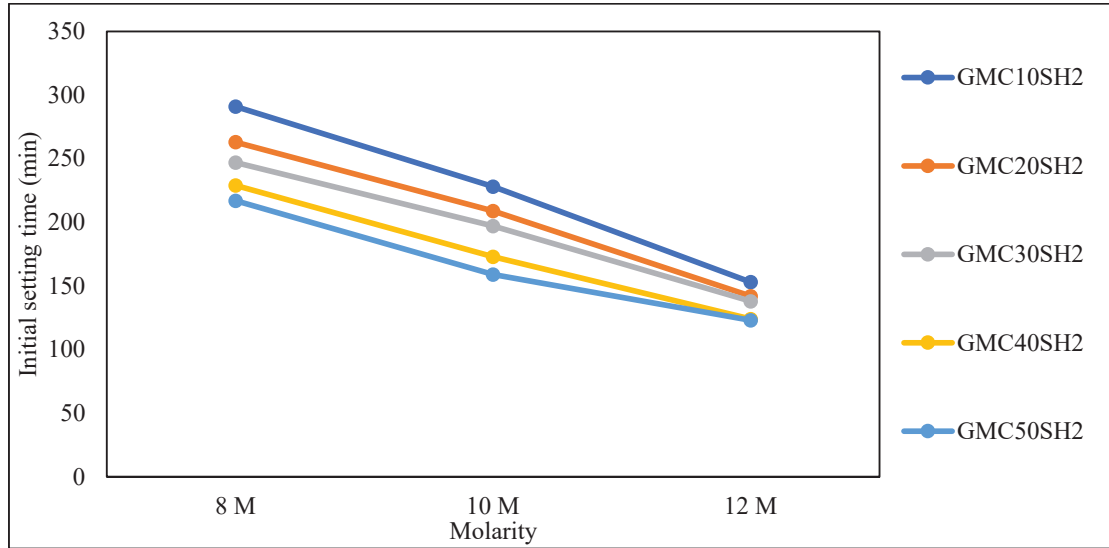


Fig 4.5: Initial setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 2.

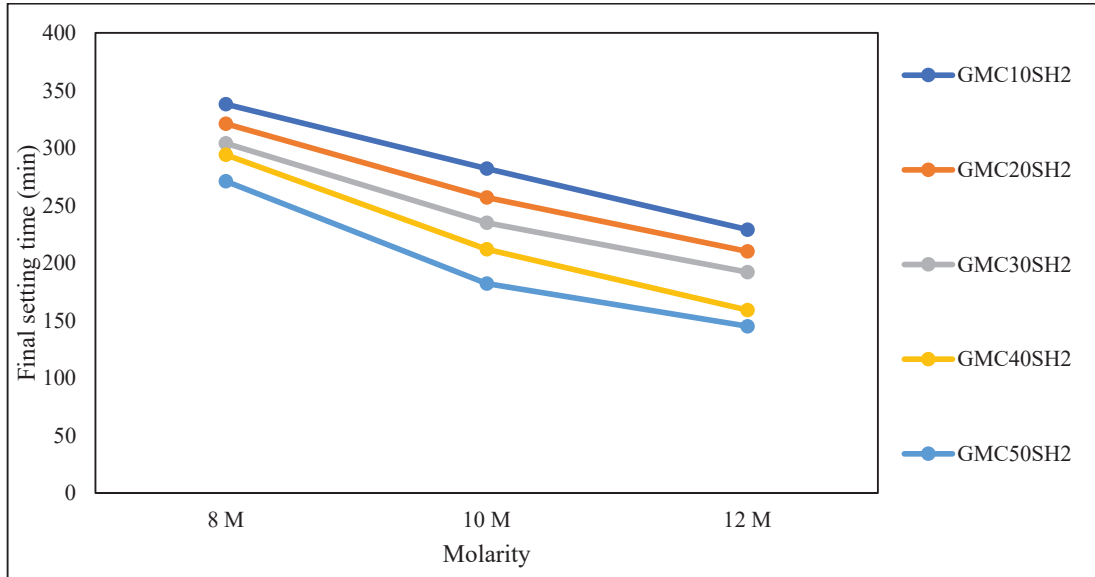


Fig 4.6: Final setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 2.

In a geopolymer mortar with an SS/SH ratio of 3, the initial setting times were systematically recorded across different NaOH molarities and copper slag percentages. Specifically, at an 8 M NaOH molarity, the initial setting times decreased from 183 minutes with a 10 % copper slag addition to 110 minutes with a 50 % addition. At a 10 M NaOH molarity, these times ranged from 157 minutes for a 10 % addition to 92 minutes for a 50 % addition. Furthermore, at a 12 M NaOH molarity, the initial setting times further reduced, starting at 102 minutes for a 10 % addition and reaching 63 minutes for a 50 % addition. The final setting times followed a similar pattern. At an 8 M NaOH molarity, the final setting times decreased from 312 minutes for a 10 % copper slag addition to 235 minutes for a 50 % addition. With a 10 M NaOH molarity, the final setting times ranged from 252 minutes for a 10 % addition to 157 minutes for a 50 % addition. At a 12 M NaOH molarity, the final setting times were observed to decrease from 218 minutes for a 10 % addition to 132 minutes for a 50 % addition, as illustrated in **Fig 4.7 and 4.8**.

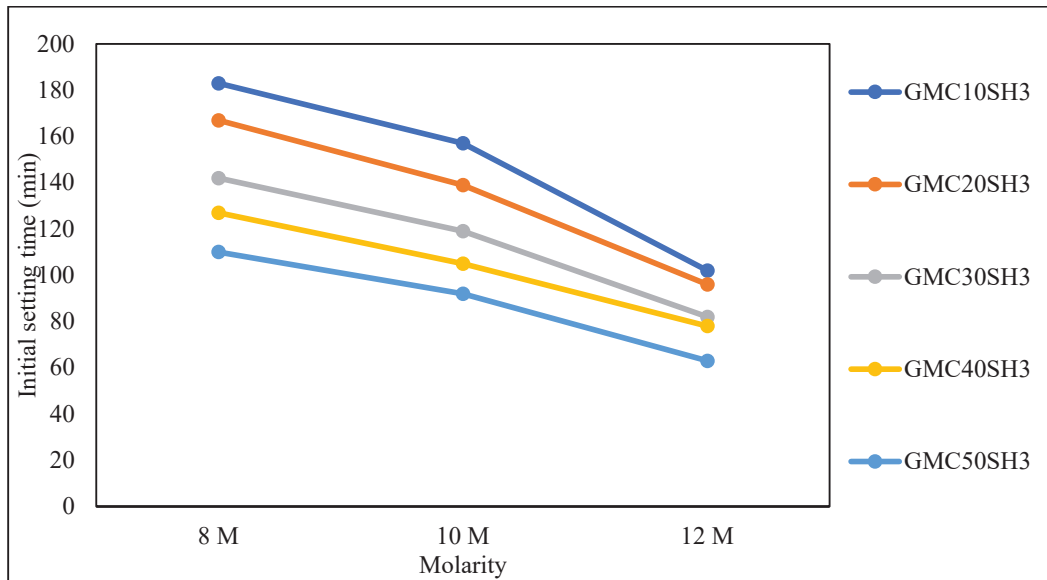


Fig 4.7: Initial setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 3.

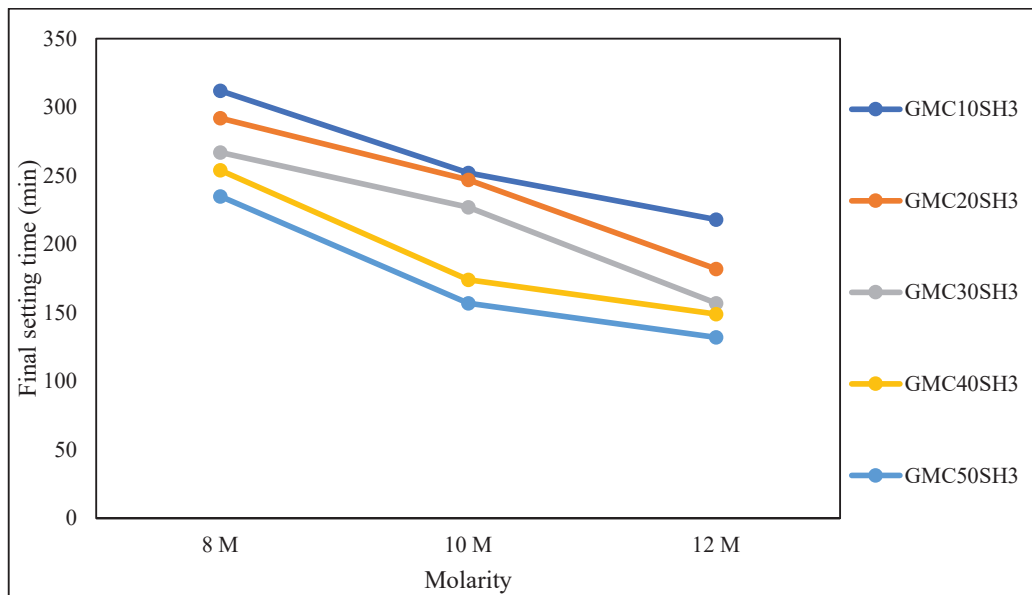


Fig 4.8: Final setting time of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 3.

The incorporation of copper slag as a partial replacement for fine aggregate significantly influences the physical properties of the mixture. Copper slag possesses a higher density and specific gravity compared to conventional fine aggregates, leading to a denser arrangement

within the mortar mix. This enhanced density may reduce the porosity of the mix, potentially accelerating the geopolymerization process and consequently shortening the setting times. Furthermore, the addition of copper slag, coupled with the utilization of higher concentrations of NaOH, is expected to improve the uniformity and compactness of the microstructure within the geopolymer matrix. Such advancements in microstructural development are likely to facilitate a more efficient geopolymerization process, thereby contributing to shorter setting times.

4.2.2 Flow values of mortar sample:

Flow value studies of geopolymer mortar are conducted in research to assess the workability of the mortar mixtures, which is crucial for ensuring proper mixing, placement, and compaction of the mortar in construction applications. These studies help in understanding how various factors, such as the type of materials used (e.g., fly ash, slag, crumb rubber), alkali activator concentration, and the ratio of sodium silicate to sodium hydroxide, influence the fluidity and ease of handling of geopolymer mortars. The workability of the mortar mix was evaluated using a flow table test, which quantified the flow as a percentage. The impact of varying sodium silicate to sodium hydroxide (SS/SH) ratios and different NaOH molarities on the initial and final setting times of conventional geopolymer mortar is detailed in **Table 4.3**.

For a mortar sample with an SS/SH ratio of 1 and an NaOH molarity of 8 M, the flow value was recorded at 142 mm. An increase in the SS/SH ratio led to a reduction in flow value, with measurements of 99 mm and 78 mm for SS/SH ratios of 2 and 3, respectively. This reduction is attributed to changes in the mixture's viscosity. As the ratio of sodium silicate to sodium hydroxide increases, the overall viscosity of the geopolymer mortar mix also rises because sodium silicate possesses a higher viscosity compared to sodium hydroxide. This increased viscosity limits the mortar's flowability, resulting in decreased flow values.

Furthermore, a rise in NaOH concentration was observed to reduce flow values. For NaOH concentrations of 10 M and 12 M, the flow value decreased to 132 mm and 130 mm, respectively, when the SS/SH ratio was 1. With an SS/SH ratio of 2, the flow values were further reduced to 103 mm and 95 mm. For an SS/SH ratio of 3, the flow values were diminished to 82 mm and 91 mm, respectively, in comparison with an NaOH molarity of 8 M, as illustrated in **Fig 4.9**. The increase in NaOH molarity enhances the viscosity of the alkaline activator solution. This higher viscosity yields a stiffer mixture that exhibits reduced flowability.

Table 4.3: Flow value of conventional geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1,2 and 3.

Mixes- Flow value (mm)	8 M	10 M	12 M
GMC0SH1	142	132	130
GMC0SH2	99	103	95
GMC0SH3	78	82	81

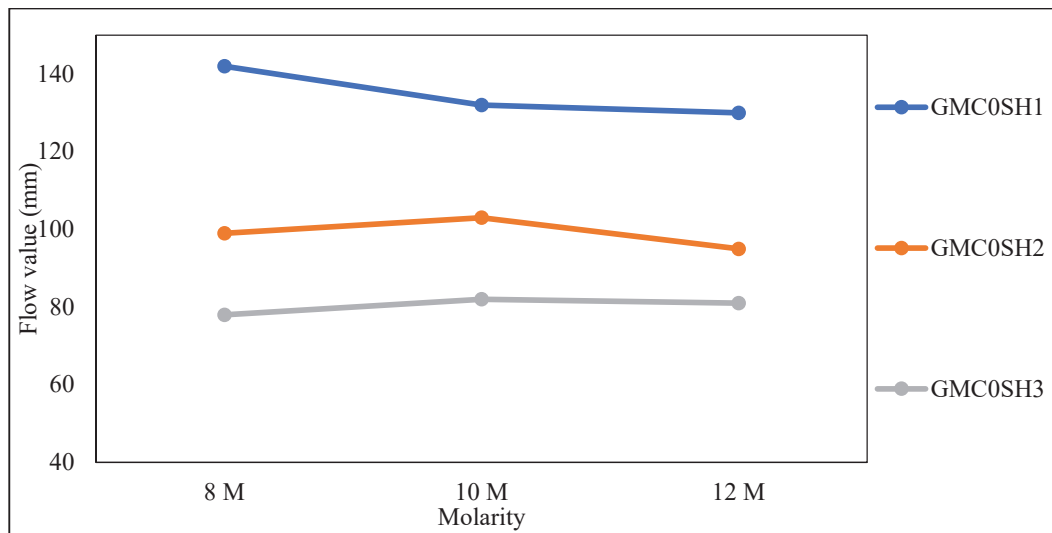


Fig 4.9: Flow value of conventional geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1,2 and 3.

The flow values of geopolymer mortar, with the substitution of fine aggregates by copper slag in increments of 10, 20, 30, 40, and 50 %, were thoroughly assessed. **Table 4.4** provides a thorough analysis of how varied ratios of sodium silicate to sodium hydroxide (SS/SH) and variable molarities of NaOH affect the initial and final setting times of copper slag-based geopolymer mortar.

Observations showed that the flow values of a geopolymer mortar with an SS/SH ratio of 1 decreased as the copper slag concentration and NaOH molarity increased. More precisely, when the molarity of NaOH was 8 M, the flow value decreased from 123 mm when 10 % copper slag was added to 101 mm when 50 % copper slag was added. For a 10 M NaOH

concentration, the flow values varied between 128 mm when adding 10 % copper slag and 108 mm when adding 50 % slag. In addition, when the molarity of NaOH was increased to 12 M, the flow value decreased from 137 mm for a 10 % addition to 112 mm for a 50 % addition as shown in **Fig 4.10**.

Table 4.4: Flow value of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1, 2 and 3.

Mixes – Flow value (mm)	8 M	10 M	12 M
GMC10SH1	123	128	137
GMC20SH1	115	123	132
GMC30SH1	113	116	128
GMC40SH1	106	110	124
GMC50SH1	101	108	112
GMC10SH2	93	99	94
GMC20SH2	93	98	92
GMC30SH2	89	94	85
GMC40SH2	87	87	83
GMC50SH2	85	83	80
GMC10SH3	79	78	75
GMC20SH3	75	73	71
GMC30SH3	72	67	67
GMC40SH3	69	64	63
GMC50SH3	66	59	58

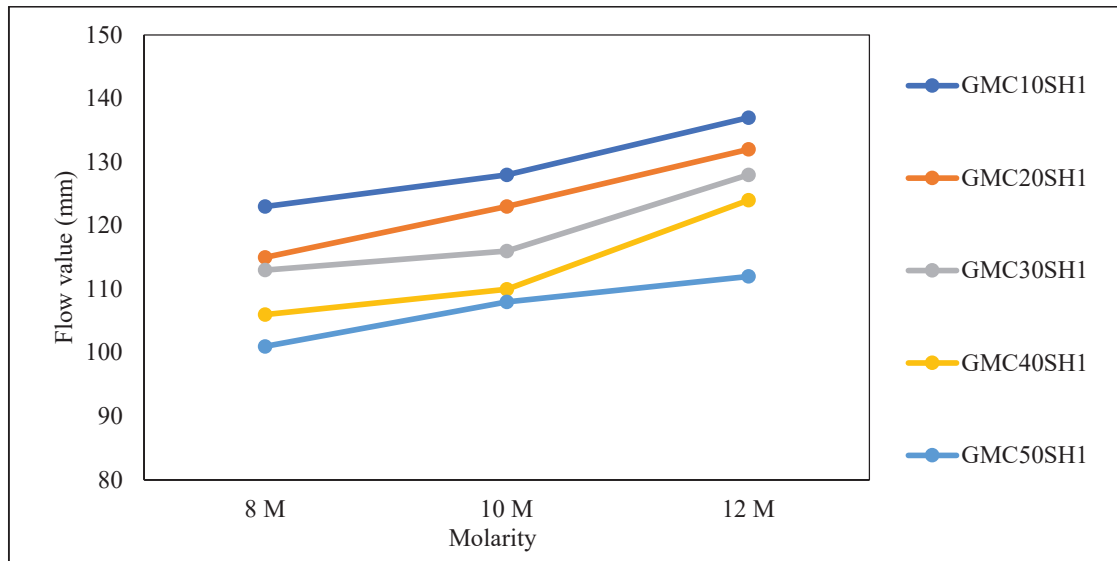


Fig 4.10: Flow value of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 1.

Observations showed that the flow values of a geopolymer mortar with an SS/SH ratio of 2 decreased as the copper slag concentration and NaOH molarity increased. More precisely, when the molarity of NaOH was 8 M, the flow value decreased from 79 mm when 10 % copper slag was added to 66 mm when 50 % copper slag was added. For a 10 M NaOH concentration, the flow values varied between 99 mm when adding 10 % copper slag and 83 mm when adding 50 % slag. In addition, when the molarity of NaOH was increased to 12 M, the flow values decreased from 94 mm for a 10 % addition to 80 mm for a 50 % addition as shown in **Fig 4.11**.

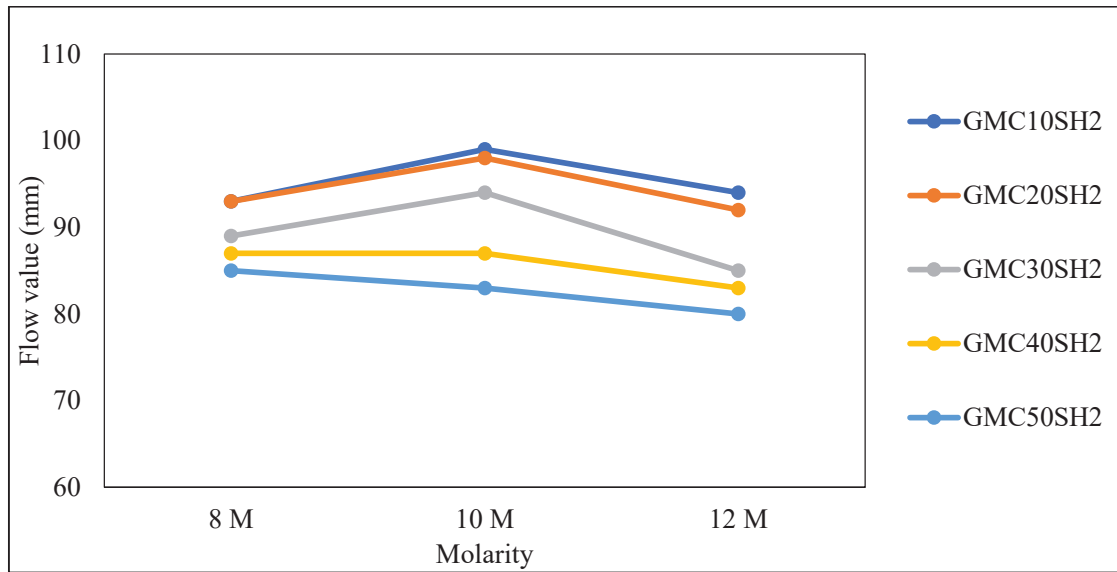


Fig 4.11: Flow value of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 2.

Observations showed that the flow values of a geopolymer mortar with an SS/SH ratio of 3 decreased as the copper slag concentration and NaOH molarity increased. More precisely, when the molarity of NaOH was 8 M, the flow value decreased from 93 mm when 10 % copper slag was added to 85 mm when 50 % copper slag was added. For a 10 M NaOH concentration, the flow values varied between 78 mm when adding 10 % copper slag and 59 mm when adding 50 % slag. In addition, when the molarity of NaOH was increased to 12 M, the flow values decreased from 75 mm for a 10 % addition to 58 mm for a 50 % addition as shown in **Fig 4.12**. Copper slag often exhibits greater density and specific gravity compared to natural sand. This has the potential to result in alterations to the mortar's consistency and workability. Increasing the density of the aggregate might decrease the workability of the mortar, thus resulting in a decrease in the flow value.

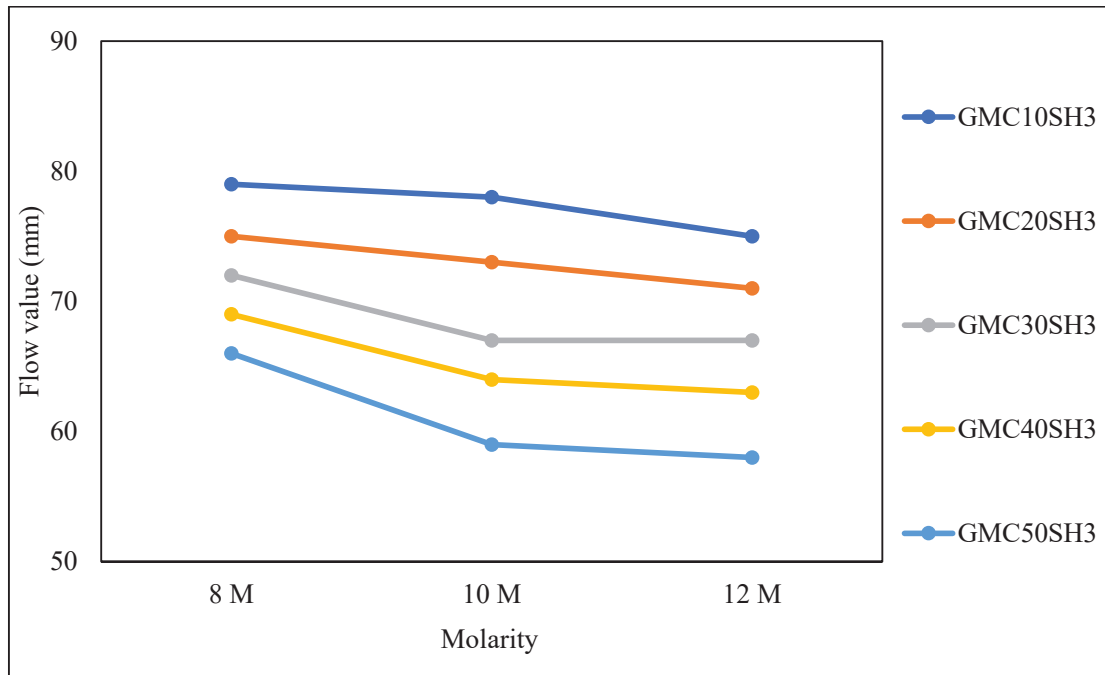


Fig 4.12: Flow value of copper slag based geopolymer mortar for NaOH molarity of 8, 10 and 12 M and SS/SH ratio of 3.

The flow values of geopolymer mortar samples with 5, 10, and 15 % replacement of fine aggregate by crumb rubber were analyzed, as presented in **Table 4.5**. The data indicate a downward trend in flow values with an increase in rubber content. Specifically, the flow value decreases from 87 mm to 58 mm as the rubber content increases from 5 to 15 %. This reduction in flowability is primarily attributed to the unique properties of crumb rubber particles. Unlike traditional aggregates, crumb rubber is less rigid and more deformable, which enhances the internal friction within the mortar mix, thereby hindering its smooth flow. Additionally, the water absorption characteristics of crumb rubber differ markedly from those of conventional aggregates. Rubber particles generally absorb less water, which can disrupt the uniform water distribution throughout the mix. This disruption may alter the consistency of the mortar, reducing its flowability.

Furthermore, the pre-treatment of rubber with NaOH appears to enhance the reactivity of the rubber within the mix. The treatment of rubber for durations of 1 hour and 24 hours demonstrates that the flow value decreases from 81 mm to 45 mm and from 59 mm to 30 mm, respectively, as the rubber content increases from 5 to 15 %. The increased addition of crumb rubber leads to a significant reduction in the workability of the mortar mix, as illustrated in **Figure 4.13**.

Table 4.5: Flow values of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

Mixes- Flow value (mm)	UNTREATED	TREATED-1 hr	TREATED-24 hr
GMC0CR5SH2	87	81	59
GMC0CR10SH2	74	74	44
GMC0CR15SH2	58	45	30

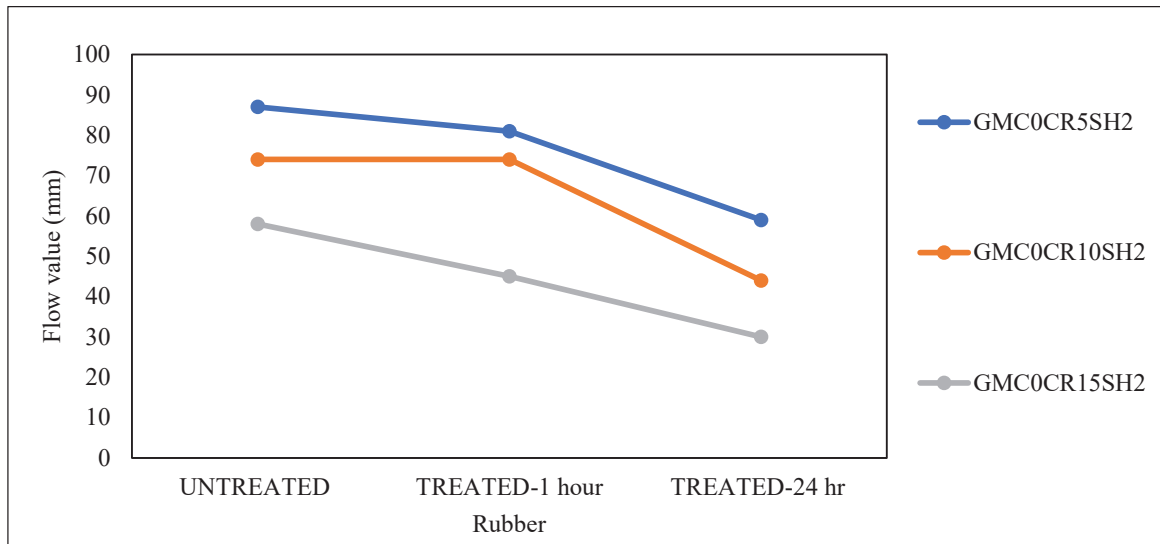


Fig 4.13: Flow values of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

The flow values of geopolymer mortar samples incorporating varying percentages of copper slag (30, 40, and 50 %) and crumb rubber (5, 10, and 15 %) as replacements for fine aggregate were examined. The impact of substituting fine aggregate with rubber and copper slag on the flow values of geopolymer mortar is detailed in **Table 4.6**. The flow value exhibited a decrease from 78 mm to 42 mm for untreated mixes, from 70 mm to 38 mm for mixes treated for 1 hour, and from 55 mm to 38 mm for mixes treated for 24 hours, as depicted in **Fig 4.14**. This reduction in flow value can be attributed to the lower water absorption capacity of both rubber and copper slag, which, in turn, leads to diminished workability of the mortar. Additionally, the interfacial bonding between the rubber, copper slag particles, and the geopolymer matrix is

generally weaker compared to that with conventional aggregates. This weaker bond results in a less cohesive mixture, further diminishing flowability as the content of copper slag and rubber increases. These observations collectively indicate a direct correlation between the augmentation of rubber and copper slag content and a decrease in workability within rubberized slag-based geopolymer mortar.

Table 4.6: Flow values of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

Mixes- Flow value (mm)	UNTREATED	TREATED-1 hour	TREATED-24 hr
GMC30CR5SH2	78	70	55
GMC30CR10SH2	72	67	43
GMC30CR15SH2	52	42	29
GMC40CR5SH2	72	68	50
GMC40CR10SH2	64	62	42
GMC40CR15SH2	47	40	26
GMC50CR5SH2	69	64	47
GMC50CR10SH2	60	58	38
GMC50CR15SH2	42	38	24

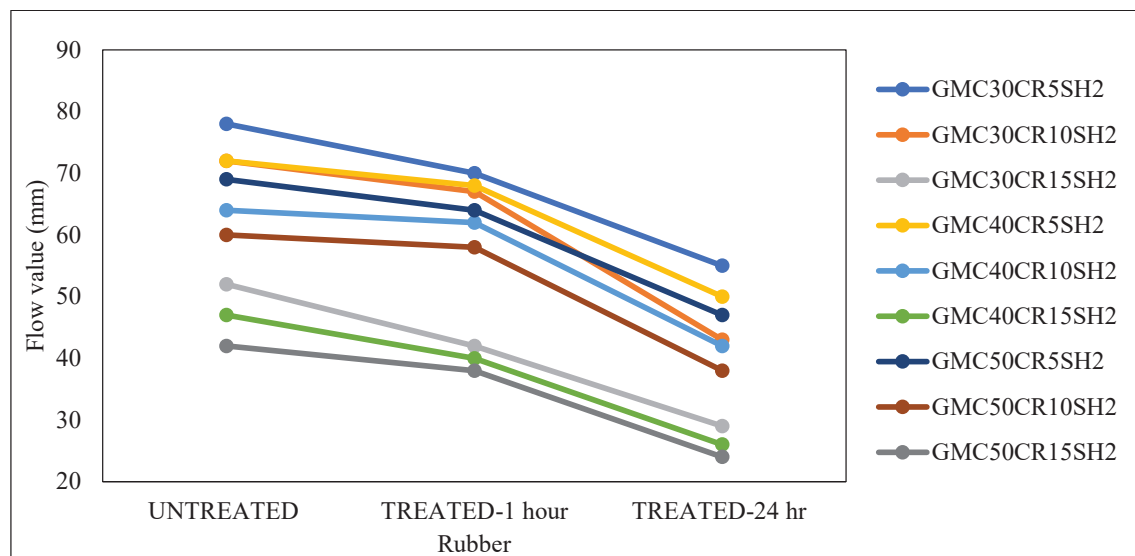


Fig 4.14: Flow values of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

4.3 Mechanical properties of mortar:

4.3.1 Compressive strength of mortar samples:

Compressive strength studies of geopolymer mortar are crucial in research because they provide essential insights into the material's structural integrity and load-bearing capacity, which are vital for determining its suitability in various construction applications. Additionally, understanding the factors that influence compressive strength, such as the mix proportions, type of binders, and curing conditions, helps in optimizing the formulation to enhance durability and performance under different environmental conditions. This study analyzes the compressive strength of conventional geopolymer mortar, considering variables such as NaOH molarity levels (8, 10, and 12) and SS/SH ratios (1, 2, and 3) over curing periods of 7, 28, and 90 days, as detailed in **Table 4.7**. It was observed that an increase in the SS/SH ratio consistently led to a reduction in compressive strength across all curing periods. Specifically, for a NaOH molarity of 8 M, compressive strengths at SS/SH ratios of 1, 2, and 3 were recorded as 22.983, 21.5812, and 20.4585 MPa respectively after 7 days; 32.6, 33.1, and 32.7 MPa after 28 days; and 34.8291, 36.6556, and 36.2 MPa after 90 days. The increased SS/SH ratio results in a decrease in the concentration of hydroxide ions, which are necessary for catalyzing the geopolymerization reaction, due to the dilution of the alkaline activator. The diluting effect negatively impacts the rate of the reaction, leading to a geopolymer matrix that is less compact and hence has less compressive strength. In addition, the greater amount of sodium silicate results in a larger water content, which leads to a more diluted mixture. This is not ideal for creating a dense and robust geopolymer matrix. Excessive water may interfere with the effective compaction process during casting, resulting in greater porosity and reduced overall integrity and strength of the mortar. At a NaOH molarity of 10 M, the strengths were 27.072, 28.7035, and 27.14 MPa at 7 days; 38.4, 41.3, and 40.87 MPa at 28 days; and 42.4309, 45.186, and 43.21 MPa at 90 days. Furthermore, for a NaOH molarity of 12 M, the compressive strengths were 27.4722, 28.0697, and 27.5114 MPa at 7 days; 42.2, 42.92, and 40.89 MPa at 28 days; and 45.0855, 45.5626, and 43.21 MPa at 90 days as shown in **Fig 4.15**. Higher concentrations of NaOH lead to increased compressive strength in geopolymer mortar. Increasing the molarity of NaOH enhances the alkalinity of the mixture, leading to better dissolution of aluminosilicate precursors and promoting a more thorough geopolymerization process. As a consequence, there is an increase in the density of the geopolymer matrix, leading to improved mechanical characteristics. Higher molarities of NaOH result in an elevated concentration of hydroxide ions, which speeds up the polymerization process of silica and

alumina. This leads to a more rapid formation of the geopolymer matrix, which is responsible for the material's strength.

Table 4.7: Compressive strength (MPa) of conventional geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 7, 28 and 90 days.

Compressive strength (MPa)									
	8 M			10 M			12 M		
Mixes	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
GMC0SH1	22.983	32.6	34.8291	27.072	38.4	42.4309	27.4722	42.2	45.0855
GMC0SH2	21.5812	33.1	36.6556	28.7035	41.3	45.186	28.0697	42.92	45.5626
GMC0SH3	20.4585	32.7	36.2	27.14	40.87	43.21	27.5114	40.89	43.21

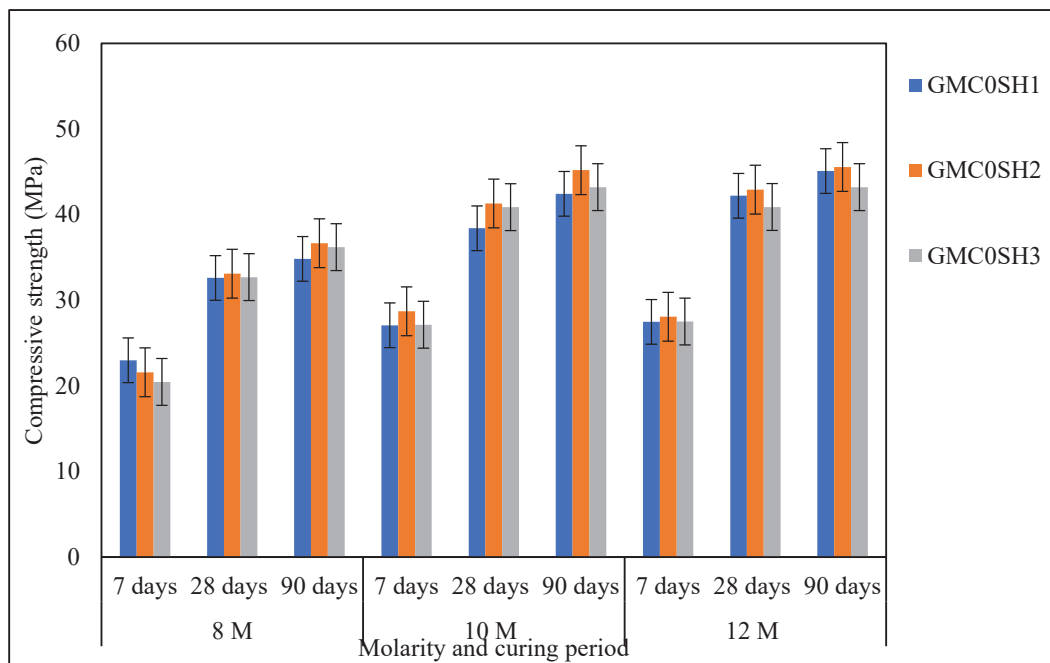


Fig 4.15: Compressive strength of conventional geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 7, 28 and 90 days.

The compressive strength of geopolymer mortar, with copper slag replacing fine aggregates at increments of 10, 20, 30, 40, and 50 %, was evaluated. The influence of varying sodium silicate to sodium hydroxide (SS/SH) ratios and different NaOH molarities on the compressive strength of copper slag-based geopolymer mortar is detailed in **Table 4.8**. For a geopolymer mortar with an SS/SH ratio of 1 and an NaOH molarity of 8 M, the compressive strength results over a 7-day curing period ranged from 26.0524 MPa with 10 % copper slag to 33.4508 MPa with 50 % copper slag. At 28 days, the strength increased from 38.2 MPa for 10 % copper slag to 48.2 MPa for 50 % copper slag, and at 90 days, it further increased from 41.29 MPa to 50.57 MPa for the same respective percentages. When the NaOH molarity was increased to 10 M, the 7-day compressive strengths ranged from 30.33 MPa for 10 % copper slag to 40.95 MPa for 50 % copper slag. At 28 days, the strengths were significantly higher, ranging from 41.9 MPa to 56.8 MPa, and at 90 days, they ranged from 45.15 MPa to 60.81 MPa. At the highest tested NaOH molarity of 12 M, the 7-day compressive strengths started at 31.66 MPa for 10 % copper slag and peaked at 42.63 MPa for 40 % copper slag, slightly decreasing to 41.65 MPa for 50 % copper slag. At 28 days, the strengths ranged from 47.4 MPa to 60.2 MPa, and at 90 days, they further increased, ranging from 51.24 MPa to 65.72 MPa, as shown in **Fig 4.16**.

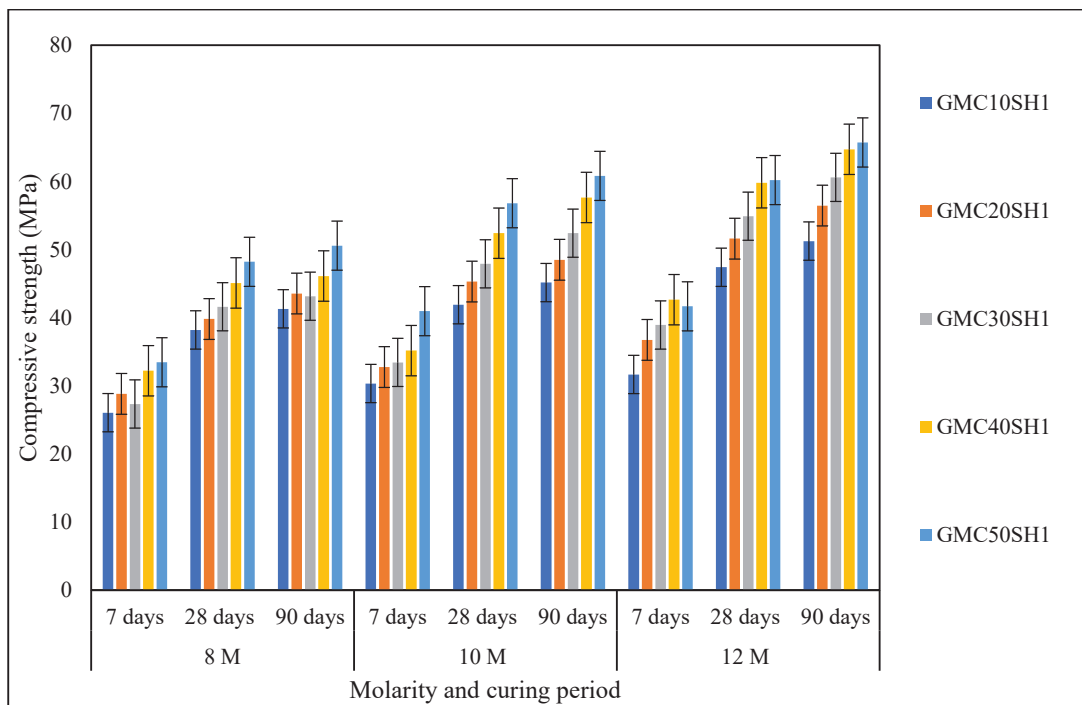


Fig 4.16: Compressive strength of copper slag based geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 7, 28 and 90 days.

Table 4.8: Compressive strength of copper slag based geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 7, 28 and 90 days.

Compressive strength (MPa)									
	8 M			10 M			12 M		
Mixes	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
GMC10SH1	26.0524	38.2	41.2973	30.3356	41.9	45.1509	31.6632	47.4	51.2432
GMC20SH1	28.8152	39.8	43.5449	32.7519	45.3	48.5011	36.7392	51.6	56.4551
GMC30SH1	27.3312	41.6	43.1535	33.4342	47.9	52.407	38.9241	54.9	60.596
GMC40SH1	32.2014	45.1	46.1145	35.1604	52.4	57.6458	42.6374	59.8	64.7186
GMC50SH1	33.4508	48.2	50.5771	40.9528	56.8	60.8137	41.6584	60.2	65.7205
GMC10SH2	25.8545	41.5	44.9134	29.0494	43.1	46.047	31.3404	49.2	53.8293
GMC20SH2	28.1399	43.9	47.1536	35.1127	48.7	53.108	35.5796	52.4	56.1028
GMC30SH2	35.3075	48.7	51.4256	35.1288	49.2	56.2	41.1387	56.9	61.3808
GMC40SH2	35.6568	49.8	54.9063	37.9828	53.8	56.7511	44.7314	62.3	69.0687
GMC50SH2	36.9045	53.1	57.8431	43.4385	59.1	63.961	46.5254	65.9	71.7865
GMC10SH3	24.1	39.7	43.71	27.48	42.58	44.12	30.58	47.65	51.47
GMC20SH3	26.42	41.8	48.8865	33.12	45.28	51.7	34.12	49.97	55.26
GMC30SH3	33.21	45.17	50.7	34.17	47.2	54.2	39.87	52.47	58.72
GMC40SH3	34.1	46.82	53.21	35.85	51.47	55.12	41.5	56.82	62.47
GMC50SH3	35.12	51.4	55.8	39.25	58.4	61.74	42.87	59.74	68.59

In a geopolymer mortar with an SS/SH ratio of 2 and an NaOH molarity of 10 M, the compressive strength results over a 7-day curing period ranged from 25.85 MPa with a 10 % copper slag addition to 36.90 MPa with a 50 % addition. At 28 days, the strength increased from 41.5 MPa for 10 % copper slag to 53.1 MPa for 50 % copper slag, and at 90 days, it further increased from 44.91 MPa to 57.84 MPa for the same respective percentages. When the NaOH molarity was increased to 12 M, the 7-day compressive strengths began at 31.34 MPa for 10 % copper slag and peaked at 46.52 MPa for 50 % copper slag. At 28 days, the strengths

ranged from 49.2 MPa to 65.9 MPa, and at 90 days, they further increased, ranging from 53.82 MPa to 71.78 MPa, as shown in **Fig 4.17**.

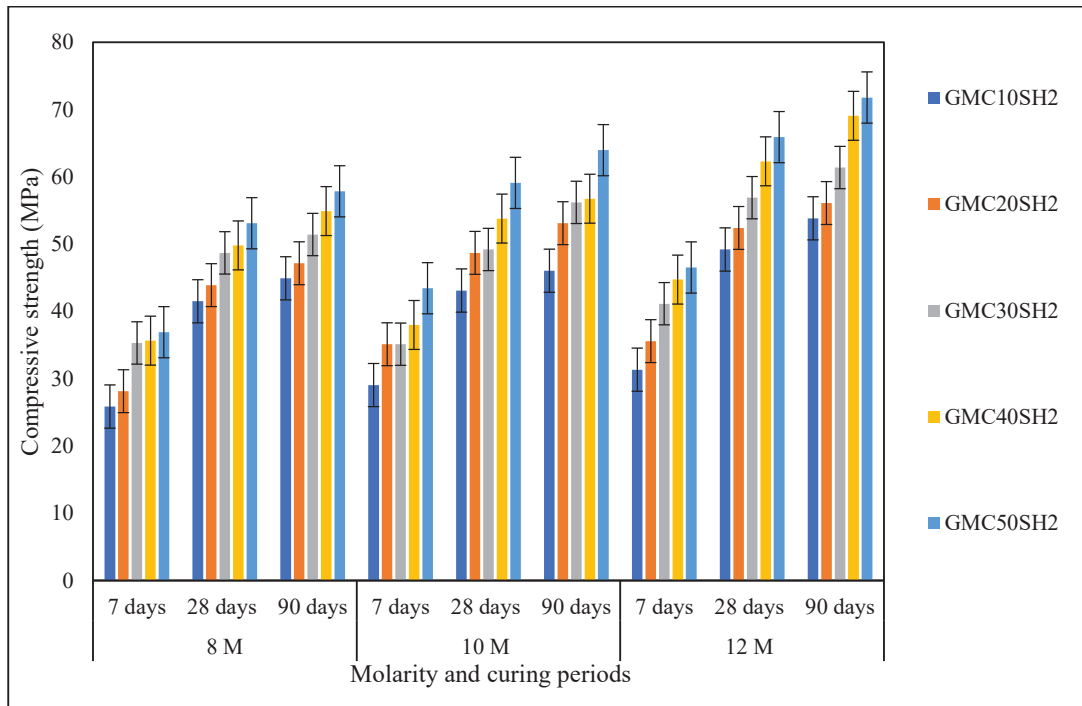


Fig 4.17: Compressive strength of copper slag based geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 2 for curing period of 7, 28 and 90 days.

In a geopolymer mortar with an SS/SH ratio of 3 and an NaOH molarity of 10 M, the compressive strength results over a 7-day curing period ranged from 24.1 MPa with a 10 % copper slag addition to 26.42 MPa with a 50 % addition. At 28 days, the strength increased from 39.7 MPa for 10 % copper slag to 51.4 MPa for 50 % copper slag, and at 90 days, it further increased from 43.71 MPa to 55.8 MPa for the same respective percentages. Upon increasing the NaOH molarity to 12 M, the 7-day compressive strengths began at 30.58 MPa for 10% copper slag and peaked at 42.87 MPa for 50 % copper slag. At 28 days, the strengths ranged from 47.65 MPa to 59.74 MPa, and at 90 days, they further increased, ranging from 51.472 MPa to 68.59 MPa, as illustrated in **Fig 4.18**.

The enhancement in compressive strength with an increased copper slag content is attributed to several factors. Copper slag, being denser and more angular than traditional sand, leads to a denser aggregate matrix, which reduces porosity and enhances the mortar's overall strength. Furthermore, the pozzolanic reactions between the copper slag and the alkaline activator likely contribute to strength development by forming additional cementitious compounds. The data

indicate that a 50% copper slag replacement level, especially at higher NaOH molarities and extended curing periods, yields the highest strength.

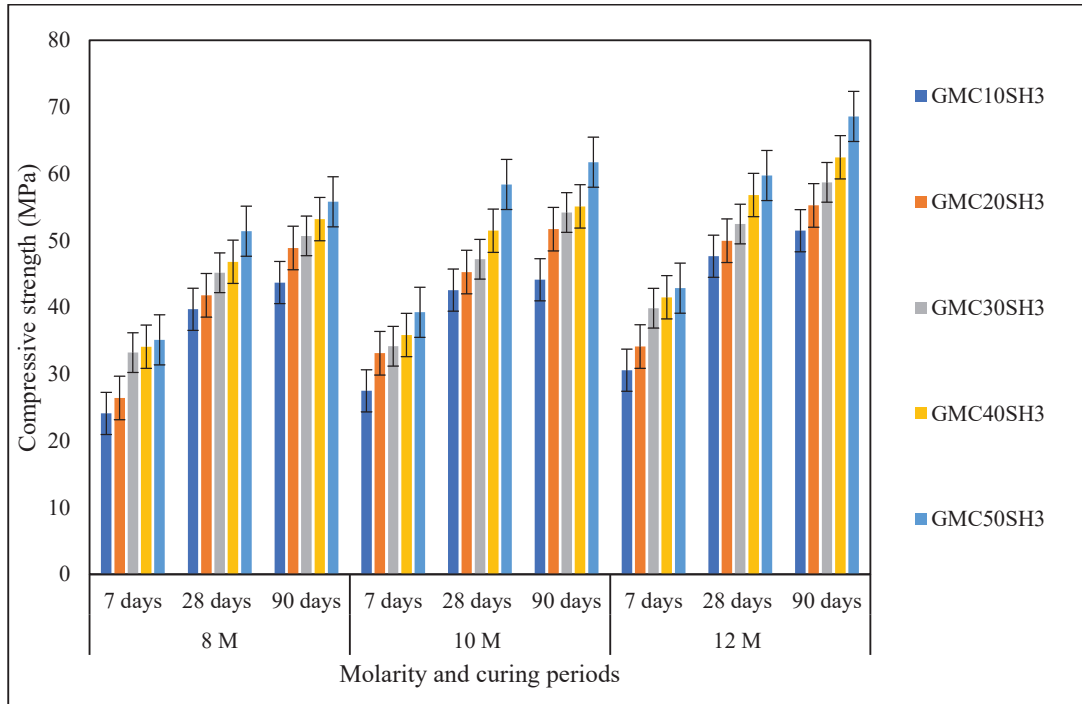


Fig 4.18: Compressive strength of copper slag based geopolymer mortar for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 3 for curing period of 7, 28 and 90 days.

The study investigated the compressive strength of geopolymer mortar with crumb rubber replacing fine aggregates at 5, 10, and 15 % levels. The analysis focused on rubberized geopolymer mortar with a sodium hydroxide (NaOH) molarity of 10 M and a sodium silicate to sodium hydroxide (SS/SH) ratio of 2, examining untreated, 1-hour-treated, and 24-hour-treated rubber conditions, as detailed in **Table 4.9**. For untreated rubberized geopolymer mortar, the compressive strengths at 7 days for 5, 10, and 15 % rubber replacements were recorded as 24.1 MPa, 21.46 MPa, and 14.72 MPa, respectively. At 28 days, these strengths were observed to be 34.44 MPa, 24.78 MPa, and 18.9 MPa. In the case of mortar with 1-hour-treated crumb rubber, the 7-day compressive strengths improved to 26.40 MPa, 23.53 MPa, and 15.48 MPa for the respective rubber contents, and at 28 days, the strengths increased to 36.34 MPa, 24.36 MPa, and 19.82 MPa. Moreover, for the 24-hour-treated rubberized geopolymer mortar, the 7-day compressive strengths further increased to 27.26 MPa, 24.97 MPa, and 18.65 MPa, and at 28 days, the strengths enhanced to 37.17 MPa, 25.60 MPa, and

20.23 MPa for 5%, 10%, and 15% rubber replacements, respectively, as illustrated in **Fig 4.19**. While rubberized geopolymer mortar offers benefits such as improved ductility and reduced density, its compressive strength tends to decrease with the increase in crumb rubber content. This decline is attributed to the inherent properties of rubber, inadequate bonding between the rubber and the geopolymer matrix, and the increased presence of pores and voids within the mortar. However, pre-treating the crumb rubber before incorporating it into the geopolymer mortar significantly enhances the compressive strength. This improvement is primarily due to the strengthened adhesion between the rubber particles and the geopolymer matrix, which substantially boosts the material's durability and structural integrity.

Table 4.9: Compressive strength of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for 7 days and 28 days curing.

Compressive strength (MPa)	UNTREATED		TREATED-1 hr		TREATED-24 hr	
Mixes	7 days	28 days	7 days	28 days	7 days	28 days
GMC0CR5SH2	24.1	34.44	26.4072	36.344	27.2683	37.17
GMC0CR10SH2	21.46	24.78	23.5369	24.367	24.972	25.606
GMC0CR15SH2	14.72	18.9	15.4999	19.824	18.6573	20.237

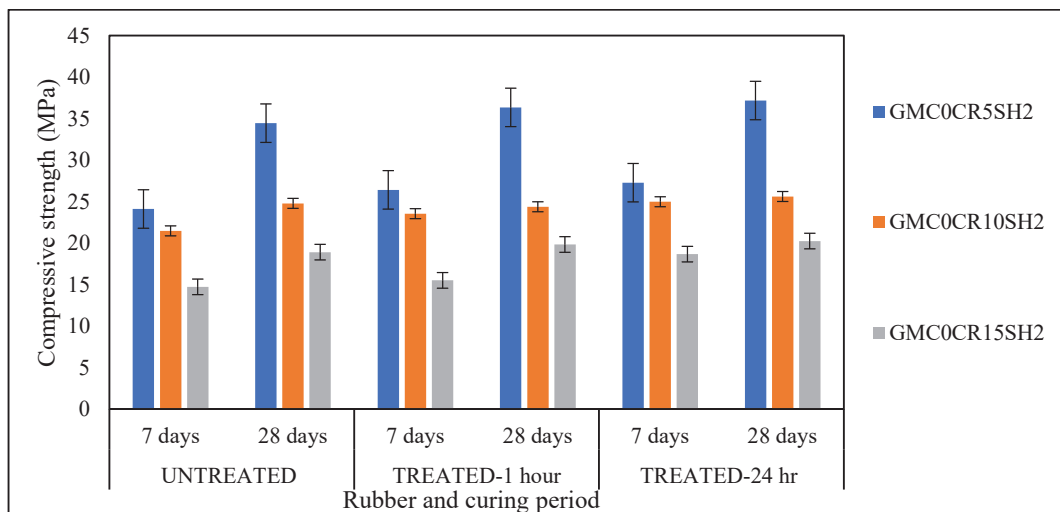


Fig 4.19: Compressive strength of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

The compressive strength of geopolymer mortar samples containing copper slag at 30, 40, and 50 % and crumb rubber at 5, 10, and 15 % was evaluated. The impact of these materials as replacements for fine aggregate on the compressive strength is detailed in **Table 4.10**. For untreated rubber mixes, the compressive strength decreased from 29.75 MPa to 22.31 MPa over a 7-day curing period, and from 40.18 MPa to 29.4 MPa over a 24-day curing period. For 1-hour treated rubber mixes, the strength decreased from 31.2646 MPa to 24.75 MPa over 7 days, and from 43.29 MPa to 29.55 MPa over 24 days. For 24-hour treated rubber mixes, the strength decreased from 32.66 MPa to 27.80 MPa over 7 days, and from 44.77 MPa to 31.32 MPa over 24 days, as illustrated in **Fig 4.20**. While the replacement of fine aggregate with copper slag generally led to an increase in compressive strength, the inclusion of rubber aggregate tended to reduce it. However, the adverse effects of rubber aggregate on compressive strength can be partially mitigated through pre-treatment processes and the synergistic use of copper slag, which enhances its interaction with the geopolymer matrix.

Table 4.10: Compressive strength of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for 7 days and 28 days curing period.

Compressive strength (MPa)	UNTREATED		TREATED-1 hour		TREATED-24 hr	
Mixes	7 days	28 days	7 days	28 days	7 days	28 days
GMC30CR5SH2	29.75	40.18	31.2646	43.296	32.6698	44.772
GMC30CR10SH2	26.2	27.44	29.5082	29.028	30.5621	29.52
GMC30CR15SH2	16.16	22.54	19.6721	23.616	22.8337	23.124
GMC40CR5SH2	32.24	45.9	34.9442	47.344	35.324	49.496
GMC40CR10SH2	28.42	32.4	31.1459	31.204	32.2854	33.356
GMC40CR15SH2	19.21	25.38	21.2704	24.748	25.0686	26.362
GMC50CR5SH2	36.92	49.2	39.9634	51.417	41.701	53.781

GMC50CR10SH2	33.01	36.6	35.1852	35.46	38.2259	37.233
GMC50CR15SH2	22.31	29.4	24.7599	29.55	27.8006	31.323

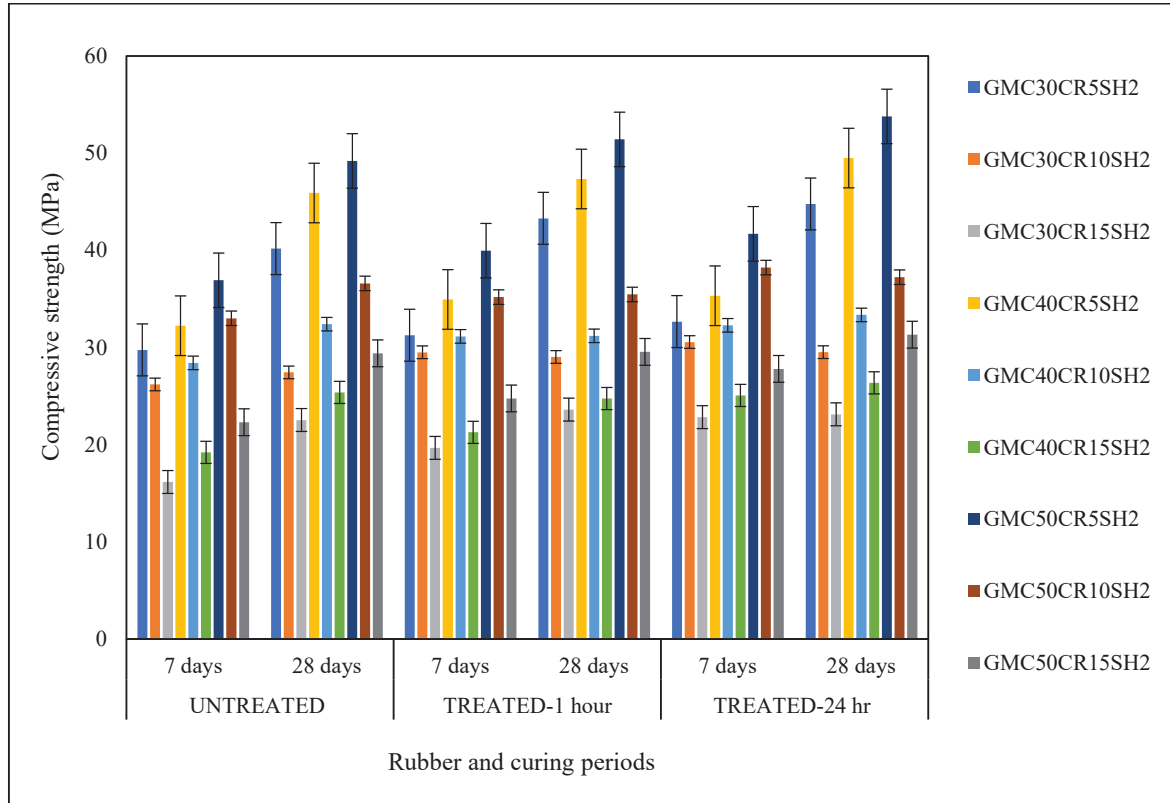


Fig 4.20: Compressive strength of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

4.4 Durability of the mortar sample:

4.4.1 Density of the mortar sample:

Density studies of geopolymer mortar are conducted in research to evaluate the material's structural lightweight potential and its influence on mechanical properties, such as compressive strength, which are crucial for determining its applicability in various construction scenarios. Additionally, understanding the density helps in assessing the porosity and durability of geopolymer mortars, factors that significantly affect their performance in different environmental conditions. The study investigates the changes in density of geopolymer mortar when fine aggregates are substituted with crumb rubber at increments of 5, 10, and 15 %. Density measurements were conducted under various conditions, including a sodium

hydroxide (NaOH) molarity of 10 M and an SS/SH ratio of 2. The assessments were performed on both untreated samples and those treated for 1 hour and 24 hours, as detailed in **Table 4.11**. The recorded densities for untreated rubberized geopolymer mortar with 5, 10, and 15 % rubber replacements were 2672 kg/m³, 2452 kg/m³, and 2386 kg/m³, respectively. After 1 hour of treatment, the densities increased to 2715 kg/m³, 2532 kg/m³, and 2416 kg/m³. Following 24 hours of treatment, the densities further rose to 2742 kg/m³, 2552 kg/m³, and 2426 kg/m³, as shown in **Fig 4.21**. The rubberized geopolymer mortar demonstrates a decrease in density as the percentage of rubber increases, which is attributed to the lower specific gravity of rubber particles compared to conventional fine aggregates such as sand. The inclusion of crumb rubber typically enhances the mortar's porosity. Additionally, rubber particles exhibit a lower bonding affinity with the geopolymer matrix than standard aggregates, leading to the formation of micro voids and gaps at the interface.

Table 4.11: Density of the rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

Mixes (kg/m ³)	UNTREATED	TREATED-1 hr	TREATED-24 hr
GMC0CR5SH2	2672	2715	2742
GMC0CR10SH2	2452	2532	2552
GMC0CR15SH2	2386	2416	2426

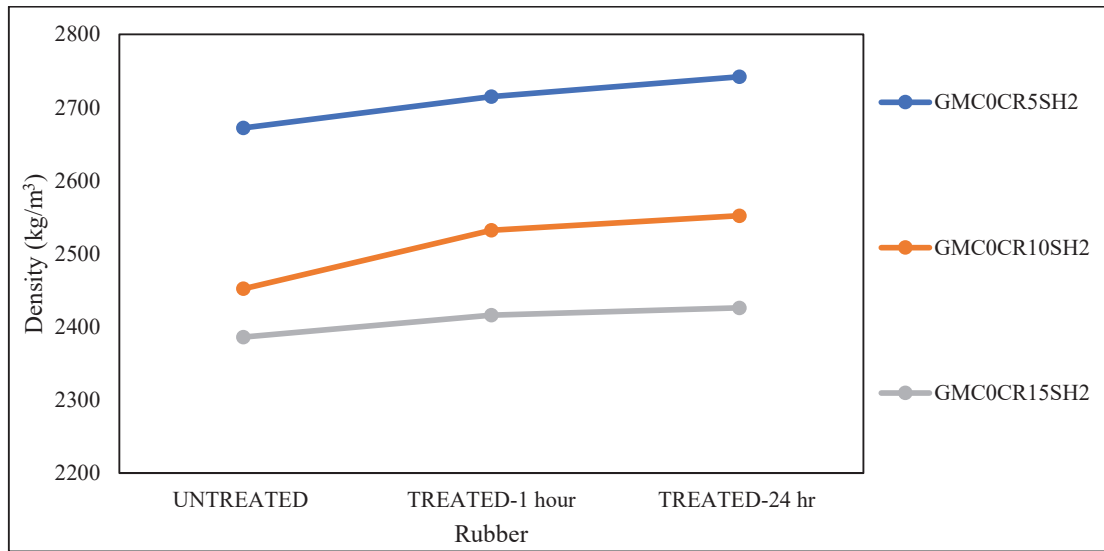


Fig 4.21: Density of the rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

This study investigates the density changes in geopolymer mortar when fine aggregates are replaced with copper slag at levels of 30, 40, and 50 %, and crumb rubber at increments of 5, 10, and 15 %. The effects of these replacements on the densities of geopolymer mortar are detailed in **Table 4.12**. The compressive strength values for untreated mixes decreased from 2684 kg/m³ to 2472 kg/m³, for 1-hour treated mixes from 2722 kg/m³ to 2451 kg/m³, and for 24-hour treated mixes from 2759 kg/m³ to 2467 kg/m³, as illustrated in **Fig 4.22**. While the inclusion of copper slag as a replacement for fine aggregate tends to increase the density of the mortar, the addition of rubber aggregate generally results in a decrease. The observed reduction in density with increasing amounts of copper slag and crumb rubber is primarily due to the inherently lower density of crumb rubber, alterations in the microstructure and porosity of the mortar, and the impact of rubber treatment on the physical properties of the mix. These factors collectively lead to the noted reductions in density in the geopolymer mortar as the content of crumb rubber increases, even when the rubber is treated with a NaOH solution.

Table 4.12: Density of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

Mixes (kg/m ³)	UNTREATED	TREATED-1 hr	TREATED-24 hr
GMC30CR5SH2	2681	2722	2759
GMC30CR10SH2	2468	2545	2571

GMC30CR15SH2	2399	2424	2439
GMC40CR5SH2	2692	2735	2771
GMC40CR10SH2	2482	2562	2589
GMC40CR15SH2	2409	2439	2452
GMC50CR5SH2	2712	2752	2796
GMC50CR10SH2	2499	2582	2599
GMC50CR15SH2	2427	2451	2467

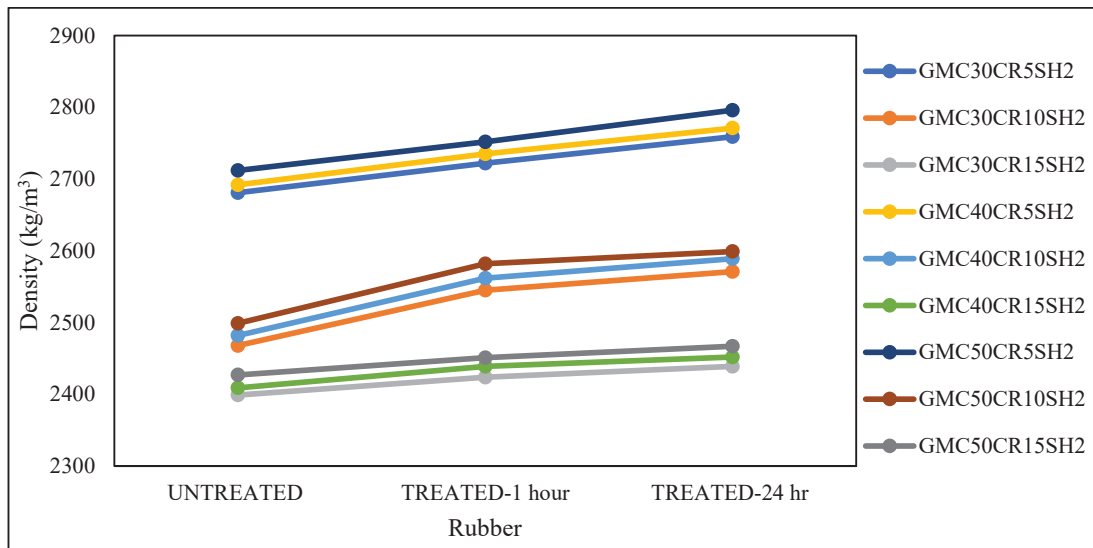


Fig 4.22: Density of rubberized slag based geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

4.4.2 Water absorption of mortar sample:

Water absorption studies of geopolymer mortar are conducted in research to evaluate the material's durability and porosity, which are critical for assessing its performance in various environmental conditions and its longevity in structural applications. These studies help determine how well geopolymer mortar resists moisture penetration, a key factor in preventing degradation and ensuring the structural integrity of constructions exposed to moisture-laden environments. The study assessed the water absorption of rubberized geopolymer mortar with a sodium hydroxide (NaOH) molarity of 10 M and a sodium silicate to sodium hydroxide

(SS/SH) ratio of 2, examining untreated, 1-hour-treated, and 24-hour-treated conditions as presented in **Table 4.13**. For untreated rubberized geopolymer mortar, the initial water absorption rates were recorded at 2.98, 3.27, and 3.52 for 5, 10, and 15 % rubber content, respectively. The corresponding final water absorption rates were 3.87, 3.96, and 4.12 %. After 1 hour of treatment, the initial water absorption rates decreased slightly to 2.76, 3.19, and 3.35 %, while the final rates were 3.72, 3.85, and 4.12 % for the respective rubber contents. Further improvements were noted with 24-hour treated rubber, where the initial water absorption rates were reduced to 2.67, 3.12, and 3.29 %, and the final rates to 3.69, 3.92, and 4.06 %. as shown in **Fig 4.23**. These findings suggest that water absorption capacity generally increases with higher percentages of rubber replacement. However, extending the treatment duration of the rubber enhances its compatibility with the geopolymer matrix, thereby slightly reducing water absorption.

Table 4.13: Water absorption of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

Mixes (%)	UNTREATED		TREATED-1 hr		TREATED-24 hr	
	I	F	I	F	I	F
GMC0CR5SH2	2.98	3.87	2.76	3.72	2.67	3.69
GMC0CR10SH2	3.27	3.96	3.19	3.85	3.12	3.92
GMC0CR15SH2	3.52	4.12	3.35	4.12	3.29	4.06

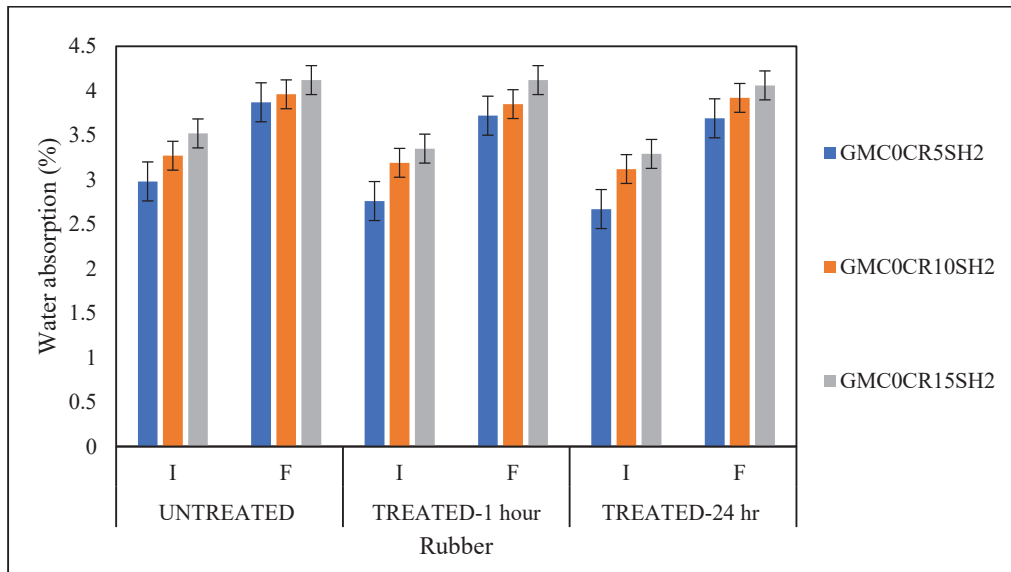


Fig 4.23: Water absorption of rubberized geopolymer mortar for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated.

4.5 Workability of concrete:

Workability studies of geopolymer concrete are essential in research because they assess the ease with which the concrete can be mixed, transported, placed, and compacted, directly influencing the quality and uniformity of construction. These studies help optimize the mix design by adjusting the proportions of components and admixtures to achieve the desired consistency and performance, ensuring efficient application and structural integrity. The workability of conventional geopolymer concrete with NaOH molarities of 8 M, 10 M, and 12 M, and SS/SH ratios of 1, 2, and 3 is presented in **Table 4.14**. The analysis indicates that the slump value for a concrete sample with an SS/SH ratio of 1 and an NaOH molarity of 8 M is 210 mm. However, as the SS/SH ratio increases, there is a noticeable decrease in flow values, with measurements of 198 mm and 187 mm for SS/SH ratios of 2 and 3, respectively. This trend suggests that an increase in the SS/SH (sodium silicate to sodium hydroxide) ratio generally leads to a decrease in workability. This relationship is observed due to the increased viscosity associated with higher proportions of sodium silicate in the mix. Sodium silicate is more viscous than sodium hydroxide, and as its proportion increases relative to sodium hydroxide, the overall mixture becomes thicker and less fluid, which negatively impacts its ease of mixing and handling. Furthermore, an increase in NaOH molarity also results in a reduction in flow values. Specifically, for an SS/SH ratio of 1, the flow values decrease to 193.2 mm and 175.8 mm for NaOH concentrations of 10 M and 12 M, respectively. When the

SS/SH ratio is increased to 2, the flow values further decrease to 180.1 mm and 165.7 mm. Similarly, for an SS/SH ratio of 3, the flow values are reduced to 165.7 mm and 154.7 mm, respectively, when compared with an NaOH molarity of 8 M, as illustrated in **Fig 4.24**. The effect of NaOH molarity on the workability of conventional geopolymer concrete is such that an increase in molarity leads to a decrease in workability. This relationship is highlighted by the observation that higher concentrations of NaOH result in a geopolymer concrete mix that is more viscous and harder to mix and cast, directly impacting its flowability and, consequently, its workability.

Table 4.14: Workability of conventional geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 1, 2 and 3.

Mixes (mm)	8 M	10 M	12 M
GCC0SH1	210	193.2	175.8
GCC0SH2	198	180.1	165.7
GCC0SH3	187	166.4	154.7

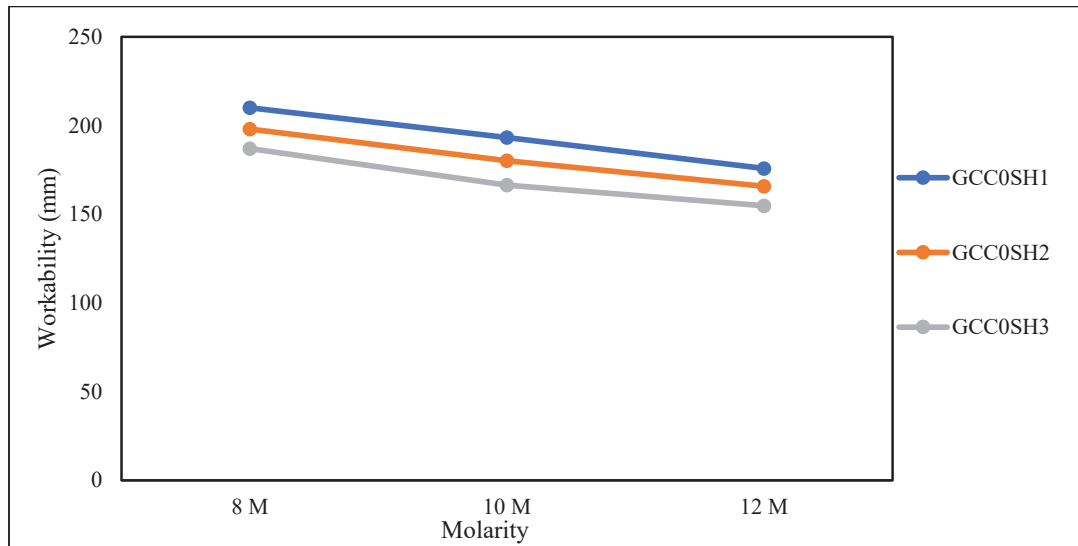


Fig 4.24: Workability of conventional geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 1, 2 and 3.

This study investigates the workability of geopolymer concrete when fine aggregates are substituted with copper slag at varying percentages (10, 20, 30, 40, and 50 %). It evaluates the influence of different sodium silicate to sodium hydroxide (SS/SH) ratios and NaOH molarities on the workability of copper slag-based geopolymer concrete, as detailed in **Table 4.15**. For geopolymer concrete with an SS/SH ratio of 1, the observed slump values indicate a decrease in workability with increasing copper slag content and NaOH molarity. Specifically, at an NaOH molarity of 8 M, slump values decreased from 192 mm with 10 % copper slag to 157 mm with 50 % copper slag. At a molarity of 10 M, the slump values ranged from 178.5 mm for 10 % copper slag to 146 mm for 50 % copper slag. At the highest tested molarity of 12 M, the slump values further declined from 164.2 mm for 10 % copper slag to 131.4 mm for 50 % copper slag, as illustrated in **Fig 4.25**. For an SS/SH ratio of 2, the trend continued with slump values at an NaOH molarity of 8 M decreasing from 181 mm for 10 % copper slag to 142 mm for 50 % copper slag. At a molarity of 10 M, the values ranged from 170.1 mm for 10 % copper slag to 127.8 mm for 50 % copper slag. At 12 M, the slump values further decreased from 154.8 mm for 10 % copper slag to 117.5 mm for 50 % copper slag, as shown in **Fig 4.26**. Similarly, for an SS/SH ratio of 3, at an NaOH molarity of 8 M, the slump values decreased from 176 mm for 10 % copper slag to 130 mm for 50 % copper slag. At a molarity of 10 M, the values ranged from 154.8 mm for 10% copper slag to 120.9 mm for 50 % copper slag. At 12 M, the slump values further decreased from 142.4 mm for 10 % copper slag to 110 mm for 50 % copper slag, as depicted in **Fig 4.27**. While copper slag can enhance workability at moderate replacement levels by improving particle packing and reducing internal friction, excessive amounts of copper slag can adversely affect workability due to poor bonding and increased segregation within the mix.

Table 4.15: Workability of copper slag based geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 1, 2 and 3.

Mixes (mm)	8 M	10 M	12 M
GCC10SH1	192	178.5	164.2
GCC20SH1	183	166.5	156.5
GCC30SH1	172	153	136.2
GCC40SH1	165	150.1	132.1
GCC50SH1	157	146	131.4

GCC10SH2	181	170.1	154.8
GCC20SH2	168	154.5	143.7
GCC30SH2	158	146.9	130.7
GCC40SH2	150	136.5	122.8
GCC50SH2	142	127.8	117.5
GCC10SH3	176	154.8	142.4
GCC20SH3	163	145.0	132
GCC30SH3	154	141.6	131.7
GCC40SH3	141	128.3	114.1
GCC50SH3	130	120.9	110

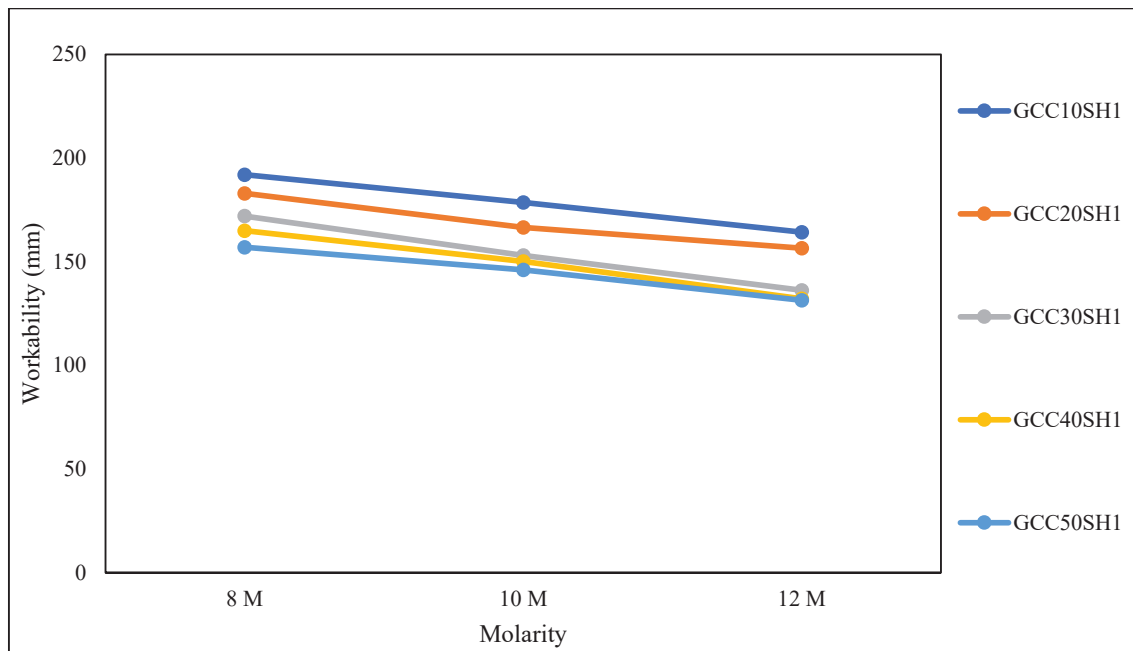


Fig 4.25: Workability of copper slag based geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 1.

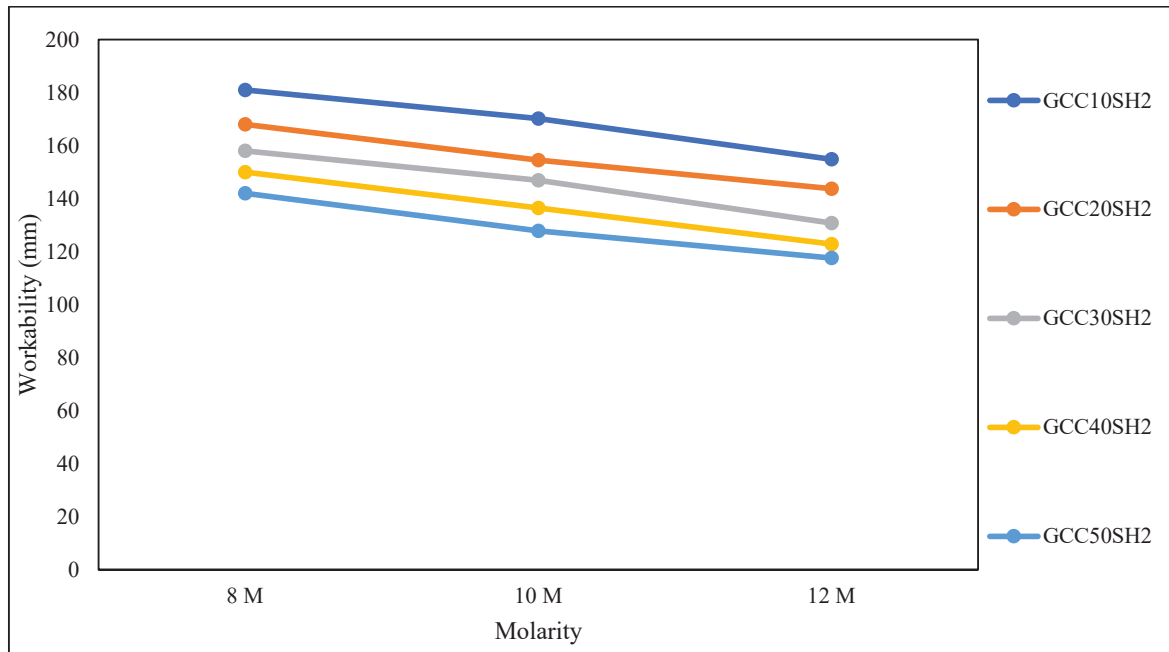


Fig 4.26: Workability of copper slag based geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 2.

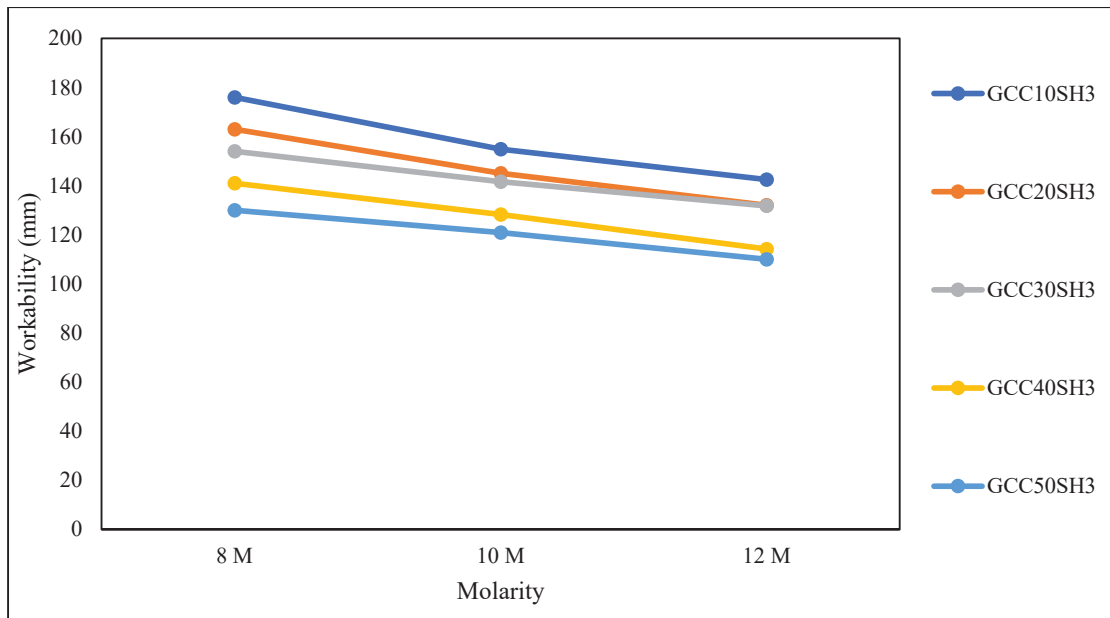


Fig 4.27: Workability of copper slag based geopolymer concrete with NaOH molarities of 8 M, 10 M and 12 M and SS/SH ratio of 3.

4.6 Mechanical properties of concrete:

4.6.1 Compressive strength of concrete:

Compressive strength studies of geopolymer concrete are conducted in research to evaluate the material's structural integrity and load-bearing capacity, which are crucial for determining its suitability for various construction applications. These studies also help in understanding how different factors, such as NaOH molarity, SS/SH ratios, and the incorporation of materials like copper slag and crumb rubber, influence the mechanical properties and durability of geopolymer concrete. This study investigates the compressive strength of conventional geopolymer concrete, analyzing the effects of various NaOH molarity levels (8, 10, and 12) and SS/SH ratios (1, 2, and 3) over different curing periods (7, 28, and 90 days), as detailed in **Table 4.16**. The findings indicate that increasing the SS/SH ratio generally leads to an increase in compressive strength across all observed curing periods up to a certain point, attributed to the enhanced geopolymerization reaction facilitated by a higher proportion of sodium silicate. This provides more soluble silica for the reaction, which is crucial for strength development.

Specifically, at an NaOH molarity of 8 M, the compressive strengths recorded for SS/SH ratios of 1, 2, and 3 were 24.82 MPa, 27.19 MPa, and 23.59 MPa, respectively, after 7 days; 31.52 MPa, 33.28 MPa, and 30.54 MPa after 28 days; and 36.61 MPa, 38.25 MPa, and 34.98 MPa after 90 days. However, increasing the SS/SH ratio beyond 2 can lead to a decrease in compressive strength, possibly due to an excess of sodium silicate which could interfere with the polymerization process or result in an unbalanced chemical composition less favorable for strength development.

At a NaOH molarity of 10 M, the strengths were 26.82 MPa, 28.56 MPa, and 24.86 MPa at 7 days; 33.56 MPa, 35.12 MPa, and 31.25 MPa at 28 days; and 35.12 MPa, 36.69 MPa, and 33.56 MPa at 90 days. Furthermore, at a NaOH molarity of 12 M, the compressive strengths were 27.12 MPa, 29.45 MPa, and 25.47 MPa at 7 days; 34.96 MPa, 36.45 MPa, and 33.57 MPa at 28 days; and 36.18 MPa, 37.65 MPa, and 34.58 MPa at 90 days, as illustrated in **Fig 4.28**.

The influence of NaOH molarity on the compressive strength of conventional geopolymer concrete shows that an increase in NaOH molarity enhances compressive strength. The optimal compressive strength of geopolymer concrete is achieved at NaOH concentrations of 10 and 12 M. This enhancement is due to the increased alkalinity of the solution, which promotes the

dissolution of aluminosilicate precursors, thereby facilitating a more thorough geopolymerization process. This results in a denser and stronger geopolymer matrix.

Table 4.16 : Compressive strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 7, 28 and 90 days.

Compressive strength (MPa)	8 M			10 M			12 M		
Mixes	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
GCC0SH1	24.82	31.52	36.61	26.82	33.56	35.12	27.12	34.96	36.18
GCC0SH2	27.19	33.28	38.25	28.56	35.12	36.69	29.45	36.45	37.65
GCC0SH3	23.59	30.54	34.98	24.86	31.25	33.56	25.47	33.57	34.58

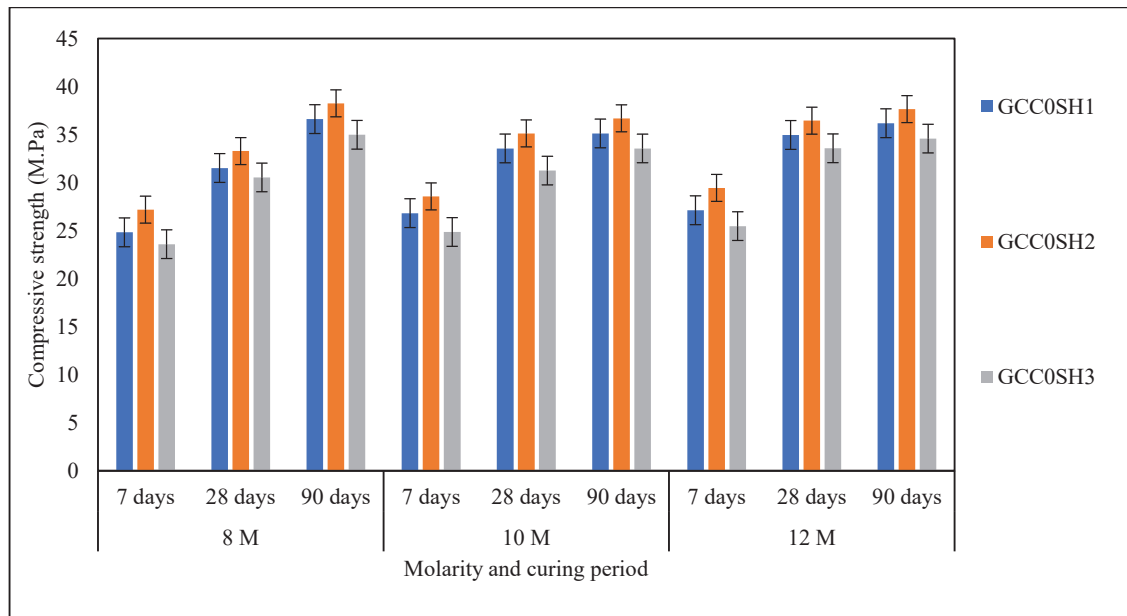


Fig 4.28: Compressive strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 7, 28 and 90 days.

This study investigates the compressive strength of geopolymer concrete when fine aggregates are substituted with copper slag at varying percentages (10, 20, 30, 40, and 50 %). It evaluates

the impact of different sodium silicate to sodium hydroxide (SS/SH) ratios and NaOH molarities on the compressive strength of copper slag-based geopolymer concrete, as detailed in **Table 4.17**. For geopolymer concrete with an SS/SH ratio of 1 and an NaOH molarity of 8 M, the compressive strength over a 7-day curing period ranges from 27.16 MPa with 10 % copper slag to 34.32 MPa with 50 % copper slag. At 28 days, the strength increases from 32.46 MPa for 10 % copper slag to 42.13 MPa for 50 % copper slag, and at 90 days, it further increases from 38.32 MPa to 48.56 MPa for the respective percentages. When the NaOH molarity is increased to 10 M, the 7-day compressive strengths range from 28.64 MPa for 10 % copper slag to 35.92 MPa for 50 % copper slag. At 28 days, the strengths are significantly higher, ranging from 34.87 MPa to 44.17 MPa, and at 90 days, they range from 36.98 MPa to 48.32 MPa. At the highest tested NaOH molarity of 12 M, the 7-day compressive strengths start at 29.32 MPa for 10 % copper slag and peak at 37.12 MPa for 50 % copper slag. At 28 days, the strengths range from 35.87 MPa to 47.28 MPa, and at 90 days, they further increase, ranging from 38.23 MPa to 49.46 MPa, as shown in **Fig 4.29**.

Table 4.17: Compressive strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 7, 28 and 90 days.

Compressive strength (MPa)	8 M			10 M			12 M		
Mixes	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
GCC10SH1	27.16	32.46	38.32	28.64	34.87	36.98	29.32	35.87	38.23
GCC20SH1	28.49	36.89	43.45	30.65	38.25	41.12	30.98	39.56	42.98
GCC30SH1	29.59	38.41	45.21	31.12	40.02	43.96	32.56	42.65	45.39
GCC40SH1	32.07	41.32	47.62	34.19	43.62	45.74	35.78	46.12	47.62
GCC50SH1	34.32	42.13	48.56	35.92	44.17	48.32	37.12	47.28	49.46
GCC10SH2	29.87	35.12	40.54	29.78	36.97	39.12	31.56	37.54	39.43
GCC20SH2	30.52	38.54	44.98	32.12	39.65	43.52	32.78	40.98	44.98

GCC30SH2	31.63	40.29	46.92	33.56	44.18	45.87	33.99	43.65	47.36
GCC40SH2	33.69	43.69	49.23	35.98	47.52	47.82	36.78	47.58	50.09
GCC50SH2	36.72	45.27	51.18	37.8	49.87	51.34	39.29	49.24	52.47
GCC10SH3	25.87	31.25	37.57	26.98	32.49	35.12	27.98	34.43	36.4
GCC20SH3	26.89	34.89	41.56	28.54	35.87	39.87	29.25	37.26	39.52
GCC30SH3	30.57	37.41	44.23	30.85	37.94	41.58	30.68	40.69	41.56
GCC40SH3	31.56	39.87	45.58	32.85	41.56	43.55	33.78	44.29	43.57
GCC50SH3	33.58	40.56	46.16	33.64	42.69	46.88	35.69	45.87	45.28

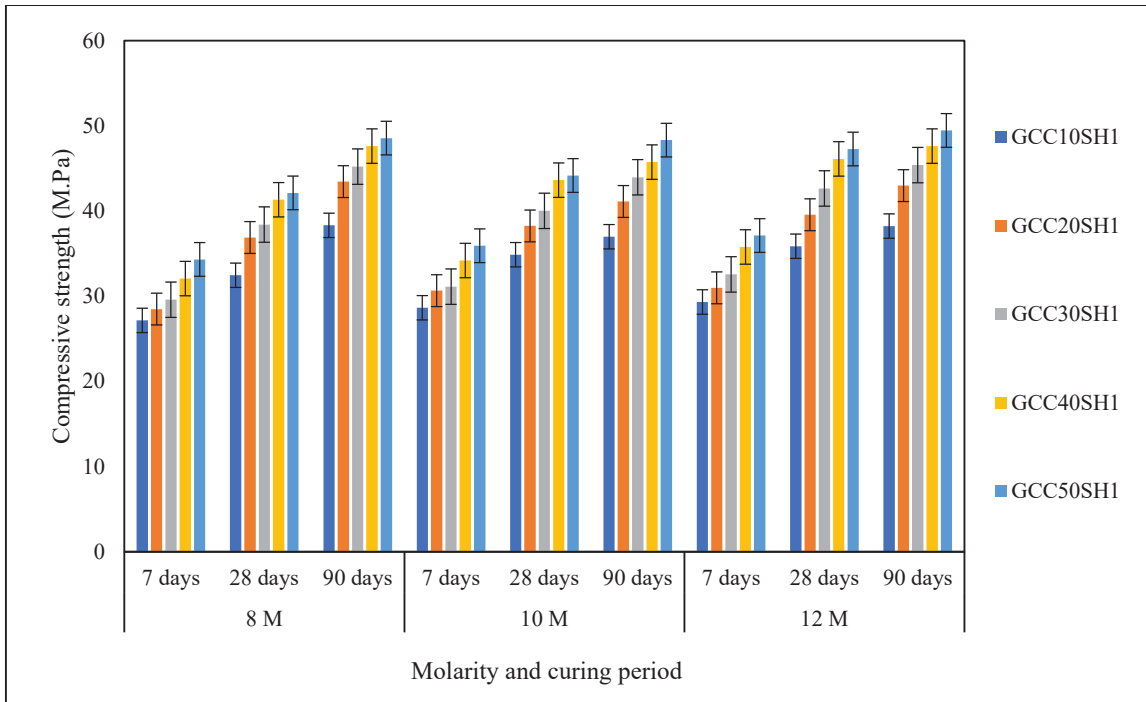


Fig 4.29: Compressive strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 7, 28 and 90 days.

For a geopolymer concrete with an SS/SH ratio of 2 and an NaOH molarity of 10 M, the compressive strength results over a 7-day curing period ranged from 29.87 MPa with a 10% copper slag addition to 36.72 MPa with a 50% addition. At 28 days, the strength increased from

35.12 MPa for a 10% copper slag addition to 45.27 MPa for a 50% addition, and at 90 days, it further increased from 40.54 MPa to 51.18 MPa for the respective percentages. When the NaOH molarity was increased to 12 M, the 7-day compressive strengths began at 31.56 MPa for a 10% copper slag addition and peaked at 39.29 MPa for a 50% addition. At 28 days, the strengths ranged from 37.54 MPa to 49.24 MPa, and at 90 days, they further increased, ranging from 39.43 MPa to 52.47 MPa, as illustrated in Fig 4.30.

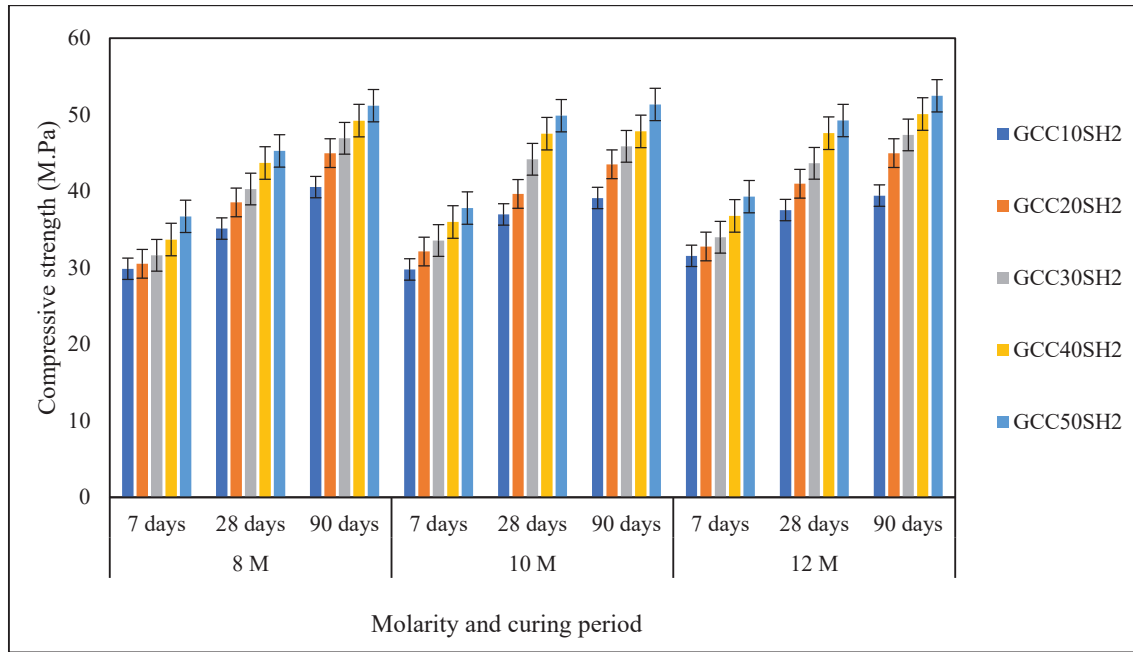


Fig 4.30: Compressive strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 2 for curing period of 7, 28 and 90 days.

For a geopolymer concrete with an SS/SH ratio of 3 and an NaOH molarity of 10 M, the compressive strength results over a 7-day curing period ranged from 25.87 MPa with 10% copper slag to 33.58 MPa with 50% copper slag. At 28 days, the strength increased from 31.25 MPa for 10% copper slag to 40.56 MPa for 50% copper slag, and at 90 days, it further increased from 37.57 MPa to 46.16 MPa for the respective percentages. When the NaOH molarity was increased to 12 M, the 7-day compressive strengths began at 27.98 MPa for 10% copper slag and peaked at 35.69 MPa for 50% copper slag. At 28 days, the strengths ranged from 34.43 MPa to 45.87 MPa, and at 90 days, they further increased, ranging from 36.4 MPa to 45.28 MPa, as illustrated in Fig 4.31.

Copper slag, being denser and more angular compared to traditional sand, contributes to a denser packing of the aggregate matrix, reducing porosity and enhancing the overall strength

of the mortar. It also exhibits pozzolanic properties, reacting with the alkaline activator in the geopolymer mix to form additional cementitious materials, thereby contributing to strength development. The inclusion of copper slag as a replacement for fine aggregates in geopolymer concrete has been shown to increase the compressive strength, particularly at replacement levels up to 50%.

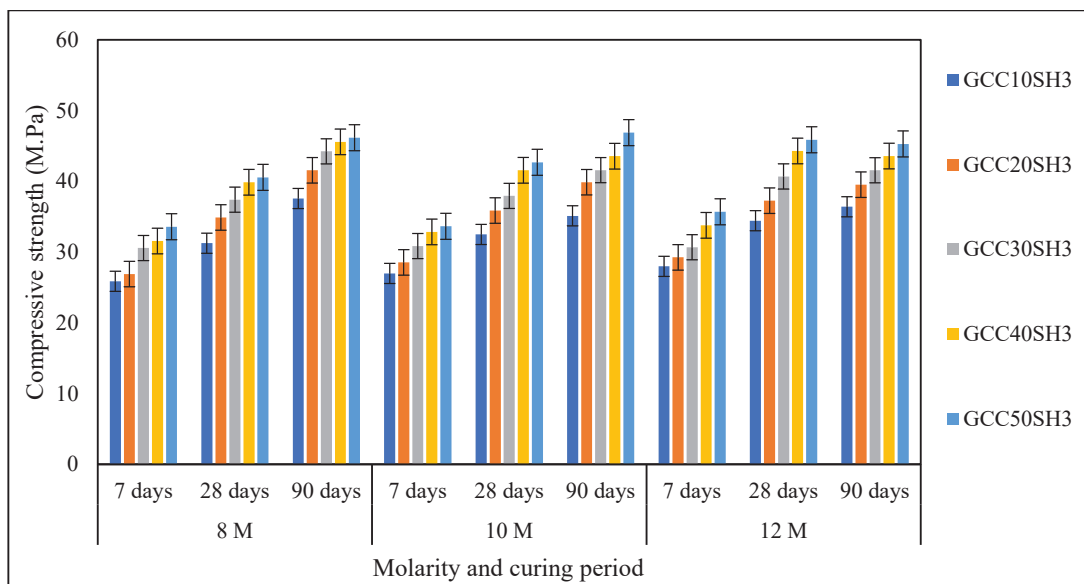


Fig 4.31: Compressive strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 3 for curing period of 7, 28 and 90 days.

This study investigates the compressive strength of geopolymer concrete when coarse aggregates are partially substituted with crumb rubber at percentages of 5%, 10%, and 15%. It assesses the impact of different crumb rubber treatment durations (untreated, treated for 1 hour, and treated for 24 hours) on the compressive strength of rubberized geopolymer concrete, maintaining a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.18**. For untreated rubberized geopolymer concrete, the compressive strengths recorded at 7 days were 34.36 MPa, 32.17 MPa, and 29.36 MPa for 5%, 10%, and 15% rubber replacements, respectively. At 28 days, the strengths were 35.62 MPa, 33.60 MPa, and 31.23 MPa for the respective percentages. When the crumb rubber underwent treatment for 1 hour, the 7-day compressive strengths improved to 35.98 MPa, 33.87 MPa, and 31.23 MPa, and at 28 days, the strengths further increased to 35.74 MPa, 34.98 MPa, and 31.25 MPa. Furthermore, for the 24-hour treated rubberized geopolymer concrete, the 7-day compressive strengths increased to 37.45 MPa, 35.36 MPa, and 33.18 MPa. At 28 days, the strengths further increased to 38.12

MPa, 36.15 MPa, and 31.98 MPa for 5%, 10%, and 15% rubber replacements, respectively, as illustrated in **Fig 4.32**.

Despite the advantages of rubberized geopolymer concrete, such as improved ductility and reduced density, its compressive strength tends to decrease with the incorporation of higher amounts of crumb rubber. This reduction in strength can be attributed to several factors: the inherent properties of rubber, insufficient bonding between the rubber and the geopolymer matrix, and an increase in porosity and voids within the concrete. Research has shown that treating crumb rubber for 1 hour results in a significant improvement in compressive strength compared to untreated rubber. Moreover, extending the treatment duration to 24 hours further enhances this strength improvement.

Table 4.18: Compressive strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 7 and 28 days.

Compressive strength (MPa)	Untreated		Treated - 1 hr		Treated - 24 hr	
	7 days	28 days	7 days	28 days	7 days	28 days
GCC0CR5SH2	34.36	35.62	35.98	35.74	37.45	38.12
GCC0CR10SH2	32.17	33.603	33.87	34.98	35.36	36.15
GCC0CR15SH2	29.36	31.52	31.23	31.25	33.18	31.98

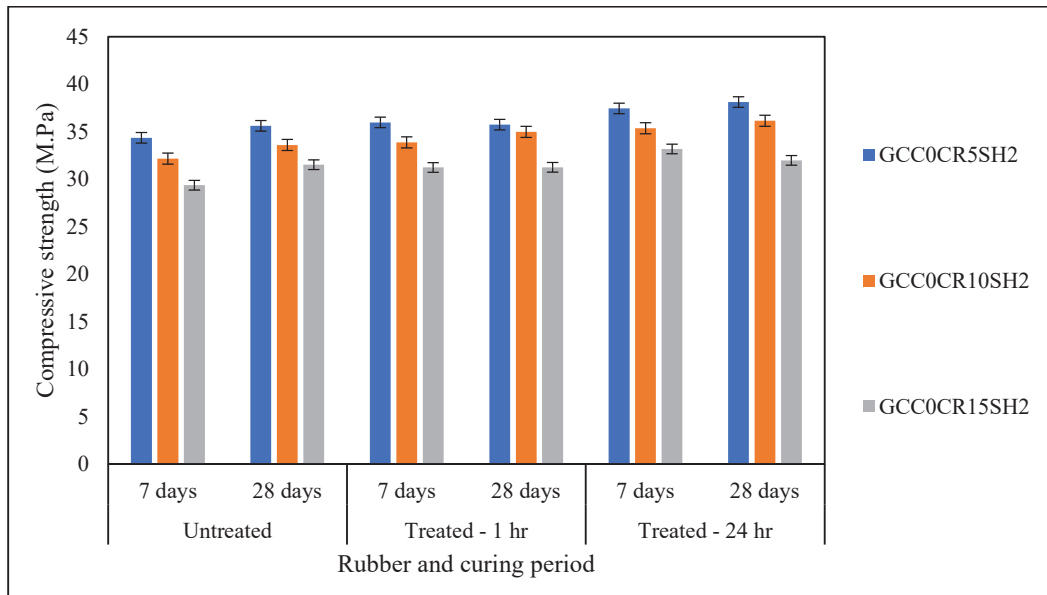


Fig 4.32: Compressive strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 7 and 28 days.

The study investigates the compressive strength of geopolymer concrete samples that incorporate copper slag at replacement levels of 30, 40, and 50 %, and crumb rubber at 5, 10, and 15 % as substitutes for fine and coarse aggregates, respectively. The impact of these replacements on the compressive strength of geopolymer concrete is detailed in **Table 4.19**. For untreated rubber mixes, a slight decrease in compressive strength was observed, from 40.83 MPa to 39.06 MPa over a 7-day curing period. In contrast, 1-hour treated rubber mixes demonstrated compressive strengths ranging from 43.21 MPa to 42.62 MPa, while 24-hour treated rubber mixes exhibited a marginal change in strength from 41.25 MPa to 41.23 MPa for the same curing period. Over a 24-day curing period, untreated rubber mixes experienced a decrease in compressive strength from 44.15 MPa to 43.18 MPa. However, 1-hour treated rubber mixes saw an increase in strength from 43.21 MPa to 43.87 MPa, and 24-hour treated rubber mixes further increased from 45.17 MPa to 44.62 MPa, as illustrated in **Fig 4.33**.

The replacement of fine aggregates with copper slag at levels of 30, 40, and 50 % tends to increase the compressive strength of geopolymer concrete. Copper slag, being denser and possessing pozzolanic properties, contributes to a denser concrete matrix and potentially participates in the geopolymerization process, thereby enhancing the concrete's strength. Conversely, the addition of crumb rubber at 5, 10, and 15 % as a replacement for coarse

aggregates generally results in a decrease in compressive strength. The specific characteristics of rubber, such as its lower stiffness and weaker bonding with the geopolymer matrix compared to conventional aggregates, lead to less efficient load transfer within the concrete.

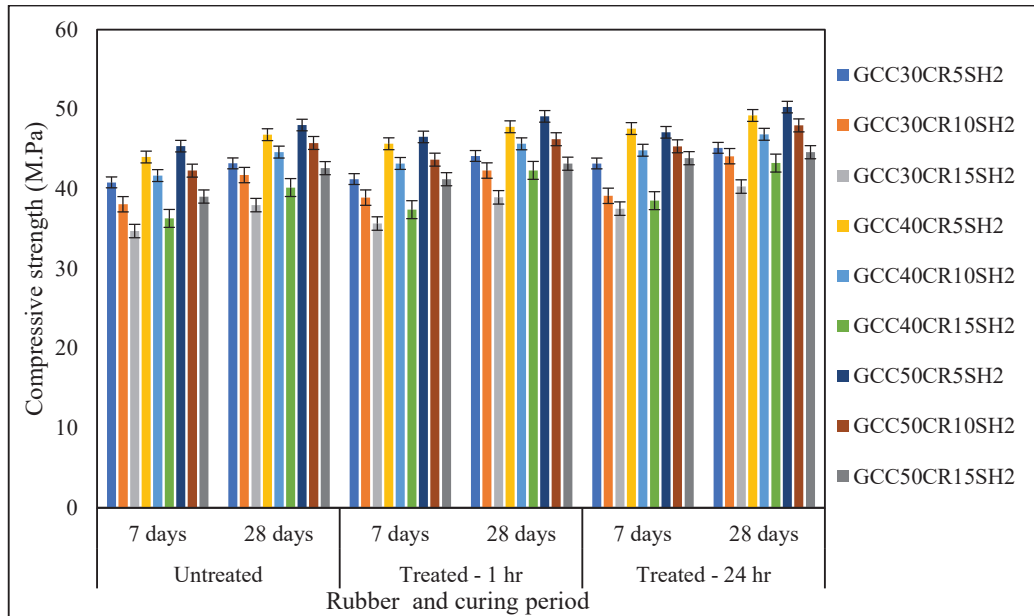


Fig 4.33: Compressive strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 7 and 28 days.

Table 4.19: Compressive strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 7 and 28 days.

Compressive strength (MPa)	Untreated		Treated - 1 hr		Treated - 24 hr	
	7 days	28 days	7 days	28 days	7 days	28 days
Mixes						
GCC30CR5SH2	40.83	43.216	41.25	44.15	43.21	45.17
GCC30CR10SH2	38.09	41.753	38.92	42.32	39.15	44.12
GCC30CR15SH2	34.73	37.983	35.67	38.96	37.54	40.31
GCC40CR5SH2	44.02	46.819	45.68	47.81	47.59	49.23
GCC40CR10SH2	41.69	44.64	43.21	45.67	44.87	46.87
GCC40CR15SH2	36.31	40.187	37.41	42.34	38.54	43.26

GCC50CR5SH2	45.38	48.031	46.54	49.12	47.12	50.28
GCC50CR10SH2	42.31	45.78	43.69	46.25	45.36	47.98
GCC50CR15SH2	39.06	42.621	41.23	43.18	43.87	44.62

4.6.2 Flexural strength of concrete:

Flexural strength studies of geopolymer concrete are conducted in research to evaluate the material's ability to resist bending forces, which is crucial for determining its structural performance and suitability for construction applications where bending stresses are prevalent. These studies also help in understanding how various factors, such as the incorporation of different aggregates, NaOH molarity, and SS/SH ratios, influence the flexural behavior and durability of geopolymer concrete under load. This study examines the flexural strength of conventional geopolymer concrete, analyzing the impact of various NaOH molarity levels (8, 10, and 12) and SS/SH ratios (1, 2, and 3) over a 28-day period as detailed in **Table 4.20**. The findings indicate that increasing the SS/SH ratio consistently leads to an increase in flexural strength. Specifically, at an NaOH molarity of 8 M, the flexural strengths recorded for SS/SH ratios of 1, 2, and 3 were 5.12 MPa, 5.32 MPa, and 5.59 MPa, respectively. This improvement in flexural strength is attributed to the enhanced geopolymerization reaction facilitated by the increased presence of sodium silicate, which provides additional soluble silica for the reaction. This enhanced geopolymerization contributes to a more robust microstructure, improving the concrete's ability to resist bending stresses. At a NaOH molarity of 10 M, the flexural strengths were 5.89 MPa, 6.03 MPa, and 6.29 MPa, respectively. Furthermore, at a NaOH molarity of 12 M, the flexural strengths were 6.23 MPa, 6.42 MPa, and 6.87 MPa, as illustrated in **Fig 4.34**. The higher NaOH molarities contribute to a more effective geopolymerization process, leading to improved flexural strength in fly ash-based geopolymer concrete.

Table 4.20: Flexural strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 28 days.

Flexural strength (MPa)	28 days		
	8 M	10 M	12 M
Mixes			
GCC0SH1	5.12	5.89	6.23
GCC0SH2	5.32	6.03	6.42

GCC0SH3	5.59	6.29	6.87
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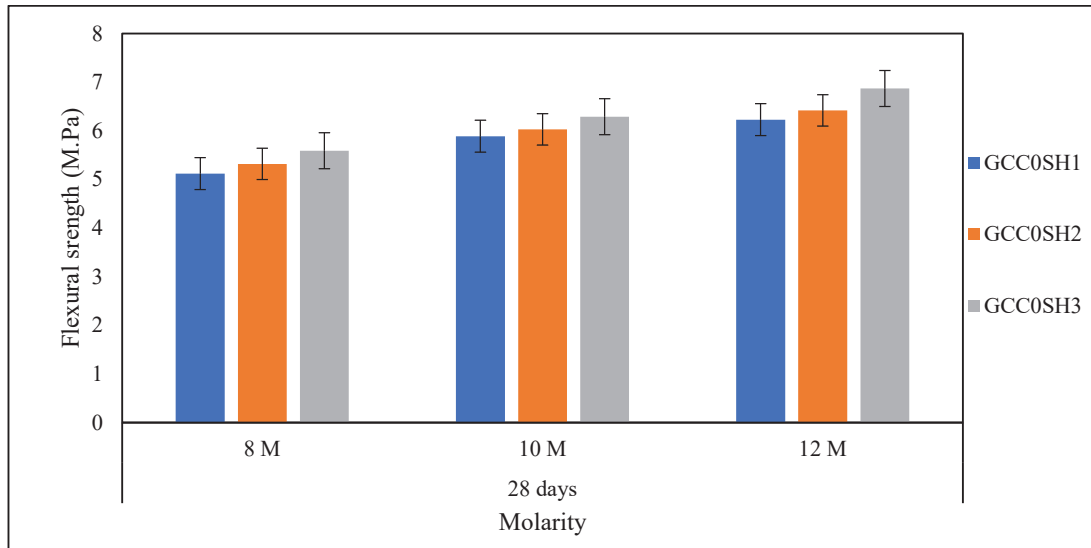


Fig 4.34: Flexural strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 28 days.

This study investigates the flexural strength of geopolymer concrete when fine aggregates are substituted with copper slag at varying percentages (10, 20, 30, 40, and 50 %). It evaluates the impact of different sodium silicate to sodium hydroxide (SS/SH) ratios and NaOH molarities on the flexural strength of copper slag-based geopolymer concrete, as detailed in **Table 4.21**. For geopolymer concrete with an SS/SH ratio of 1 and an NaOH molarity of 8 M, the flexural strength over a 28-day curing period ranges from 5.26 MPa with 10 % copper slag to 5.72 MPa with 50 % copper slag. When the NaOH molarity is increased to 10 M, the 28-day flexural strengths range from 5.95 MPa for 10 % copper slag to 6.38 MPa for 50 % copper slag. At the highest tested NaOH molarity of 12 M, the 28-day flexural strengths start at 6.34 MPa for 10 % copper slag and peak at 6.82 MPa for 50 % copper slag, as illustrated in **Fig 4.35**.

Table 4.21: Flexural strength of coper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 28 days.

Flexural strength (MPa)	28 days		
Mixes	8 M	10 M	12 M
GCC10SH1	5.26	5.95	6.34

GCC20SH1	5.38	6.04	6.45
GCC30SH1	5.42	6.13	6.59
GCC40SH1	5.59	6.23	6.7
GCC50SH1	5.72	6.38	6.82
GCC10SH2	5.46	6.18	6.54
GCC20SH2	5.61	6.29	6.67
GCC30SH2	5.78	6.37	6.79
GCC40SH2	5.82	6.46	6.83
GCC50SH2	5.97	6.58	6.89
GCC10SH3	5.63	6.38	6.94
GCC20SH3	5.82	6.49	7.01
GCC30SH3	5.94	6.62	7.12
GCC40SH3	5.98	6.71	7.18
GCC50SH3	6.08	6.89	7.22

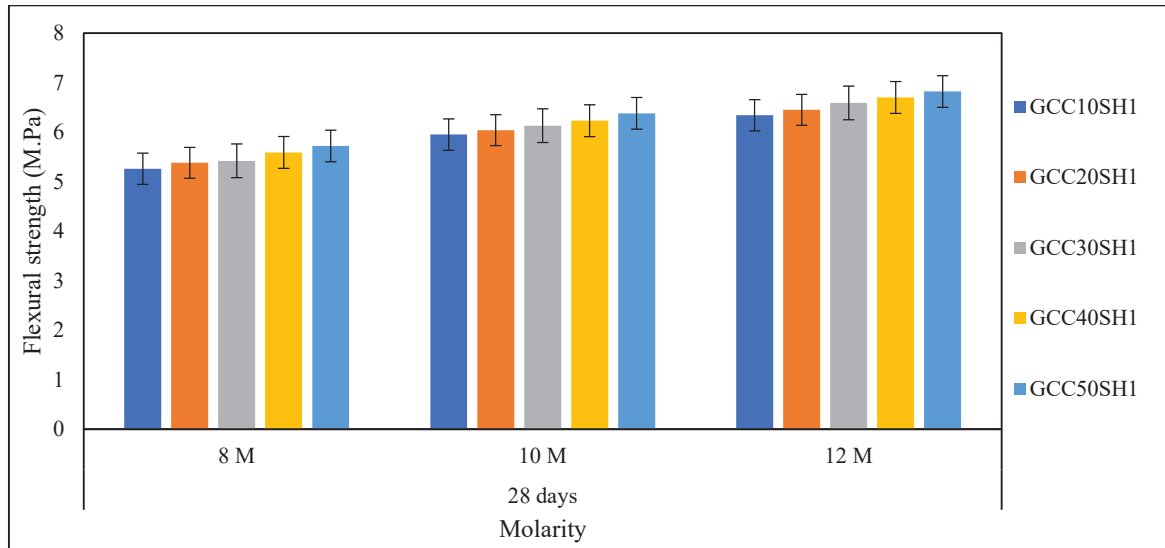


Fig 4.35: Flexural strength of coper slag based geopolymner concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 28 days.

This study examines the flexural strength of geopolymner concrete with an SS/SH ratio of 2 and varying NaOH molarities over a 28-day curing period. For a NaOH molarity of 8 M, the flexural strength ranges from 5.46 MPa with a 10 % copper slag replacement to 5.97 MPa with a 50 % replacement. When the NaOH molarity is increased to 10 M, the 28-day flexural

strengths range from 6.18 MPa for 10 % copper slag to 6.58 MPa for 50 % copper slag. At the highest tested NaOH molarity of 12 M, the 28-day flexural strengths begin at 6.54 MPa for 10% copper slag and peak at 6.89 MPa for 50 % copper slag, as illustrated in **Fig 4.36**.

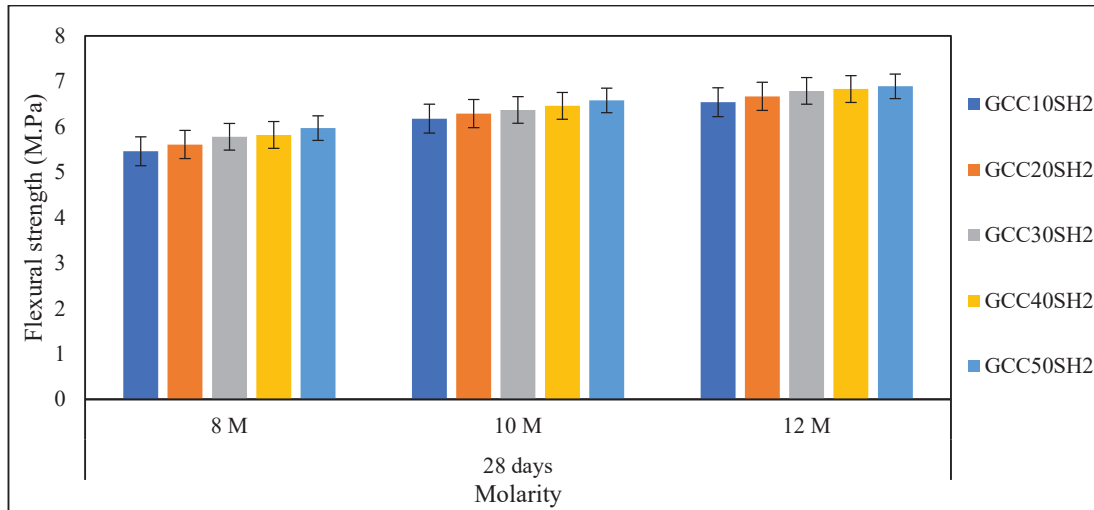


Fig 4.36: Flexural strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 2 for curing period of 28 days.

For geopolymer concrete with an SS/SH ratio of 3 and an NaOH molarity of 8 M, the flexural strength over a 28-day curing period ranged from 5.63 MPa with 10 % copper slag to 6.08 MPa with 50 % copper slag. When the NaOH molarity was increased to 10 M, the 28-day flexural strengths ranged from 6.38 MPa for 10 % copper slag to 6.89 MPa for 50 % copper slag. At the highest tested NaOH molarity of 12 M, the 28-day flexural strengths began at 6.94 MPa for 10 % copper slag and peaked at 7.22 MPa for 50 % copper slag, as illustrated in **Fig 4.37**. The increase in flexural strength can be attributed to the angular and rough texture of copper slag particles, which may enhance the interlocking and bonding within the geopolymer matrix. Additionally, the pozzolanic reaction of copper slag with the alkaline activators in the geopolymer mix could contribute to a denser, more cohesive matrix, thereby improving the flexural strength.

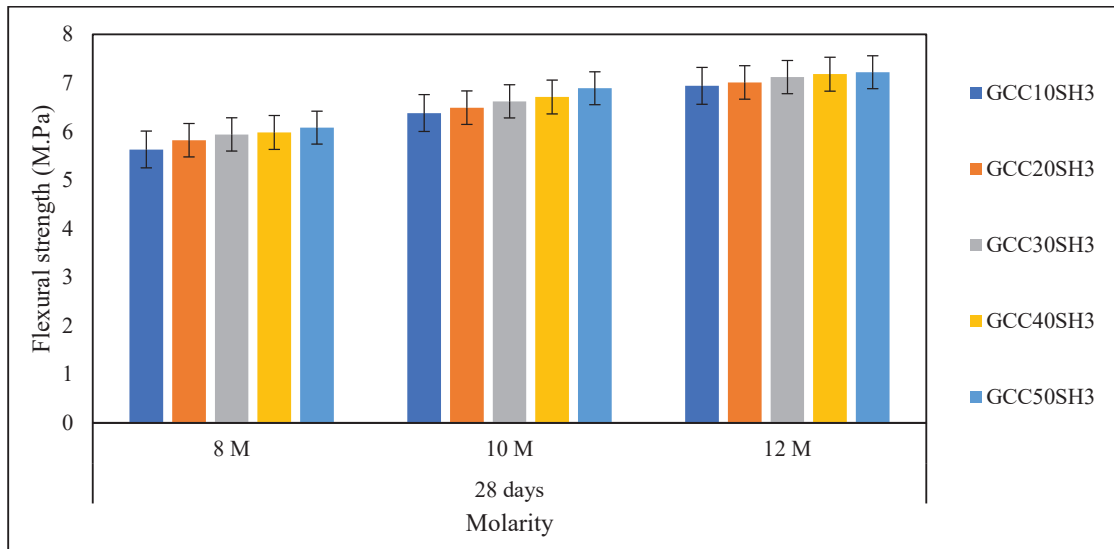


Fig 4.37: Flexural strength of coper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 3 for curing period for curing period of 28 days.

This study investigates the flexural strength of geopolymer concrete when coarse aggregates are partially substituted with crumb rubber at percentages of 5, 10, and 15 %. It assesses the impact of varying treatment durations of crumb rubber (untreated, treated for 1 hour, and treated for 24 hours) on the flexural strength of rubberized geopolymer concrete, maintaining a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.22**. For untreated rubberized geopolymer concrete, the flexural strengths recorded at 28 days were 6.51 MPa, 6.65 MPa, and 6.72 MPa for 5%, 10%, and 15% rubber replacements, respectively. When the crumb rubber underwent treatment for 1 hour, the 28-day flexural strengths slightly improved to 6.53 MPa, 6.69 MPa, and 6.75 MPa. Furthermore, for the 24-hour treated rubberized geopolymer concrete, the 28-day flexural strengths increased to 6.58 MPa, 6.73 MPa, and 6.8 MPa, respectively, as illustrated in **Fig 4.38**.

Table 4.22: Flexural strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

Flexural strength (MPa)	10 M		
Mixes	Untreated	Treated - 1 hr	Treated - 24 hr
GCC0CR5SH2	6.51	6.53	6.58
GCC0CR10SH2	6.65	6.69	6.73
GCC0CR15SH2	6.72	6.75	6.8

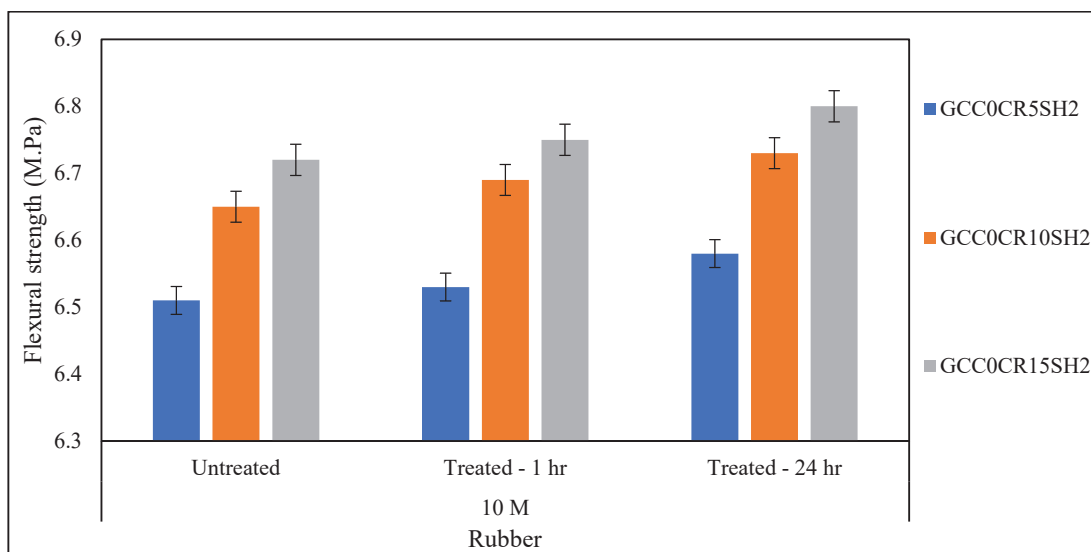


Fig 4.38: Flexural strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

This study investigates the flexural strength of geopolymer concrete samples that incorporate copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively. The impact of these replacements on the flexural strength of geopolymer concrete is detailed in **Table 4.23**. For untreated rubber mixes, the flexural strength slightly increased from 6.8 MPa to 7.01 MPa over a 28-day curing period. In contrast, 1-hour treated rubber mixes demonstrated flexural strengths ranging from 6.82 MPa to 7.07 MPa, while 24-hour treated rubber mixes exhibited a marginal change in strength from 6.86 MPa to 7.12 MPa for the same curing period, as illustrated in **Fig 4.39**.

Table 4.23: Flexural strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

Flexural strength (MPa)	10 M		
Mixes	Untreated	Treated - 1 hr	Treated - 24 hr
GCC30CR5SH2	6.8	6.82	6.86
GCC30CR10SH2	6.87	6.91	6.95

GCC30CR15SH2	6.92	6.98	7.03
GCC40CR5SH2	6.85	6.89	6.96
GCC40CR10SH2	6.94	6.99	7.03
GCC40CR15SH2	6.97	7.02	7.08
GCC50CR5SH2	6.89	6.95	6.99
GCC50CR10SH2	6.95	7.02	7.06
GCC50CR15SH2	7.01	7.07	7.12

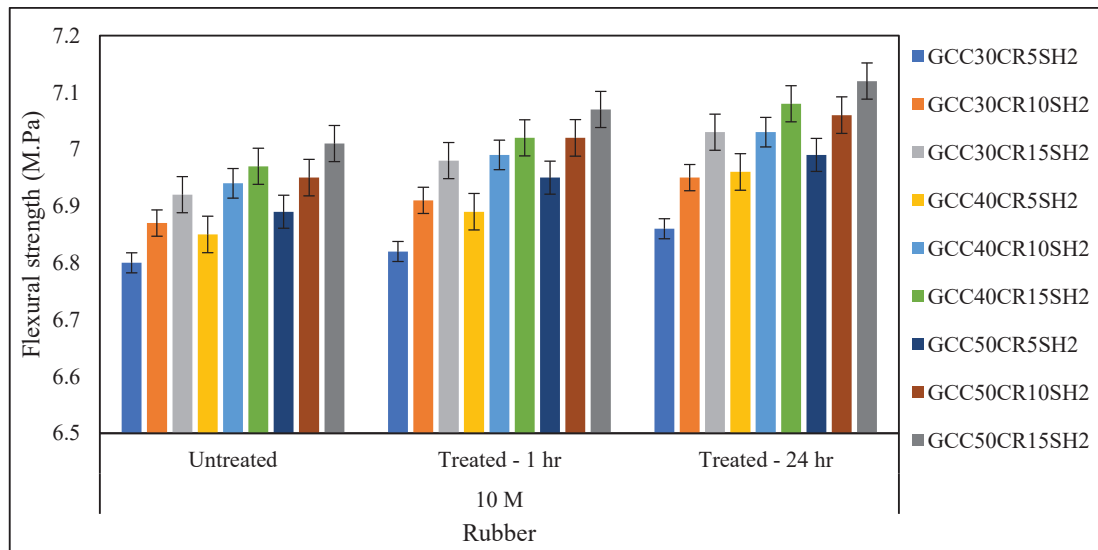


Fig 4.39: Flexural strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

4.6.3 Split tensile strength of concrete:

Split tensile strength studies of geopolymer concrete are conducted in research to evaluate the material's tensile performance, which is crucial for understanding its behavior under tensile loads and its structural integrity in practical applications. These studies help in assessing the suitability of geopolymer concrete for construction scenarios where tensile stress is significant, and in optimizing mix designs to enhance durability and strength. This study investigates the split tensile strength of conventional geopolymer concrete, analyzing the influence of various NaOH molarity levels (8, 10, and 12) and SS/SH ratios (1, 2, and 3) over a 28-day period as detailed in **Table 4.24**. The findings indicate that increasing the SS/SH ratio consistently leads to an increase in split tensile strength. Specifically, at an NaOH molarity of 8 M, the split tensile

strengths recorded for SS/SH ratios of 1, 2, and 3 were 4.2 MPa, 4.38 MPa, and 4.56 MPa, respectively. This improvement in split tensile strength is attributed to the increased availability of soluble silica from the sodium silicate, which enhances the geopolymerization process, leading to a denser and more cohesive material structure. At a NaOH molarity of 10 M, the strengths were 4.6 MPa, 4.75 MPa, and 4.86 MPa, respectively. Additionally, at a NaOH molarity of 12 M, the split tensile strengths were 4.78 MPa, 4.98 MPa, and 5.06 MPa, as illustrated in **Fig 4.40**. These findings suggest that higher NaOH molarities not only improve the geopolymerization process by providing a more alkaline environment conducive to the dissolution of silicate structures in fly ash but also contribute to the development of a more robust microstructure, enhancing the material's resistance to tensile stresses.

Table 4.24: Split tensile strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 28 days.

Split tensile strength (MPa)	28 days		
Mixes	8 M	10 M	12 M
GCC0SH1	4.2	4.6	4.78
GCC0SH2	4.38	4.75	4.98
GCC0SH3	4.56	4.86	5.06

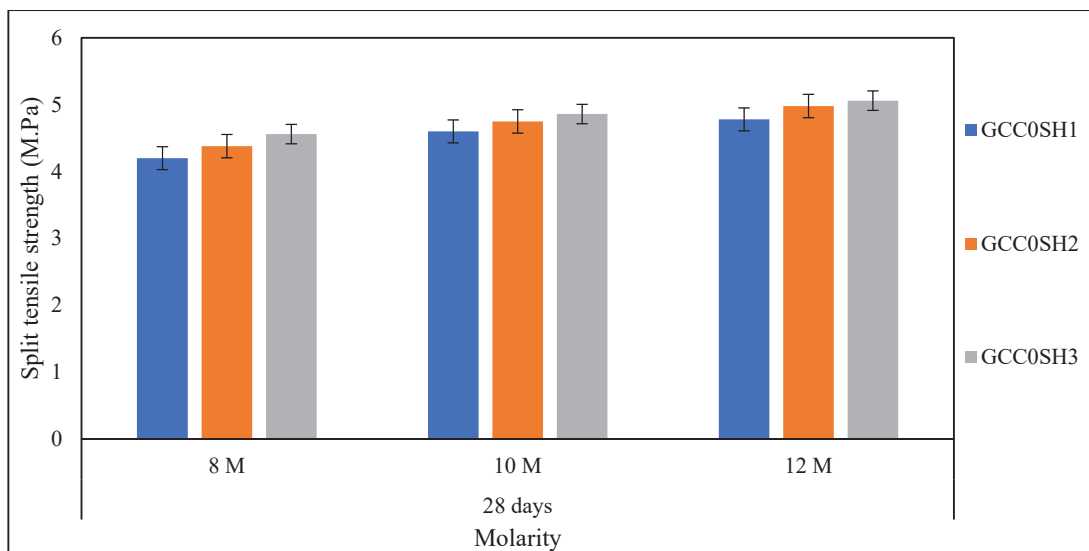


Fig 4.40: Split tensile strength of conventional geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1, 2 and 3 for curing period of 28 days.

This study investigates the split tensile strength of geopolymer concrete when fine aggregates are substituted with copper slag at varying percentages (10%, 20%, 30%, 40%, and 50%). It assesses the impact of different sodium silicate to sodium hydroxide (SS/SH) ratios and NaOH molarities on the split tensile strength of copper slag-based geopolymer concrete, as outlined in **Table 4.25**. For geopolymer concrete with an SS/SH ratio of 1 and an NaOH molarity of 8 M, the split tensile strength over a 28-day curing period ranged from 4.44 MPa with 10% copper slag to 4.86 MPa with 50% copper slag. When the NaOH molarity was increased to 10 M, the 28-day split tensile strengths ranged from 4.72 MPa for 10% copper slag to 4.98 MPa for 50% copper slag. At the highest tested NaOH molarity of 12 M, the 28-day split tensile strengths began at 4.89 MPa for 10% copper slag and peaked at 5.18 MPa for 50% copper slag, as illustrated in **Fig 4.41**.

Table 4.25: Split tensile strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 28 days.

Split tensile strength (MPa)	28 days		
Mixes	8 M	10 M	12 M
GCC10SH1	4.44	4.72	4.89
GCC20SH1	4.52	4.79	4.98
GCC30SH1	4.66	4.85	5.09
GCC40SH1	4.78	4.92	5.12
GCC50SH1	4.86	4.98	5.18
GCC10SH2	4.49	4.86	5.07
GCC20SH2	4.58	4.95	5.18
GCC30SH2	4.62	4.99	5.26
GCC40SH2	4.68	5.06	5.32
GCC50SH2	4.76	5.12	5.47
GCC10SH3	4.62	4.98	5.14
GCC20SH3	4.71	5.07	5.22
GCC30SH3	4.78	5.12	5.28
GCC40SH3	4.82	5.19	5.35
GCC50SH3	4.89	5.27	5.46

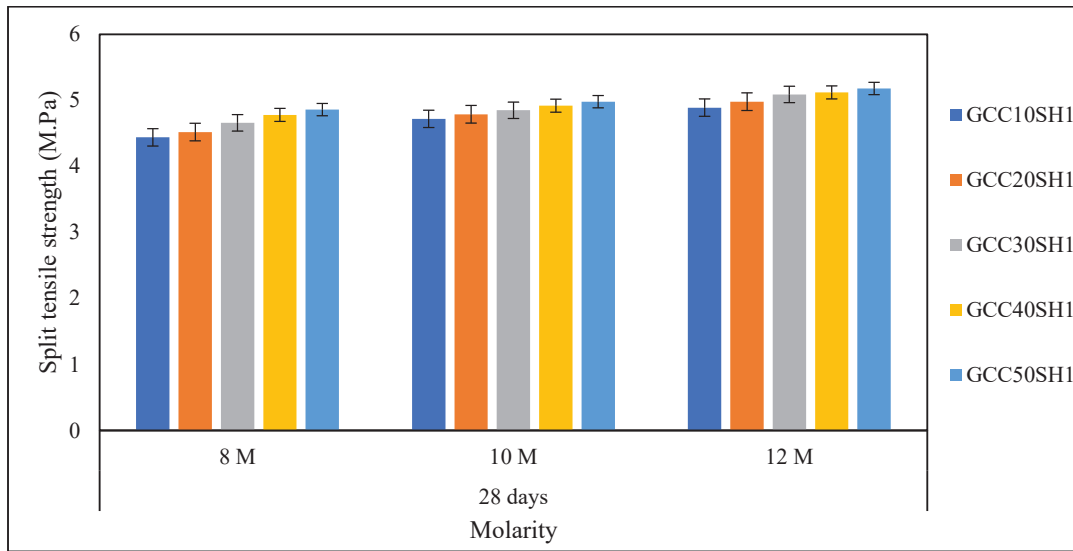


Fig 4.41: Split tensile strength of coprer slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 1 for curing period of 28 days.

For geopolymer concrete with an SS/SH ratio of 2 and an NaOH molarity of 8 M, the split tensile strength over a 28-day curing period ranged from 4.49 MPa with a 10% copper slag replacement to 4.76 MPa with a 50% replacement. When the NaOH molarity was increased to 10 M, the 28-day split tensile strengths ranged from 4.86 MPa for a 10% copper slag replacement to 5.12 MPa for a 50% replacement. At the highest tested NaOH molarity of 12 M, the 28-day split tensile strengths began at 5.07 MPa for a 10% copper slag replacement and peaked at 5.47 MPa for a 50% replacement, as illustrated in **Fig 4.42**.

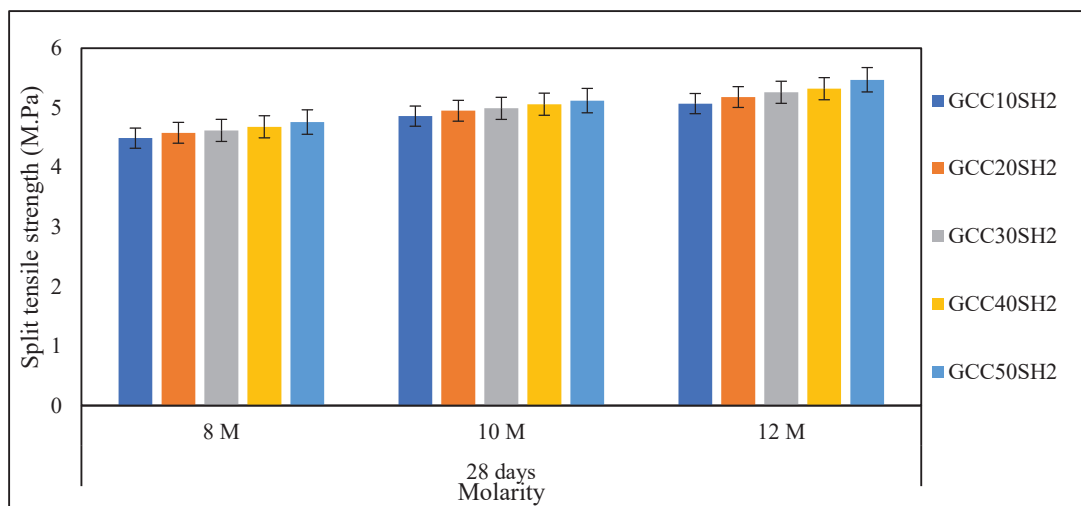


Fig 4.42: Split tensile strength of coprer slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 2 for curing period of 28 days.

For geopolymer concrete with an SS/SH ratio of 3 and an NaOH molarity of 8 M, the split tensile strength over a 28-day curing period ranged from 4.62 MPa with 10% copper slag to 4.89 MPa with 50% copper slag. When the NaOH molarity was increased to 10 M, the 28-day split tensile strengths ranged from 4.98 MPa for 10% copper slag to 5.27 MPa for 50% copper slag. At the highest tested NaOH molarity of 12 M, the 28-day split tensile strengths began at 5.14 MPa for 10% copper slag and peaked at 5.46 MPa for 50% copper slag, as illustrated in **Fig 4.43**. The optimal enhancement in strength is achieved through a balance between the physical contributions of copper slag and the chemical dynamics of the geopolymerization process. Replacing fine aggregate with copper slag beyond 50% leads to a reduction in strength, likely due to an oversaturation of the mix with materials that do not contribute as effectively to the matrix's structural integrity.

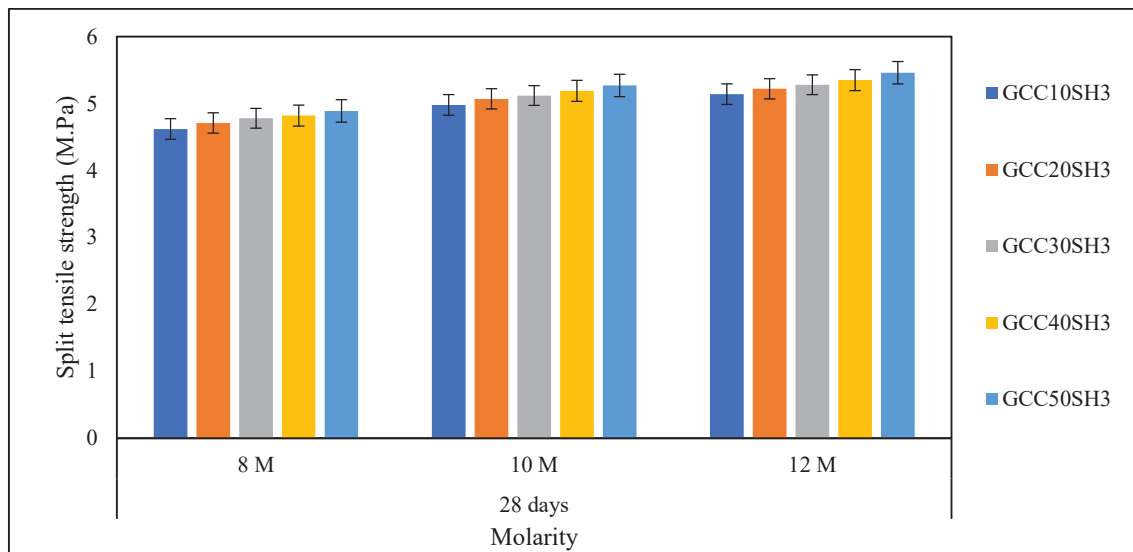


Fig 4.43: Split tensile strength of copper slag based geopolymer concrete for NaOH molarity of 8, 10, and 12 and SS/SH ratio of 3 for curing period of 28 days.

This study investigates the split tensile strength of geopolymer concrete when coarse aggregates are partially replaced with crumb rubber at percentages of 5%, 10%, and 15%. It assesses the impact of different treatment durations of crumb rubber (untreated, treated for 1 hour, and treated for 24 hours) on the split tensile strength of rubberized geopolymer concrete, maintaining a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.26**. For untreated rubberized geopolymer concrete, the split tensile strengths recorded at 28 days were 5.03 MPa, 5.11 MPa, and 5.17 MPa for 5%, 10%, and 15% rubber replacements, respectively. When the crumb rubber underwent treatment for 1 hour, the 28-day split tensile

strengths slightly improved to 5.08 MPa, 5.15 MPa, and 5.20 MPa. Furthermore, for the 24-hour treated rubberized geopolymer concrete, the 28-day split tensile strengths increased to 5.13 MPa, 5.19 MPa, and 5.26 MPa, respectively, as illustrated in **Fig 4.44**.

Table 4.26: Split tensile strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

Split tensile strength (MPa)	10 M		
Mixes	Untreated	Treated - 1 hr	Treated - 24 hr
GCC0CR5SH2	5.03	5.08	5.13
GCC0CR10SH2	5.11	5.15	5.19
GCC0CR15SH2	5.17	5.2	5.26

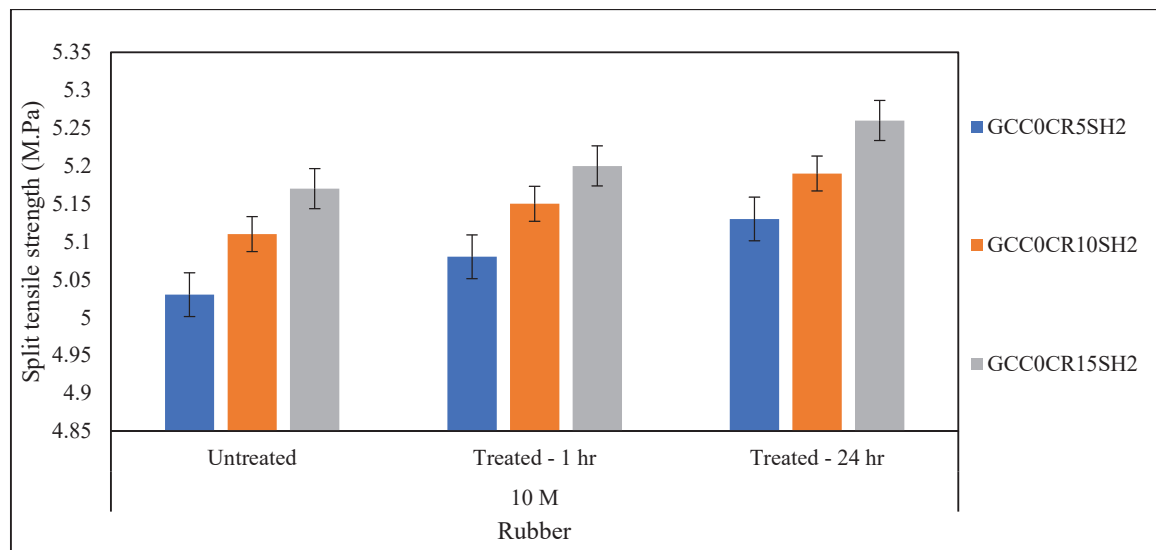


Fig 4.44: Split tensile strength of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

This study investigates the split tensile strength of geopolymer concrete samples that incorporate copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively. The impact of these replacements on the split tensile strength of geopolymer concrete is detailed in **Table 4.27**. For

untreated rubber mixes, the split tensile strength slightly increased from 5.28 MPa to 5.64 MPa over a 28-day curing period. In contrast, rubber mixes treated for 1 hour exhibited split tensile strengths ranging from 5.32 MPa to 5.68 MPa. Additionally, rubber mixes treated for 24 hours showed a marginal change in strength, from 5.37 MPa to 5.71 MPa over the same curing period, as illustrated in **Fig 4.45**.

Table 4.27: Split tensile strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

Split tensile strength (MPa) for Mixes	10 M		
	Untreated	Treated - 1 hr	Treated - 24 hr
GCC30CR5SH2	5.28	5.32	5.37
GCC30CR10SH2	5.32	5.38	5.46
GCC30CR15SH2	5.39	5.42	5.48
GCC40CR5SH2	5.36	5.39	5.43
GCC40CR10SH2	5.43	5.46	5.49
GCC40CR15SH2	5.5	5.57	5.61
GCC50CR5SH2	5.49	5.53	5.62
GCC50CR10SH2	5.58	5.61	5.64
GCC50CR15SH2	5.64	5.68	5.71

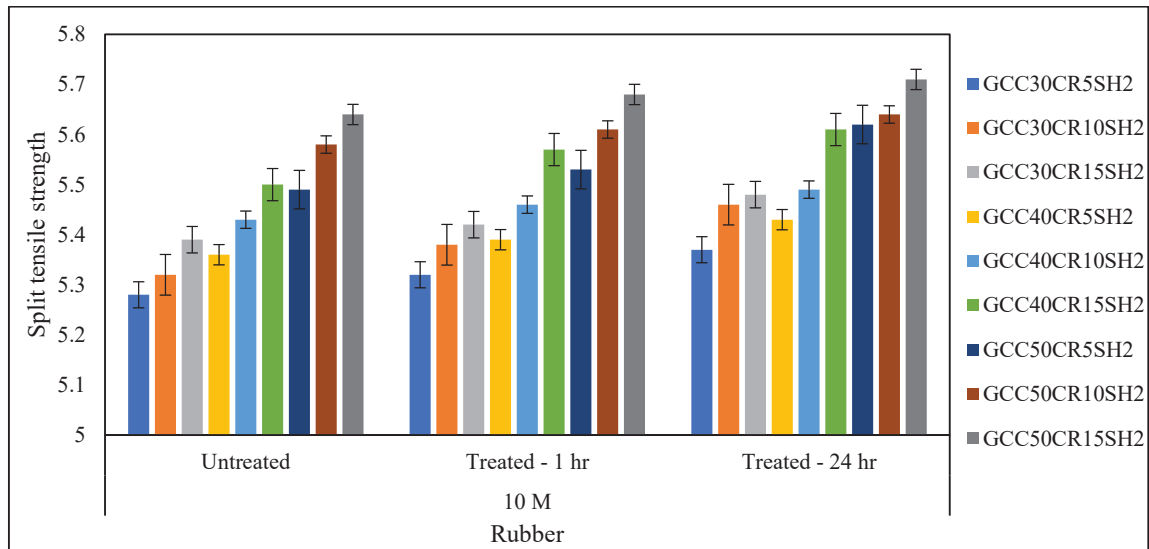


Fig 4.45: Split tensile strength of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for untreated, 1 hr.-treated, 24 hr.-treated for curing period of 28 days.

4.7 Durability of concrete

4.7.1 Sorptivity of concrete:

Sorptivity studies of geopolymer concrete are conducted in research to assess the material's ability to absorb and transmit water by capillary action, which is crucial for understanding its durability and performance in moisture-laden environments. These studies provide insights into the porosity and permeability of geopolymer concrete, influencing decisions on its use in various construction applications, especially those exposed to water and other fluids. The water permeation through unsaturated concrete is significantly influenced by its sorptivity, which is determined by a variety of factors including the mix proportions, the type of admixtures used, the incorporation of supplementary cementitious materials, the physical characteristics of the aggregates, and the concrete placement method. This study focuses on the sorptivity of geopolymer concrete when coarse aggregates are partially substituted with crumb rubber at percentages of 5%, 10%, and 15%. It assesses the impact of different crumb rubber treatment durations (untreated, treated for 1 hour, and treated for 24 hours) on the sorptivity of rubberized geopolymer concrete, maintaining a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as outlined in **Table 4.28**. **Figure 4.46** depicts the relationship between the sorptivity

coefficient ($\text{mm/sec}^{0.5}$) and various mixes of rubberized slag-based geopolymer concrete (GPC). The results indicate that the addition of rubber leads to an increase in sorptivity by 18% and 25% for 10% and 15% rubber replacements, respectively, as coarse aggregate, due to its propensity to facilitate water ingress from the bottom surface.

Table 4.28: Sorptivity of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Mixes ($\text{mm/sec}^{0.5}$)	28 days	90 days
GCC0CR5SH2	0.00938	0.00862
GCC0CR10SH2	0.01116	0.01017
GCC0CR15SH2	0.01144	0.01094

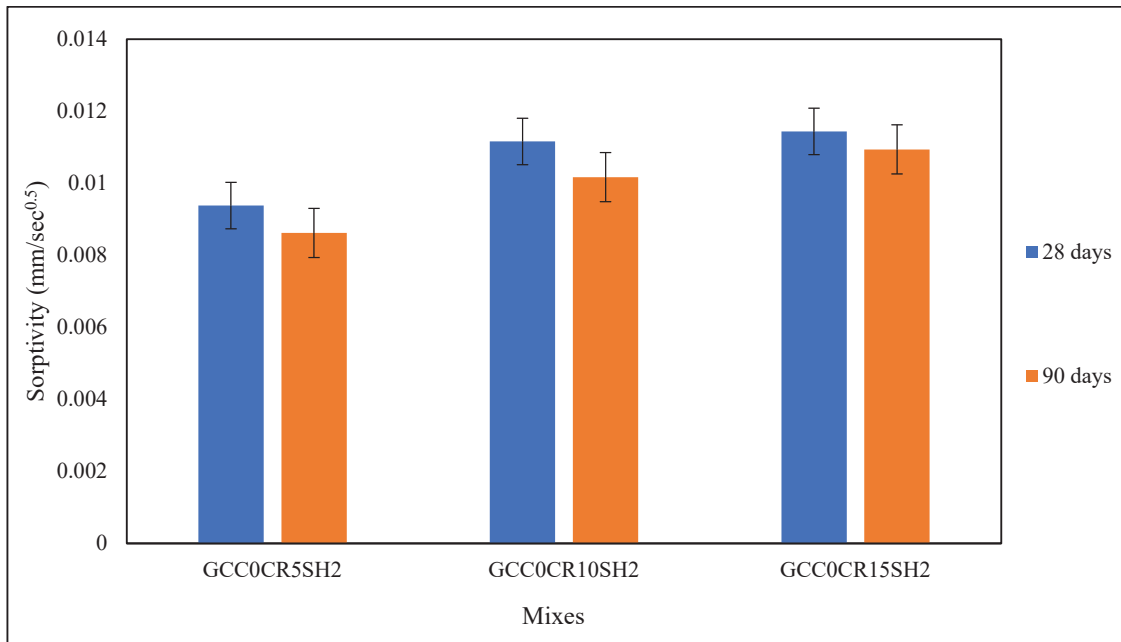


Fig 4.46: Sorptivity of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Table 4.29: Sorptivity of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Mixes (mm/sec ^{0.5})	28 days	90 days
GCC30CR5SH2	0.00727	0.007
GCC30CR10SH2	0.00836	0.00812
GCC30CR15SH2	0.00872	0.00868
GCC40CR5SH2	0.00801	0.00738
GCC40CR10SH2	0.00905	0.00826
GCC40CR15SH2	0.00945	0.00885
GCC50CR5SH2	0.00827	0.00755
GCC50CR10SH2	0.00924	0.00829
GCC50CR15SH2	0.00952	0.00892

This study investigates the sorptivity of geopolymer concrete samples that incorporate copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively. The impact of these replacements on the sorptivity of geopolymer concrete is detailed in **Table 4.29**. It was observed that the combination of copper slag and fly ash effectively reduced sorptivity values. Specifically, as the copper slag content increased from 0% to 30%, there was a notable decrease in sorptivity, followed by an upward trend in geopolymer concrete (GPC). After 28 days of curing, the sorptivity decreased by 29%, 17%, and 15% for 30%, 40%, and 50% copper slag replacements, respectively. Moreover, the mix with 30% copper slag exhibited a 23% decrease in sorptivity after 90 days of curing compared to the mix with 0% copper slag, as shown in **Fig 4.47**. This reduction can be attributed to the improved pore structure of the GPC matrix, resulting from the copper slag acting as a filler material and contributing additional calcium-based reaction products. Large, permeable pores were partially filled by the extra calcium products generated by the copper slag, leading to smaller, non-permeable pores and a denser GPC matrix over time. This observation aligns with the water absorption results. Overall, sorptivity decreased as curing ages increased, leading to a more robust matrix structure and reduced water permeability.

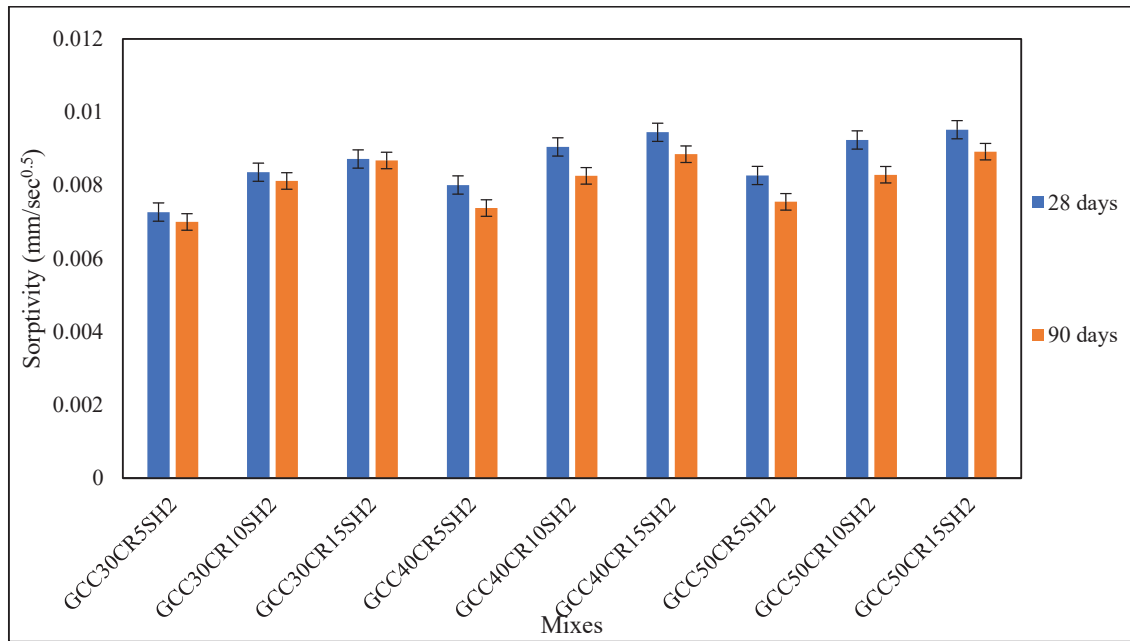


Fig 4.47: Sorptivity of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

4.7.2 RCPT of concrete:

The Rapid Chloride Permeability Test (RCPT) is conducted to assess the concrete's resistance to chloride ion infiltration, a critical factor since chloride ions can cause corrosion of steel reinforcement within the concrete, compromising its structural integrity. The RCPT is widely utilized due to its rapid and reliable measurement of concrete's chloride permeability, essential for evaluating its durability and suitability for various applications, particularly in structures exposed to seawater or de-icing chemicals.

This study evaluates the impact of partial replacement of coarse aggregates with crumb rubber at percentages of 5%, 10%, and 15% on the sorptivity of rubberized geopolymer concrete. The concrete maintained a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.30**. Additionally, the study investigates the sorptivity of geopolymer concrete samples incorporating copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively, as outlined in **Table 4.31**.

The RCPT values, recorded at 28 and 90 days, are depicted in **Fig 4.48 and 4.49**. At 28 days, the RCPT values ranged from 761.04 to 1138.41 Coulombs, with the GCC0CR5SH2 mix and GCC30CR15SH2 mix showing the maximum and minimum values, respectively. By 90 days,

these figures had declined to a range of 518.62-631.84 Coulombs. Across all ages, the lowest RCPT values were noted for the GCC30CR15SH2 mix. When the content of copper slag exceeded 30%, there was a rise in RCPT values, indicating diminished resistance to chloride ion penetration. This decline can be attributed to several factors: (1) the inclusion of copper slag, which reduced the air content in the matrix structure, thereby fortifying its microstructure; (2) the additional binding effect from the copper slag led to a more compact microstructure. Consequently, there was a decrease in RCPT values. However, when the copper slag content surpassed 30%, it was anticipated that the microstructure would degrade, resulting in an increase in void numbers. This created a more accessible path for chloride ion penetration, elevating the likelihood of chloride-induced corrosion. Additionally, as the age increased, so did the resistance to chloride ion penetration, as signified by the declining RCPT values. This underscores that an enhanced microstructure over time contributes to increased resistance.

The water-repellent characteristics of rubber make it more resilient to chloride in concrete. Incorporating rubber aggregates into concrete helps reduce voids by addressing inadequate bonding between rubber aggregates and the binder. The categorization of chloride penetration resistance, based on the charge passed, was conducted following the ASTM C1202 (2012) guidelines, as detailed in **Table 4.32**. All the mixes were classified under the 'very low' category, which is crucial for ensuring long-term durability performance.

Table 4.30: RCPT of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Mixes (Coulombs)	28 days	90 days
GCC0CR5SH2	1138.41	631.84
GCC0CR10SH2	1079.44	611.62
GCC0CR15SH2	1072.46	599.05

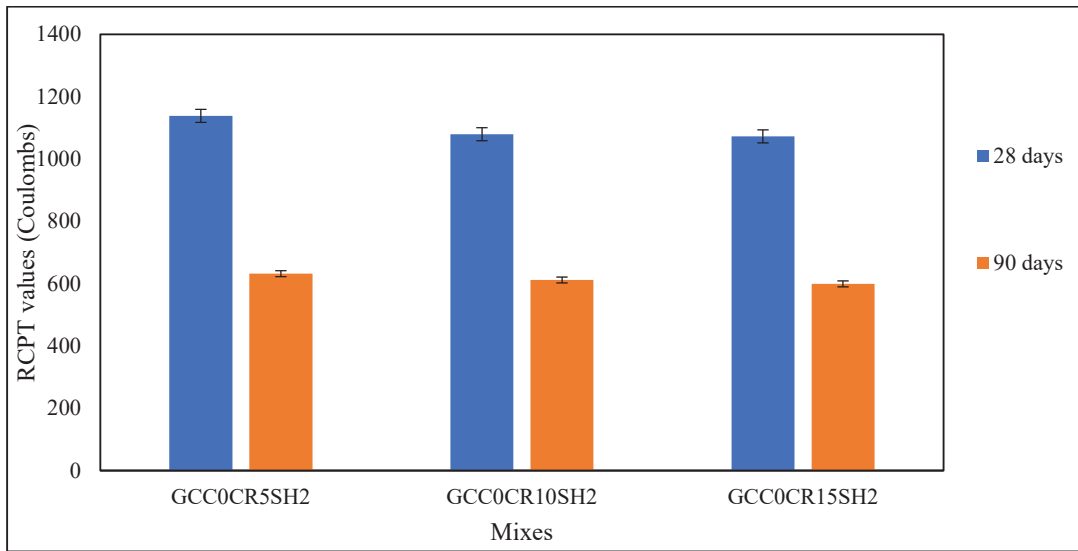


Fig 4.48: RCPT of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Table 4.31: RCPT of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Mixes (Coulombs)	28 days	90 days
GCC30CR5SH2	807.84	547
GCC30CR10SH2	765.99	529.49
GCC30CR15SH2	761.04	518.62
GCC40CR5SH2	952.32	574.9
GCC40CR10SH2	902.99	556.5
GCC40CR15SH2	897.15	545.07
GCC50CR5SH2	1036.61	603.93
GCC50CR10SH2	982.9	584.6
GCC50CR15SH2	976.55	572.59

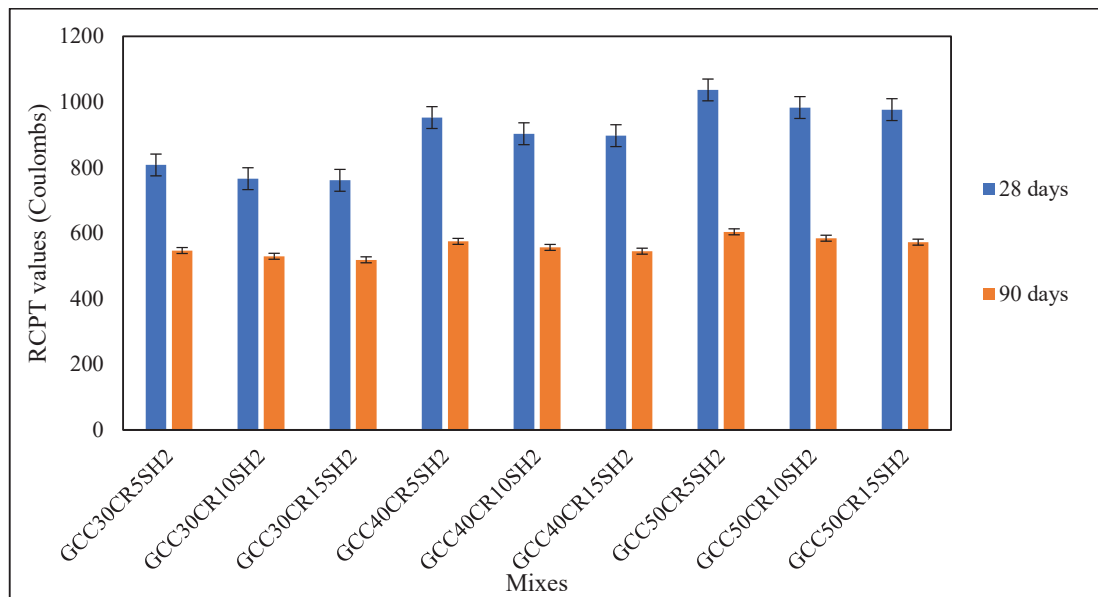


Fig 4.49: RCPT of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 days and 90 days.

Table 4.32: RCPT values suggested by ASTM C1202 (2012)

Charge passed (Coulombs)	Chloride ion permeability range as per ASTM C1202
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
< 100	Negligible

4.7.3 Acid attack on concrete:

4.7.3.1 Weight loss of concrete: Exposure to acidic conditions, such as those found in industrial waste sites, sewage systems, and agricultural areas, presents significant durability challenges for concrete structures. The interaction between acidic substances and the components of the concrete matrix leads to the dissolution of its elements, resulting in reduced

strength, mass loss, and surface erosion. Geopolymer concrete (GPC) samples using copper slag as fine aggregates exhibit expansion cracks due to the abundant formation of gypsum near the surfaces, which results in an increase in the mass of all specimens, as illustrated in the figure above. However, as the replacement of sand by copper slag (CS) increases, the initial gains in mass diminish, and over time, mass losses are observed. The mass loss observed in GPC could be attributed to the solubility of CS fine aggregates in the acidic medium.

This study evaluates the impact of partial replacement of coarse aggregates with crumb rubber at percentages of 5%, 10%, and 15% on the weight loss of rubberized geopolymer concrete. The concrete maintained a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.33**. Additionally, the study investigates the weight loss of geopolymer concrete samples incorporating copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively, as outlined in **Table 4.34**.

The **Fig 50 and 51** shows that the percentage of weight loss decreased with increasing levels of rubber aggregate replacements compared to the control mix of each group after 28, 90, and 120 days of immersion in a sulfuric acid solution. The control mix, GCC50CR15SH2, reported the maximum weight loss, whereas the GCC0CR15SH2 mix exhibited the smallest weight loss of -5.03304 as shown in Table 33 and 34. It is evident that the specimens without rubber aggregates in their mix lost more surface compounds than those containing rubber aggregates. The specimens with 15% rubber aggregates were deemed the best among all samples because they maintained a smoother surface with fewer exposed components and minimal spalling. This suggests that the inclusion of rubber aggregates enhances the acid resistance of the concrete, contributing to better preservation of structural integrity under acidic conditions.

Table 4.33: Weight loss of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 90 and 120 days.

Mixes (%)	28 days	90 days	120 days
GCC0CR5SH2	82.4627	17.538	-5.0866
GCC0CR10SH2	82.025	17.464	-5.0545
GCC0CR15SH2	81.8499	17.3715	-5.033

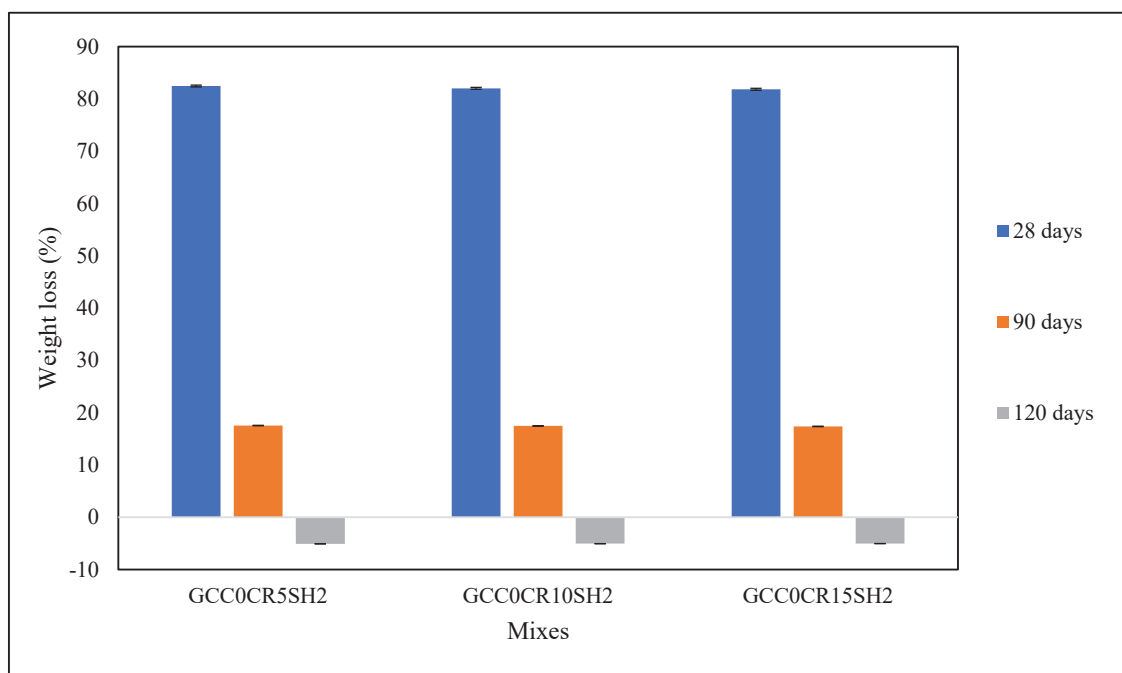


Fig 4.50: Weight loss of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 90 and 120 days.

Table 4.34: Weight loss of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 , 90 and 120 days.

Mixes (%)	28 days	90 days	120 days
GCC30CR5SH2	63.4154	-1.8884	-18.612
GCC30CR10SH2	63.0788	-1.8804	-18.494
GCC30CR15SH2	62.9442	-1.8705	-18.416
GCC40CR5SH2	53.5904	-2.5179	-24.815

GCC40CR10SH2	53.3059	-2.5073	-24.659
GCC40CR15SH2	53.1922	-2.494	-24.554
GCC50CR5SH2	47.5635	-7.802	-28.717
GCC50CR10SH2	47.311	-7.7691	-28.535
GCC50CR15SH2	47.21	-7.728	-28.414

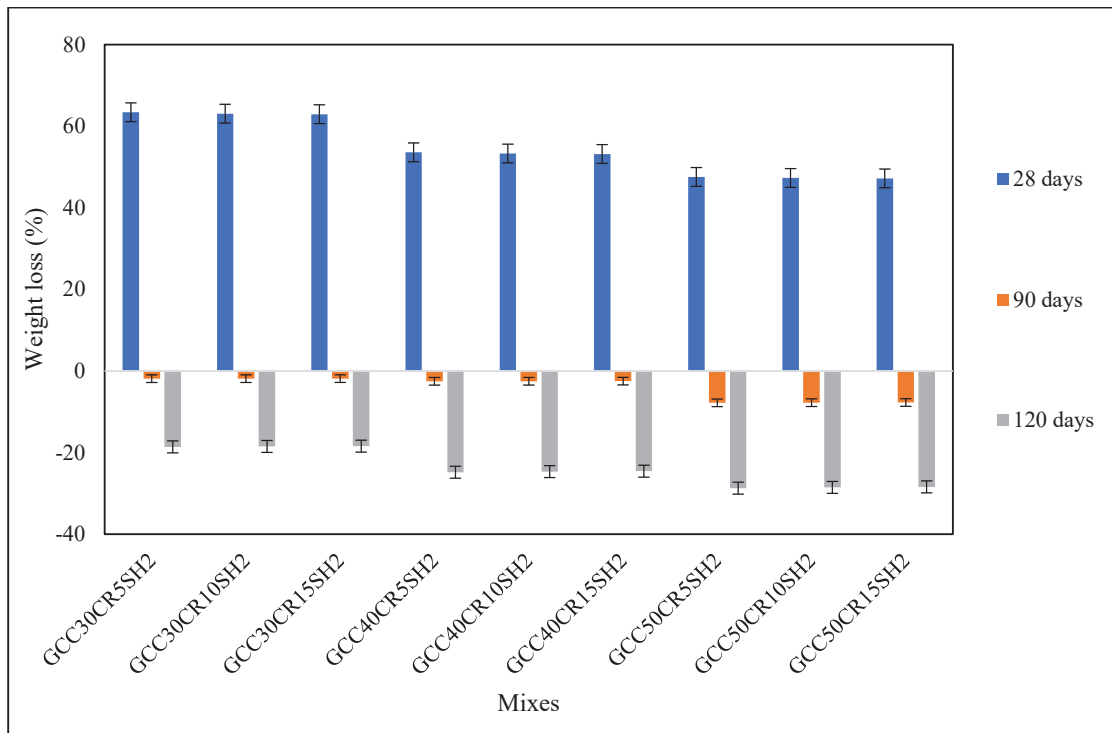


Fig 4.51: Weight loss of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 , 90 and 120 days.

4.7.3.2 Strength loss of concrete: The progress in compressive strength throughout the experiment is illustrated in the figure 52 and 53. There is an approximate 30-50% decrease in strength at 120 days for all Geopolymer Concrete (GPC) samples. The substitution of Copper Slag (CS) for river sand in GPC mixes leads to a decline in compressive strength. This can be ascribed to the earlier dissolution of CS aggregates, with the resultant voids being replaced by acid-filled pores. Further dissolution of CS enlarges the acid-filled pores, thereby speeding up the acid's diffusion through these pores and facilitating its transportation to deeper levels, resulting in increased corrosion.

This study evaluates the impact of partial replacement of coarse aggregates with crumb rubber at percentages of 5%, 10%, and 15% on the compressive strength loss of rubberized geopolymer concrete. The concrete maintained a constant NaOH molarity of 10 M and an SS/SH ratio of 2, as detailed in **Table 4.35**. Additionally, the study investigates the compressive strength loss of geopolymer concrete samples incorporating copper slag at replacement levels of 30%, 40%, and 50%, and crumb rubber at 5%, 10%, and 15% as substitutes for fine and coarse aggregates, respectively, as outlined in **Table 4.36**.

As indicated above, the compressive strength of the specimen subjected to acid attack diminishes with an increase in rubber content. The GCC50CR5SH2 mix, however, maintains the highest compressive strength even after 120 days, registering 26.58 MPa as shown in **Table 4.35 and 4.36**. When sulfuric acid reacts with the hydration products of concrete, it forms Sulphoaluminate, similar to ettringite. The abundant formation of ettringite generates substantial internal pressure within the concrete, leading to crack development that weakens the concrete's upper layer, causing a loss of mass. Mixes containing rubber aggregates have microstructural voids, providing more space for ettringite growth without inducing internal pressure in the concrete. Since rubber is an elastic material, it can absorb the expansion energy induced by ettringite, averting structural failure and resulting in somewhat better compressive load performance. Additionally, the reaction between sulfuric acid and calcium hydroxide in concrete produces gypsum, which appears as a white paste on the concrete samples. During weight measurements, this upper layer of white paste is washed away from the surface of the sample, resulting in a loss of mass. The resilience of rubber particles resists the corrosive effects of sulfuric acid by maintaining their structure, which helps to restrict the development of cracks throughout the concrete matrix.

Table 4.35: Strength loss of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 90 and 120 days.

Mixes (MPa)	28 days	90 days	120 days
GCC0CR5SH2	20.65	14.89	11.64
GCC0CR10SH2	19.63	13.57	10.58
GCC0CR15SH2	17.59	12.78	9.45

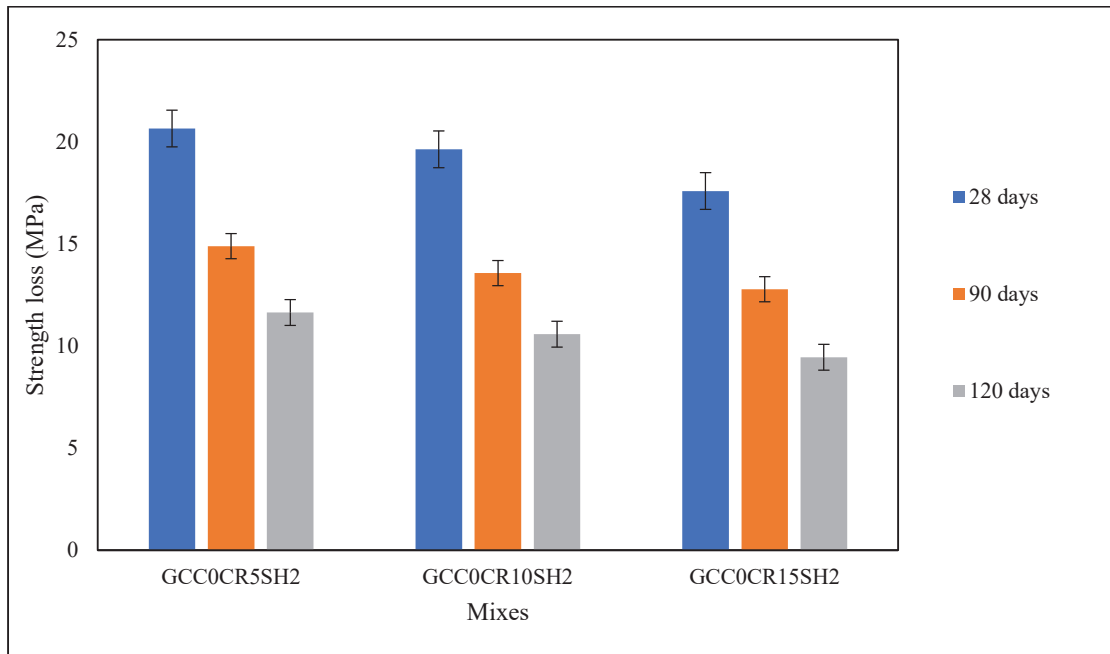


Fig 4.52: Strength loss of rubberized geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 90 and 120 days.

Table 4.36: Strength loss of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 , 90 and 120 days.

Mixes (MPa)	28 days	90 days	120 days
GCC30CR5SH2	30.56	25.53	18.73
GCC30CR10SH2	28.46	23.46	16.47
GCC30CR15SH2	25.13	20.38	15.24
GCC40CR5SH2	41.89	34.16	24.18
GCC40CR10SH2	38.25	29.54	21.62
GCC40CR15SH2	34.76	26.18	19.45
GCC50CR5SH2	46.56	34.97	26.58
GCC50CR10SH2	42.87	31.23	22.76
GCC50CR15SH2	39.58	28.25	20.18

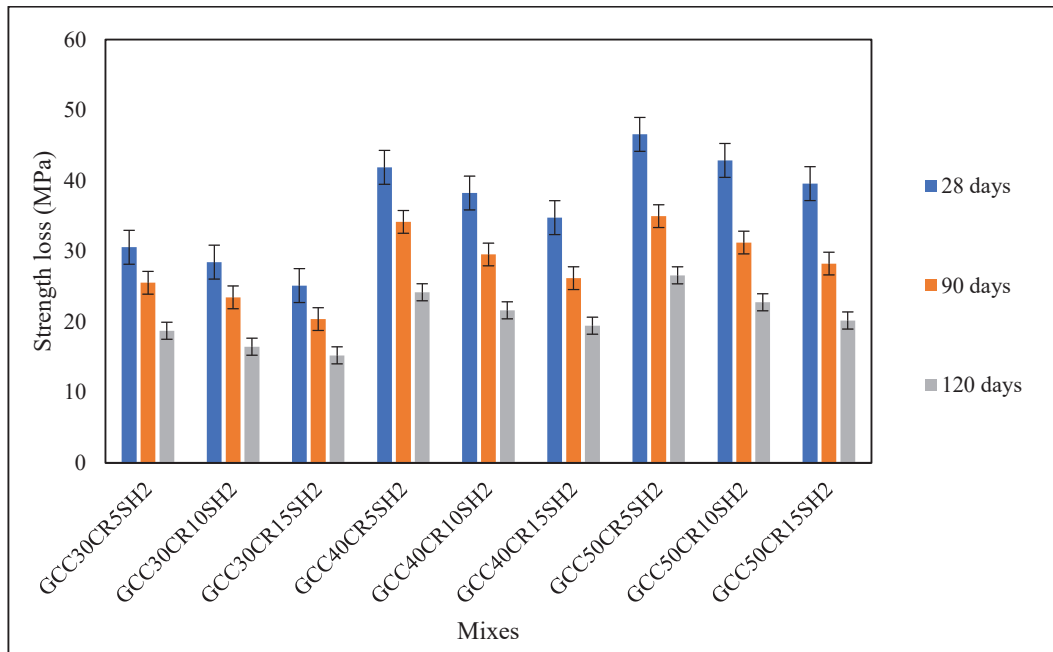


Fig 4.53: Strength loss of rubberized slag based geopolymer concrete for NaOH molarity of 10 M and SS/SH ratio of 2 for 1 hr-treated for curing period of 28 , 90 and 120 days.

4.8 Micro structural analysis:

Scanning Electron Microscopy (SEM) tests were conducted to analyze the bonding morphology and structural characteristics of Geopolymer Concrete (GPC) mixes, with the images presented in Fig 4.54. The plain GPC mix displayed a robust microstructure; however, the presence of partially unreacted fly ash particles suggested that the mix had not achieved its full developmental potential, as corroborated by compressive strength results. The micrographs appeared heterogeneous, compact, and dense, demonstrating a high degree of cohesiveness between the binder phase and coarse particles, which accounts for the observed good mechanical performance.

The GPC mix containing copper slag was analyzed and found to consist of three components: (a) an aggregate, (b) a binder matrix, and (c) an interfacial transition zone (ITZ). A strong pozzolanic-binder matrix was formed due to the reaction between the alkaline solution and copper slag, which encapsulated the surface of the aggregate. At a magnification of 100 μm , a dense ITZ was observed, serving as a separation layer between the aggregate and the polymeric matrix. This ITZ was strengthened by the dissolution of the outer edges of the copper slag aggregate by the alkaline solution, which was then held in place, hindering the polycondensation reaction with the copper slag matrix. These processes contributed to the

formation of a dense matrix, thereby enhancing the concrete's strength. Specimens with 15% rubber replacement exhibited an increase in void volume and crack size around the rubber particles. Additionally, fly ash particles were rarely observed within the matrix, indicating the complete utilization of the binder ingredients. The surfaces of the geopolymer compounds were covered by a scratchy CASH layer at higher resolution, indicating the presence of hydrated calcium-based compounds within the geopolymer matrix.

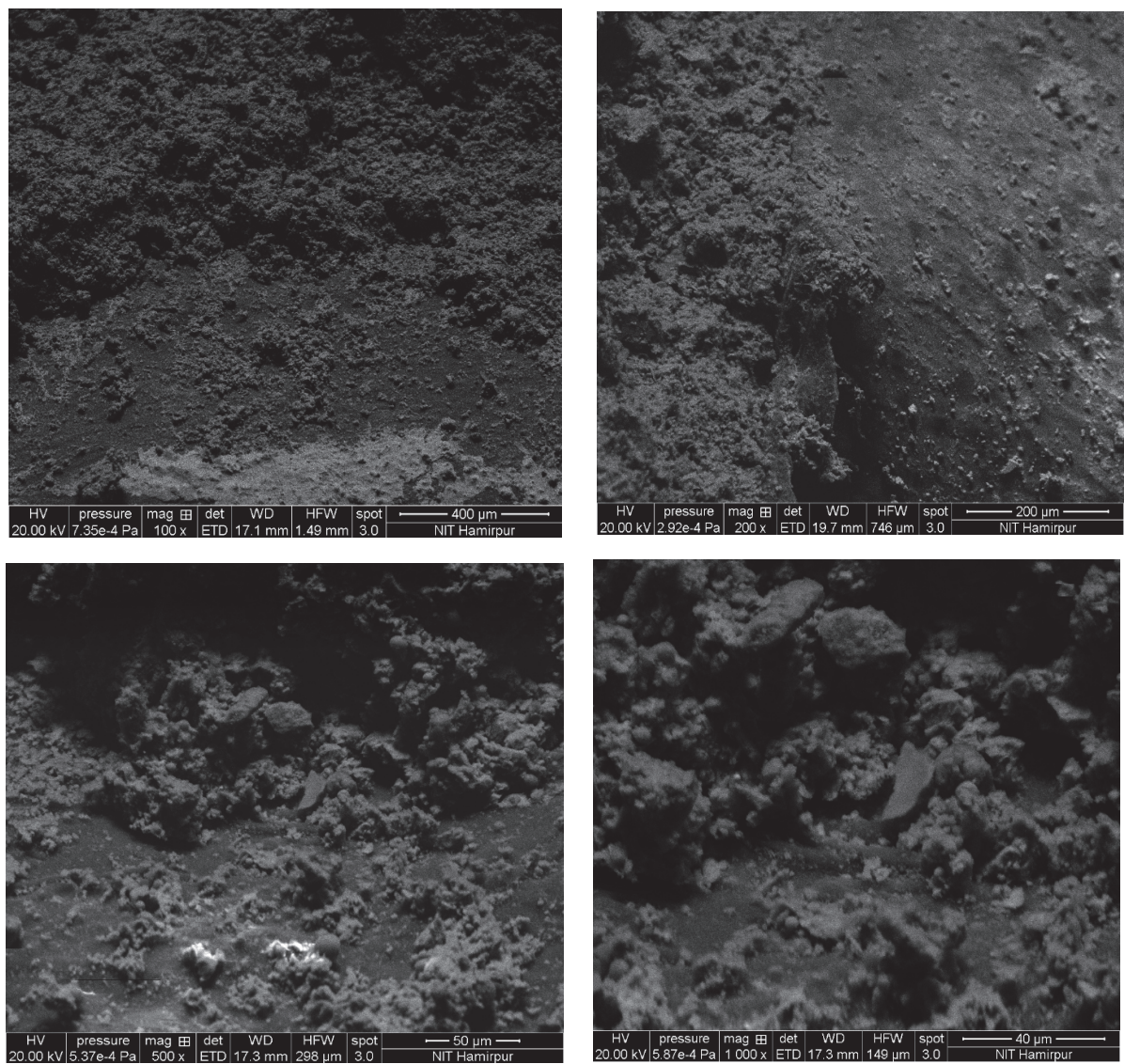


Fig 4.54: SEM analysis of rubberised slag based geopolymer concrete

4.9 Bond properties of GFREP based geopolymer concrete:

Bond properties refer to the ability of reinforcement (e.g., steel bars, GFRP bars) to adhere or 'stick' to the surrounding concrete and transfer forces between them. The bond is developed through mechanical interlocking and adhesion between the reinforcement and the concrete. The quality of this bond is influenced by several factors, including the surface texture of the reinforcement, the mix design of the concrete, the curing conditions, and the loading conditions.

Table 4.37: Bond strength of comparison of steel and GFRP's reinforced for OPC and GPC for 12mm dia size and 6 mm embedded length

Mixes	Compressive strength (MPa)	Peak Load (KN)	Average bond strength (MPa)	Free end Slip (mm)	Loaded end slip (mm)	Failure mode
OCS12-6d	38.9	61.3	22.6	-	-	Pullout failure
GCS12-6d	42.6	55.37	20.4	-	-	Pullout failure
OCG12-6d	43.4	49.7	18.3	0.45	1.45	Pullout failure
GCG12-6d	46.6	24.2	17.4	0.1	0.74	Pullout failure

Table 4.38: Bond strength of GFRP's reinforced for OPC and GPC for 16 mm dia size and 3, 6, and 9 mm embedded length

Mixes	Compressive strength (MPa)	Peak Load (KN)	Average bond strength (MPa)	Free end Slip (mm)	Loaded end slip (mm)	Failure mode
OCG16-3d	42	40.6	16.8	0.24	0.98	Pullout failure
OCG16-6d	42	66	13.7	0.27	1.2	Splitting failure
OCG16-9d	42	70.6	9.8	0.04	1.11	Splitting failure
GCG16-3d	49.3	43.3	18	0.37	0.99	Pullout failure

GCG16-6d	49.3	76.7	15.9	0.14	1.32	Splitting failure
GCG16-9d	49.3	93.8	12.9	0.05	1.42	Splitting failure

4.9.1 Modes of failure:

The experimental results, detailing measured slips at the free end and adjusted slips at the loaded end, are presented in **Table 4.37** for OPC and GPC concrete reinforced with steel and GFRP bars of 12 mm diameter and 6 mm embedded length, and in **Table 4.38** for GFRP-reinforced OPC and GPC with a 16 mm diameter and embedded lengths of 3, 6, and 9 mm. According to Tables 37 and 38, both pullout and splitting failures were observed. Pullout failure typically occurs when the concrete provides sufficient confinement, particularly evident in specimens with smaller embedment lengths and bar diameters. This failure mode arises when the shear strength of the bond between the concrete and the reinforcement is surpassed. Notably, specimens with comparable compressive strength and bar diameter exhibited pullout failure at shorter embedment lengths, a phenomenon consistent across both OPC and GPC concrete types. Conversely, insufficient concrete confinement to withstand the radial stresses from the bond leads to longitudinal cracks at the interface, which propagate to the surface and result in splitting failure. Such failures in both GPC and OPC concrete specimens were noted to be brittle

4.9.2 Effect of Embedment Length:

The experimental findings consistently demonstrate that an increase in embedment length correlates with a reduction in the average bond strength. As detailed in **Table 4.37**, specimens with a 9d embedment length exhibited lower bond strengths compared to those with 6d and 3d embedment lengths in both OPC and GPC concretes. This decrease in bond strength for specimens with longer embedment lengths is attributed to the occurrence of splitting failure, which prevents the development of full bond strength, and is further exacerbated by the non-linear distribution of bond along the embedment length. Additionally, a longer embedment length resulted in greater displacement at the loaded end for both OPC and GPC concretes. This is due to the increased failure load associated with longer embedment lengths and the lower elastic modulus of GFRP bars, leading to bar elongation and, consequently, an increase in loaded-end displacement. Conversely, the slip at the free end was observed to decrease with

longer embedment lengths, a phenomenon that can be explained by the more pronounced non-linearity of the bond in these cases.

4.9.3 Effect of Compressive Strength and Bar Diameter:

The bond strength of straight GFRP bars has been observed to vary with the compressive strength of the concrete. Unlike steel bars, where bond strength typically correlates with compressive strength, the GFRP-reinforced GPC concrete specimens in this study did not exhibit a consistent trend, as detailed in **Table 4.38**. Although the results were not conclusive enough to quantify this behavior fully, the occurrence of splitting failures in some specimens indicates a relationship between bond strength and concrete's compressive strength, as splitting failure is contingent upon reaching the concrete's tensile strength. Additionally, during pullout stress, a slight reduction in the bar's diameter was noted, which increased with the bar's diameter. This reduction diminishes the friction and mechanical locking stress between the bar and the concrete, influencing the overall bond strength.

4.9.4 Comparison between GFRP-Reinforced GPC Concrete and GFRP-Reinforced OPC Concrete:

Comparative analysis of GPC and OPC concrete specimens with similar parameters revealed that GFRP-reinforced GPC concrete specimens exhibited superior average bond strength compared to their OPC counterparts. Specifically, the average bond strength for the GCG16-3d specimens was recorded at 18 MPa, while the OCG16-3d specimens showed a slightly lower strength of 16.8 MPa. Notably, the GPC concrete specimens failed due to splitting of the concrete, whereas the OPC concrete specimens experienced pullout failure. Generally, splitting failure is associated with lower bond strength compared to pullout failure; however, in this instance, the GPC concrete specimens demonstrated higher bond strengths. This anomaly might be attributed to the higher bond strength in GPC concrete specimens inducing greater radial stresses, which led to splitting failure. Despite the slightly lower compressive strength, the enhanced bond strength of the GPC specimens underscores their potential as a robust alternative to steel or GFRP-reinforced OPC concrete.

4.10 Cost analysis of geopolymer concrete:

The cost analysis of geopolymer concrete (GPC) compared to ordinary Portland cement (OPC) concrete involves evaluating the material costs for producing 1 cubic meter of each type of concrete. **Table 4.39** provides a detailed breakdown of these costs.

From the data provided, it is evident that the cost of producing 1 cubic meter of GPC is significantly higher than that of OPC. The total cost for GPC is 7399.28 compared to 5538 for OPC, indicating a higher cost for GPC by 1861.28 per cubic meter. This higher cost for GPC can be attributed to the use of more expensive materials such as copper slag, rubber aggregate, and chemical activators like sodium hydroxide and sodium silicate, which are not used in traditional OPC concrete. These materials contribute to the enhanced properties of GPC, such as improved durability and reduced environmental impact, but they also increase the cost. In summary, while GPC offers environmental and durability advantages, it comes at a higher material cost compared to OPC. This cost analysis highlights the economic considerations that must be balanced against the environmental benefits when choosing between GPC and OPC for construction projects.

Table 4.39: Cost analysis of rubberised geopolymer concrete

Calculation of quantities of materials of CC			
Material for CC	per Kg/m ³	Price per Kg	Price for 1 m ³ of concrete
Cement	410	7.8	3198
Sand	850	1.4	1190
Coarse aggregate	1150	1	1150
		Total	5538
Calculation of quantities of materials of GPC			
Material for GPC	per Kg/m ³	Price per Kg	Price per 1 m ³ of concrete
Fly ash	400	2	800
Sand	337.5	1.4	472.5

Copper slag	337.5	4.5	1518.75
Coarse aggregate	1138.5	1	1138.5
Rubber aggregate	126.5	10	1265
Sodium hydroxide	53.33	5	266.65
Sodium silicate	107.66	18	1937.88
		Total	7399.28

The cost analysis carried out for geopolymer concrete (GPC) and ordinary Portland cement (OPC) concrete indicates a noticeable difference in their material costs for producing 1 m³ of concrete. The total cost of GPC was found to be ₹7399.28, whereas OPC concrete required ₹5538.00, making GPC approximately 33.6% more expensive with a cost difference of ₹1861.28 per m³. This increase in cost can be primarily attributed to the inclusion of alkaline activators such as sodium hydroxide and sodium silicate, along with alternative materials like copper slag and rubber aggregate, which are comparatively costlier than conventional constituents. Among these, sodium silicate contributes significantly to the total cost, followed by copper slag and rubber aggregate. Although fly ash, used as a binder in GPC, is relatively economical, the overall cost escalates due to the requirement of these specialized materials essential for the geopolymerization process. In contrast, OPC concrete relies on readily available and standardized materials such as cement, sand, and coarse aggregates, resulting in a comparatively lower cost. However, it is important to consider that this analysis focuses only on the initial material cost and does not account for long-term economic benefits. Geopolymer concrete is known to offer superior durability, reduced permeability, improved resistance to chemical attack, and lower carbon emissions due to reduced cement usage. Therefore, despite the higher initial cost, GPC may prove to be more economical over its service life, especially in aggressive environmental conditions where maintenance and repair costs of OPC concrete are significantly higher. Thus, the selection between GPC and OPC concrete should be based on a comprehensive evaluation of both initial cost and long-term performance benefits.

Chapter 5

Estimation of compressive strength of rubberized slag-based geopolymer concrete applying soft computing-based models.

5.1 General:

Concrete is unique and most important construction materials used in all the construction projects (Jeyaseela, 2024). Last few decades population has increased tremendously, and people have moved to urban areas. Due to urbanization and enhanced living standards, there is a high demand for infrastructure all over the world (Manzoor et al., 2024). For infrastructure development or construction projects the most widely implemented material is concrete due to their strength and resilience. In concrete, ordinary Portland cement (OPC) is the primary binder material used in construction projects (Yu et al., 2024). During the production of OPC, leads to release of large amounts of carbon dioxide gas which contributes to the global warming into the environment. For the reduction in carbon dioxide from the cement industry. Nowadays many scientists and researchers suggest that supplemental cementitious materials (SCMs) like various classes of fly ash (Halstead, 1986), GGBS (Baawain et al., 2021), slag (Wang et al., 2013), silica fumes (Bameri et al., 2022) and metakaolin (Riyap et al., 2021) are used as partial to fully replaced materials instead of OPC.

The necessity of ecologically sustainable substitutes for concrete has been acknowledged by researchers worldwide. To achieve carbon neutrality and reduce carbon footprint, it is advisable to choose binders that have lower carbon dioxide emissions for potential green construction. Geopolymer has emerged as an eco-friendly substitute for Ordinary Portland cement (OPC) to lower the environmental consequences of cement, high early strength, durability, fire safety, and its endurance to acid and sulfate attack. The development of the very first geopolymer in late 1978 is attributed to Davidovits. GPC may utilize a range of industrial by-products as its raw materials. red mud, silica fume (SF), metakaolin, rice husk ash (RHA), Ground granulated blast furnace slag (GGBS), calcinated clay (CC), and corn cob ash (CCA), are utilized in the geopolymerization process to produce GPC in an alkaline environment. The process of polymerization occurs when reactive alumino silicates undergo fast dissolution, resulting in the liberation of free SiO_4 and AlO_4 tetrahedral units within the solution. Geopolymer binders have the potential to serve as a viable substitute for acid-resistant concrete due to their reliance on aluminum silicate hydrate bonds, as opposed to calcium silicate hydrate associations which interim enhancing mechanical stiffness. Geopolymers that may be synthesized and solidified

at room temperature refers to a category of inorganic polymeric composites, achieved utilizing extremely alkaline conditions.

Last few decades several researchers have successfully applied computational techniques such as support vector mechanism (SVM), adaptive network-based fuzzy inference system (ANFIS), backpropagation neural network (BPNN), random forest (RF), artificial neural network (ANN), gene expression program (GEP), gaussian progression (GP), Fuzzy logic, extreme learning machine (ELM), etc. along with statical methods (LR, NLR) in the area of engineering and medical to resolve the very complicated issues. Several researchers used soft computing methods for the prediction or estimation whereas some researchers successfully used soft computing techniques for optimization purposes in the field of construction to estimate the strength and durabilities of various materials (Xu et al., 2023, Abdellatief et al., 2023). Linear regression shows that there is a singular connection between observed and estimated variables which results in limitations of results when nonlinear data is used especially in concrete mechanical strength predictions. Muliauwan et al. (2020) studies show the use of linear regression to predict compressive strength. The model's predictions are largely affected by the linear regression due to their sensitivity to outliers of the dataset (Schreiber-Gregory et al., 2018). ANN soft computing technique has been used to determine the mechanical properties of high-performance in the self-compacting concrete with the recycled aggregate (Alyaseen et al., 2023), fly ash-based GPC (Verma et al., 2023), alccofine-based GPC (Diksha et al., 2023). The SVM technique has been used to define a hyperplane which can categorize the dataset into diverse categories. The SVM is a parametric approach used in analyzing nonlinear datasets that use various kernel functions to transfer into a higher-dimensional space (Abdul Hamid et al., 2011). Pham et al., (2016) used SVM computing techniques to predict the mechanical properties of concrete composites. Random forests are ensembles of tree predictors constructed using independently and uniformly sampled vectors, with the overview error converging to a boundary as the number of the trees increases, influenced by the individual tree strength and their correlation (Breiman, 2001). The subset of the input variable and arithmetic mean over many trees in random forest regression leads to less prone to overfitting (Breiman 2001). Verma (2023) performed random forest and deep learning to assess the compressive strength of the GPC. The optimized design by Akbhari et al., (2017) to determine the seismic effect of steel structures with genetic algorithm methods. Various machine learning tools such as ANN, GEP, and SVM are performed by Diksha et al., (2023) to forecast the compressive strength of alccofine-based GPC. Fuzzy logic (ANFIS) is used by Liu et al., (2022) with hybrid

fiber reinforcement based Ultra high-performance concrete to determining the various AI techniques to analyze explosive spalling. Yaswanth et al., (2022) show that the use of gene expression programming (GEP) based strain hardening geopolymer composites to determine compressive strength. The estimated the electrical resistivity by Dong et al., (2020) in the concrete to monitor the health of the structure by XG boost algorithm. The small datasets lead to overfitting in the soft computing models learning process (Cawley et al., 2010). Peng et al., (2022) used SVM, ELM, and BPNN to predict the compressive strength of the fly ash as binder component in GPC but the study was inadequate in determining the findings due to a limited data set.

Adaptability of soft computing techniques helps in reducing the cost, and duration of experiments due to reduction in trial mixes. While performing prediction analysis it is important to consider all the factors as input variables irrespective of their significance as they help in the precise prediction of the observations. In predicting the concrete's compressive strength input variables such as water-to-binder ratio, activators, binder quantity, aggregate quantity, molarity, and curing time are significantly considered even when collecting the data. In this paper the mechanical strength of rubberized slag-based GPC for curing periods of 7, 28, and 90 days. In this research study GPC used fly ash, sodium silicate, and sodium hydroxide as binder paste. The fine aggregate is partially substituted with copper slag and the coarse aggregate has been replaced with rubber aggregate. The novelty of this investigation is to estimate the compressive strength using various soft computing techniques of rubberized slag-based GPC with various inputs even considering the secondary mix design such as Molarity and NaOH/ Na₂SiO₃ ratio. Previous studies estimated the compressive strength for 28 days curing period as the prediction parameter but in this study curing time is also one of the input parameters.

5.2 Overview of soft-computing techniques:

The need of using machine learning (ML) and artificial intelligence (AI) without regression programming to create the models and their algorithms in recognising patterns and make decisions accordingly. In the following subsections, brief explanations of the used machine learning (ML) techniques in the current study are provided.

5.2.1 Multiple Linear Regression:

Multiple linear regression (MLR) is a straightforward method which uses the least square error technique. In the MLR model, a linear relationship is developed among two or more independent variables with dependent variables.

$$y = V_0 + V_1x_1 + V_2x_2 + \dots + V_nx_n \quad (5.1)$$

where y is the dependent feature, V_0 is the y -intercept constant, $x_1, x_2, \dots, x_n$ are the independent features and $V_1, V_2, \dots, V_n$ are partial regression coefficients of the model, estimated during the training process, directing to decrease the difference between the actual and estimated values of dependent variable.

5.2.2 Gaussian Process Regression:

The Gaussian process represents a broader conceptualization of the Gaussian probability distribution. It is illustrated beside a mean function along with the usage of the covariance function. The nonparametric administered machine learning algorithm in Gaussian Process Regression (GPR) is used for conducting regression analysis. In contrast to other machine learning techniques, one notable advantage of GPR is its ability to explicitly assess the uncertainty within prediction results, owing to its foundation in probabilistic theory. Moreover, this method has attracted the interest of engineers because of its capacity to effectively manage nonlinear data through the utilization of kernel functions (also known as the covariance function). The kernel function defines the approach for measuring data similarity and exerts a significant influence on the predictions.

5.2.3 Support Vector Machine:

SVM is a sturdy ML method for resolving classification and regression challenges, C-SVM and SVR, respectively. At its core, the basic idea behind SVM revolves around the strategic separation of given features using a hyperplane, known as a support vector regressor or classifier, this hyperplane is designed to maximize its margin, i.e., to represent the largest feasible corridor that encompasses the observed data points. Considering the continuous nature of the anticipated results, SVM seeks to identify the ideal hyperplane that best matches the data. The equation for the hyperplane in our SVM study is formulated as:

$$y_i = w \cdot \varphi(x_i) + b \quad (5.2)$$

In this context, y_i and x_i signify the i^{th} input and the i^{th} output within the training data, w and b represent parameter vector of the hyperplane in which w is weight matrix, b is bias, and $\varphi(x)$ is a that transforms x into a higher-dimensional space in mapping kernel function.

The remoteness between the nearest data point and hyperplane from each set is known as the margin ($\mp \epsilon$). SVM seeks to maximize this margin. The data point situated at the margin's boundary is called the support vector, these data points influence the standing and briefing of the hyperplane and also these points are crucial in determining the margin. For a regression problem, the objective is to identify the mathematical equation of the hyperplane that most

effectively represents the data points. There is no deviation for elements within the boundaries ($\pm\epsilon$). For points outside the margins ($\pm\epsilon$), the deviation is determined by the gap of these elements to the margins (ξ_i and ξ_i^*). The expression of Support Vector Regression (SVR) for the loss function is

$$\text{minimize: } \frac{1}{2} \|\omega\|^2 + C \sum_{i=0}^n (\xi_i - \xi_i^*) \quad (5.3)$$

$$\text{Constraints are: } y_i - wx_i - b \leq \epsilon + \xi_i \quad (5.4)$$

$$wx_i + b - y_i \leq \epsilon + \xi_i^* \quad (5.5)$$

$$\xi_i, \xi_i^* \geq 0 \quad (5.6)$$

Here, the terms $\frac{1}{2} \|\omega\|^2$ functions as a regularization term, aiming to find a hyperplane with minimal weight and maximum flatness. The Parameter C governs the trade-off which helps completing a low training error and a low testing error. A smaller 'C' promotes a broader margin but permits for more errors, while a larger 'C' penalizes errors more severely. This principle holds for both classification and regression scenarios, where errors may be defined differently but is nonetheless influenced by the value of 'C'.

The kernel trick is a fundamental component of Support Vector Machines (SVMs), augmenting their capacity to adeptly handle non-linear relationships within datasets. This technique enables SVMs into a higher-dimensional space for mapping input data, offering a robust mechanism for capturing intricate patterns and enhancing the model's performance. This is particularly beneficial in scenarios where linear relationships are insufficient to adequately represent the essential structure of the data.

5.2.4 Random Forest:

Random Forest (RF) is the ML algorithm classified under tree-based ensemble learning, representing an addition for widely used Random Forest process. During the training phase, RF constructs multiple decision trees and generates an average prediction based on the individual trees for regression tasks. Every tree in the ensemble originates from a bootstrap sample, obtained by drawing instances with replacements from the training set. This resampling technique enhances diversity within the base trees, contributing to the robustness and generalization capabilities of the RF algorithm. Furthermore, during the node-splitting process of the base tree, the optimal split is determined from a randomly selected subset of features, the size of which is regulated by the hyperparameter. The inclusion of both types of randomness, involving random samples and features, serves the purpose of reducing variance and enhancing the generalization ability of the ensemble estimator, without significantly

amplifying bias-related errors. As individual decision trees often display high variance, making them susceptible to overfitting, aggregating the average probabilistic predictions from each tree within the ensemble serves to mitigate prediction errors in the overall prediction.

5.3 Data Collection and Methodology:

5.3.1 Illustration of the data set through soft computing techniques:

In this research study, a total of 186 observations have been utilized from the present investigation in forecasting the mechanical properties of the rubberized slag-based GPC. Out of 186 observations, the data is at random split into dual sets of larger and smaller sets. The larger part contains 130 observations and the smaller part contains 56 observations. The model development of the data set used for this study in which the larger part (130 observations) was used for training and the rest smaller part (56 observations) was used for testing. the statistical analysis of the both training and testing data set is provided in **Table 5.1**. Fly ash, the molarity of NaOH, NaOH quantity, Na₂SiO₃ quantity, sand quantity, copper slag quantity, coarse aggregate quantity, and rubber aggregate quantity were chosen as independent (input) variables while the compressive strength of rubberized slag-based GPC was measured as the dependent (output) variable.

Table 5.1: Statistical analysis of training and testing data set.

Descriptive statistics	Fly ash Quantity (FA)	NaOH Molarity (M)	NaOH quantity(q)	Na ₂ SiO ₃ Quantity (Naq)	Sand (S)	Copper Slag (CoS)	Coarse aggregate (CA)	Rubber aggregate (RA)	Curing period (D)	compressive strength (CS)
Training data set										
Mean	1350	10.10769	192.1154	345.1154	1653.385	546.6154	3943.077	56.92308	38.53846	38.2474665
Standard Deviation	0	1.521149	52.7972	60.96595	374.8313	374.8313	157.9611	157.9611	33.7793	6.48759512
Minimum	1350	8	135	0	1100	0	3400	0	7	23.59
Maximum	1350	12	270	405	2200	1100	4000	600	90	51.18
Testing data set										

Mean	1350	9.75	195.2 679	344. 7321	1595	605	3960. 714	39.28 571	38.5 7143	38.411 8939
Standard Deviation	0	1.52 8517	53.09 014	53.0 9014	402. 9392	402. 9392	117.0 525	117.0 525	35.3 6606	6.8746 2644
Minimum	1350	8	135	270	1100	0	3400	0	7	24.82
Maximum	1350	12	270	405	2200	1100	4000	600	90	52.47

5.4 Performance evaluation indicators:

In our evaluation of modeling approaches, we employed the Nash–Sutcliffe efficiency (NSE), correlation coefficient (C.C), root mean square error (RMSE), mean absolute error (MAE), and scattering index (SI) as key performance metrics to determine the suitability of these approaches. These metrics serve as fundamental indicators of the accuracy and reliability of our models.

The correlation analysis uniqueness of the truly extensively used and described statistical techniques which is also renowned as the Pearson’s correlation. The C.C., is a measure that ranges between -1 and 1. A C.C. of 1 signifies a perfect positive linear relationship between two variables. In such cases, as one variable quantity surges, the other also surges linearly, and conversely, as one reduces, the other follows suit. Conversely, a C.C. of the -1 indicates a absolute negative linear relationship, where one variable surges as the other reduces linearly, and the other way around. A C.C. of 0 implies that there is no linear relationship among the two variables, but they are essential to note that this doesn't necessarily imply the absence of any relationship; it merely signifies the absence of a linear connection. There may still exist other types of relationships between the variables that are not captured by the correlation coefficient. Mean absolute error (MAE) is used to estimate the convenience of the estimated outcome whereas root mean square error (RMSE) is used to decide the standard deviation of the estimated (E) and actual (A) values. When considering MAE and RMSE as evaluation metrics, our objective was to minimize these values to identify the superior model or method that yields the highest accurate estimates. The maximum MAE and RMSE occur when the estimated values deviate furthest from the actual values, indicating a substantial degree of prediction error. Conversely it's crucial to say that the absolute maximum value for MAE varies depending on the specific data scale and the magnitude of errors in the dataset. The minimum value for MAE and RMSE is 0, signifying a perfect alignment between predictions and actual values, where no errors exist, and the accuracy of predictions is at its peak. These evaluation

metrics collectively provide a robust framework for assessing the performance of our modeling approaches, enabling us to make informed decisions about the effectiveness and reliability of the models under consideration. The Scattering index (SI) is the percentage of the RMSE to the actual values. If the consequence of the error between actual and estimated is 1 it is said to be the perfect match. The Nash–Sutcliffe efficiency (NSE) coefficient which is also known as the efficiency index is used to determine the betterness of the models. The index value ranges from 0 to +1 for the unbiased prediction and negative for the biased prediction.

The equation for the calculation of CC is as follows:

$$CC = \frac{\sum_{i=1}^N (A_i - \bar{A}_i)(E_i - \bar{E}_i)}{\sqrt{\sum_{i=1}^N (A_i - \bar{A}_i)^2} \sqrt{\sum_{i=1}^N (E_i - \bar{E}_i)^2}} \quad (5.7)$$

The equation for the calculation of MAE is as follows:

$$MAE = \frac{1}{N} \sum_{i=0}^N |E_i - A_i| \quad (5.8)$$

The equation for the calculation of RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=0}^N (E_i - A_i)^2} \quad (5.9)$$

The equation for the calculation of SI is as follows:

$$SI = \frac{\sqrt{\frac{1}{N} \sum_{i=0}^N (E_i - A_i)^2}}{\bar{A}_i} \quad (5.10)$$

The equation for the calculation of NSE is as follows:

$$NSE = 1 - \left[\frac{\sum_{i=1}^N (E_i - A_i)^2}{\sum_{i=1}^N (E_i - \bar{E}_i)^2} \right] \quad (5.11)$$

Where E= Estimated, A= Actual, N= 1,2,3.....

5.5 Kernel function-based aspects of GPR and SVR :

In this research study the Normalised Polynomial, Polynomial, Radial Basis Kernel function and Pearson VII Universal Kernel function are used as the kernel purposes to forecast the compressive strength of the rubberized slag-based GPC as they show an significant role in complex dataset relationships.

The Polynomial equation applied is as follows:

$$Z(A, E) = (1 + (A, E))^d \quad (5.12)$$

The Normalised polynomial equation applied is as follows:

$$Z(A, E) = \frac{K(A, E)}{\sqrt{K(A, A)K(E, E)}} \quad (5.13)$$

The Pearson VII function kernel (PUK) equation applied is as follows:

$$Z(A, E) = \left(1 / \left[1 + \left[2 \frac{\sqrt{\|A-E\|^2 \left(\sqrt{2 \left(\frac{1}{\omega} \right)} - 1 \right)}}{\sigma} \right]^2 \right]^\omega \right) \quad (5.14)$$

The Radial basis kernel (RBF) equation applied is as follows:

$$Z(A, E) = e^{(-\gamma \|A-E\|^2)} \quad (5.15)$$

5.6 Result and discussion:

In this investigate, the accuracy of the applied soft computing techniques was evaluated by considering performance parameters such as CC, MAE, RMSE, SI, and NSE. To forecast the compressive strength of rubberized slag-based GPC 186 experimental observations were considered and divided into two groups training set to improve the model and testing set to support the model. The user-defined parameters for this model are been evaluated by various trials.

5.6.1 Assessment of predictive accuracy of MLR-based model:

The MLR soft computing techniques have been evaluated by the least square process. The observed and estimated strength properties of rubberized slag-based GPC is illustrated in **Fig 5.1(a) and 5.1(b)** for both training and testing. The performance assessment keys calculated for MLR in the approximation of compressive strength of rubberized slag-based GPC are 0.8820 and 0.8641 for CC, 2.6376 and 3.0412 for MAE, 3.0453 and 3.5376 for RMSE, 0.0796 and 0.0921 for SI, and 0.7780 and 0.7304 for NSE respectively, for the training and testing data set. The prediction equation for determining the compressive strength of rubberized slag-based GPC using MLR is shown in the equation below.

$$CS = 0.3889 M - 0.0089 Naq - 0.0051 S + 0.0051 CoS + 0.0031 RA + 0.1151 D + 38.4783 \quad (5.16)$$

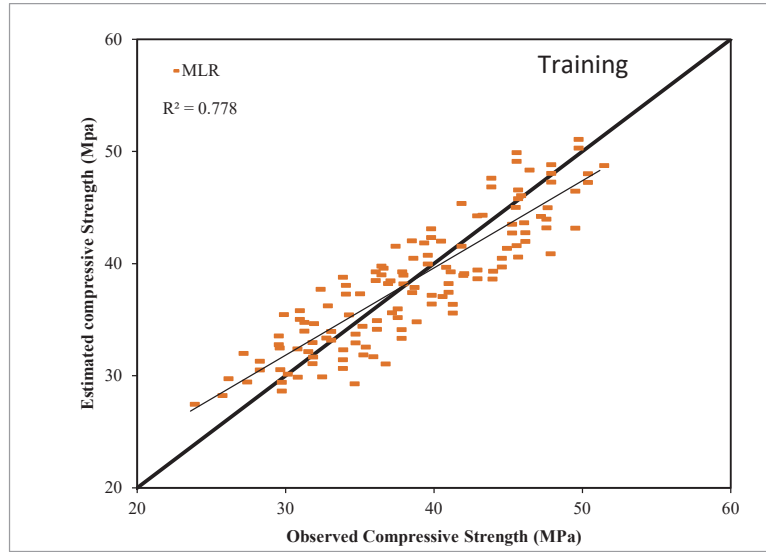


Fig 5.1 (a): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using MLR for training stage

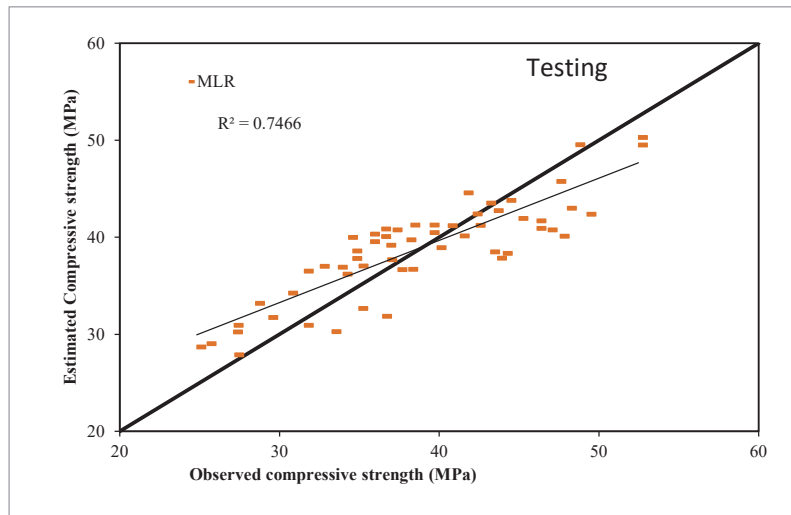


Fig 5.1 (b): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using MLR for the testing stage

5.6.2 Assessment of predictive accuracy of random forest model:

The RF soft computing techniques have been evaluated by the tryout process. The user-defined parameters used for this study are the number of trees (K) is 10 and the number of variables selected (m) is 1. The observed and estimated compressive strength of rubberized slag-based GPC are shown in **Figures 5.2(a) and 5.2(b)** for both training and testing. . The performance assessment keys calculated for RF in the estimation of compressive strength of rubberized slag-

based GPC are as follows: 0.9958 and 0.9631 (CC), 0.4618 and 1.4863 (MAE), 0.6218 and 1.9364 (RMSE), 0.0163 and 0.0504 (SI), and 0.9907 and 0.9192 (NSE) respectively, for the training and testing data set.

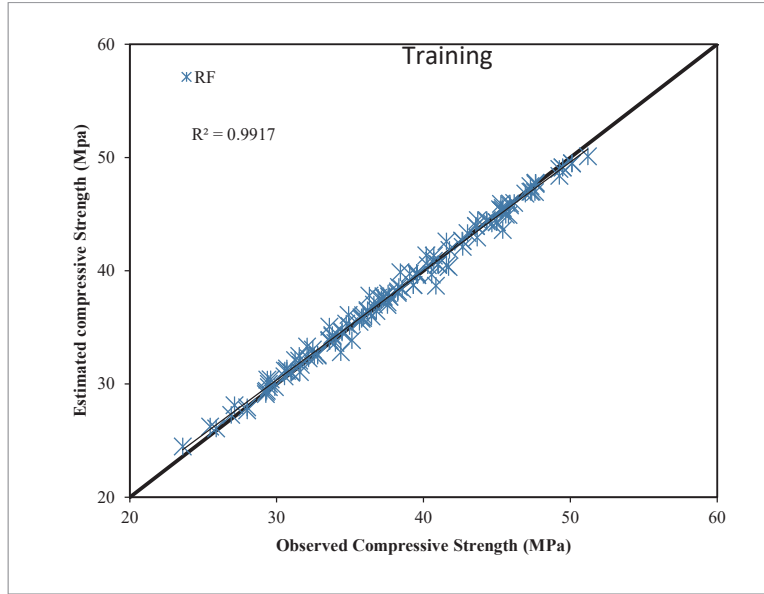


Fig 5.2 (a): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using the random forest for training stage

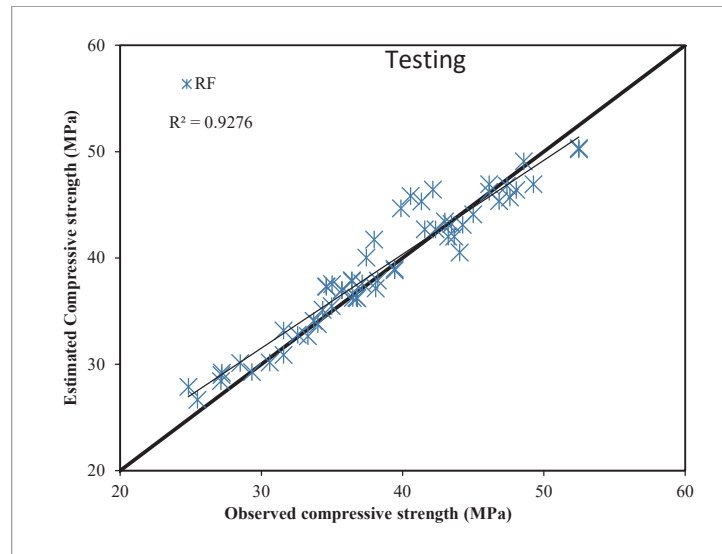


Fig 5.2 (b): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using the random forest for the testing stage

5.6.3 Assessment of predictive accuracy of GPR-based model:

The GPR soft computing technique is been evaluated by an iterative method with kernel-based functions such as Npoly, Poly, PUK, and RBF. The user-defined parameter for GPR is noise and its optimal value is 0.01. optimum user-defined parameters for various kernel functions are exponent (d) = 3 for the Normalized polynomial kernel function, exponent (d) = 3 for the polynomial kernel function, $\sigma=1$, $\omega= 0.1$ for the Pearson VII kernel function, and $\gamma= 1$ for Radial basis kernel function. The performance analysis of GPR_Npoly, GPR_Poly, GPR_PUK, and GPR_RBF are shown in **Fig 5.3(a) and 5.3(b)** for both training and testing. The results suggest that the GPR_Poly indicates the best performance compared to GPR_Npoly, GPR_PUK, and GPR_RBF. . The performance assessment keys calculated for GPR_Poly in the estimation of compressive strength of rubberized slag-based GPC are as follows: 0.9965 and 0.9902 (CC), 0.4408 and 0.7622 (MAE), 0.5416 and 0.9509 (RMSE), 0.0142 and 0.0248 (SI), and 0.9930 and 0.9805 (NSE) respectively, for the training and testing data set. The Performance of the training and testing of the GPR model in the estimation of compressive strength of rubberized slag-based GPC for Normalised polynomial, Polynomial, Pearson VII function kernel, and Radial basis kernel are shown in **Table 5.2**.

Table 5.2: Performance parameters of GPR-based models for training and testing.

Performance parameters	GPR_PUK	GPR_Npoly	GPR_RBF	GPR_Poly
	Training data set			
CC	1.0000	0.9952	0.9999	0.9965
MAE	0.0005	0.4885	0.0581	0.4408
RMSE	0.0007	0.6305	0.0901	0.5416
SI	0.0000	0.0165	0.0024	0.0142
NSE	1.0000	0.9905	0.9998	0.9930
	Testing data set			
CC	0.9785	0.9841	0.9887	0.9902
MAE	1.3472	0.9646	0.8702	0.7622
RMSE	1.6504	1.2458	1.1252	0.9509
SI	0.0430	0.0324	0.0293	0.0248
NSE	0.9413	0.9666	0.9727	0.9805

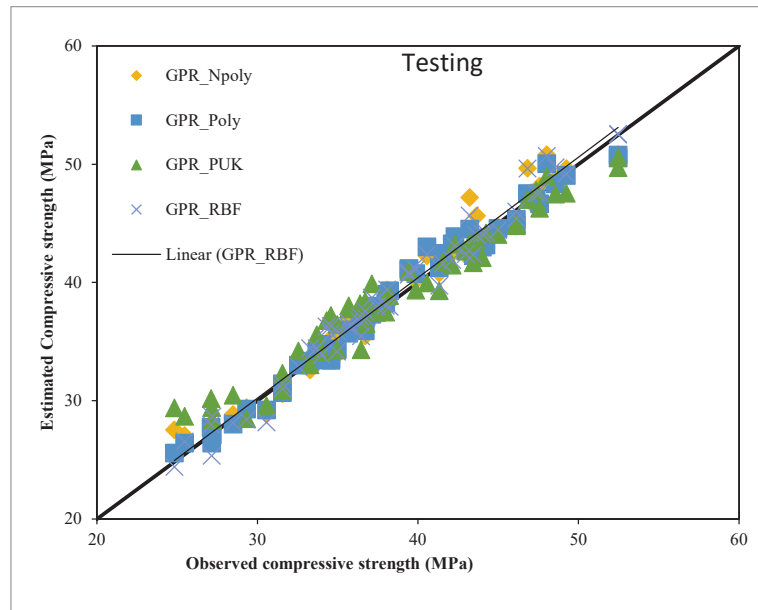


Fig 5.3 (a): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using various kernel function-based GPR models for training stage

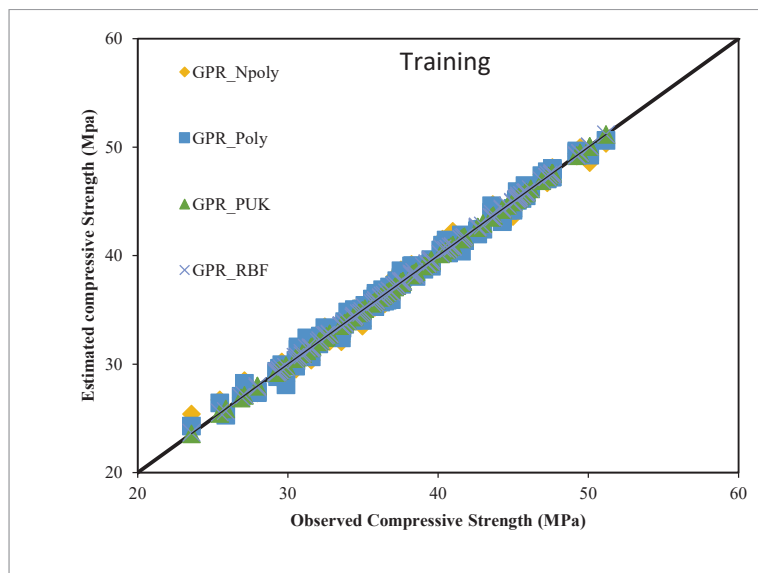


Fig 5.3 (b): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using various kernel function-based GPR models for the testing stage

5.6.4 Assessment of predictive accuracy of SVR-based model:

The SVM soft computing technique is been evaluated by an iterative method with kernel-based functions such as Npoly, Poly, PUK, and RBF. The optimal values of the user-defined parameter for SVR are obtained as C is 2. The other user-defined parameters of all kernel functions are kept constant as used in the GPR model for a fair comparison among developed models. The performance analysis of SVR_Npoly, SVR_Poly, SVM_PUK, and SVM_RBF are shown in **Fig 5.4(a) and 5.4(b)** for both training and testing. The results suggest that the SVR_Poly indicates the best performance compared to SVR_Npoly, SVM_PUK, and SVM_RBF. . The performance assessment keys calculated for SVR_Poly in the estimation of compressive strength of rubberized slag-based GPC are as follows: 0.9958 and 0.9878 (CC), 0.4086 and 0.8335 (MAE), 0.5914 and 1.0693 (RMSE), 0.0155 and 0.0278 (SI), and 0.9916 and 0.9754 (NSE) respectively, for the training and testing data set. The Performance of the training and testing of the SVM model in the estimation of compressive strength of rubberized slag-based GPC for Normalised polynomial, Polynomial, Pearson VII function kernel, and Radial basis kernel are shown in **Table 5.3**.

Table 5.3: Performance parameters of SVR-based models for training and testing.

Performance parameters	SVR_PUK	SVR_Npoly	SVR_RBF	SVR_Poly
	Training data set			
CC	1.0000	0.9878	0.9975	0.9958
MAE	0.0309	0.7073	0.2477	0.4086
RMSE	0.0327	1.0452	0.4578	0.5914
SI	0.0009	0.0273	0.0120	0.0155
NSE	1.0000	0.9738	0.9950	0.9916
	Testing data set			
CC	0.9792	0.9826	0.9846	0.9878
MAE	1.3364	1.0162	0.9784	0.8335
RMSE	1.6192	1.3008	1.2497	1.0693
SI	0.0422	0.0339	0.0325	0.0278
NSE	0.9435	0.9635	0.9664	0.9754

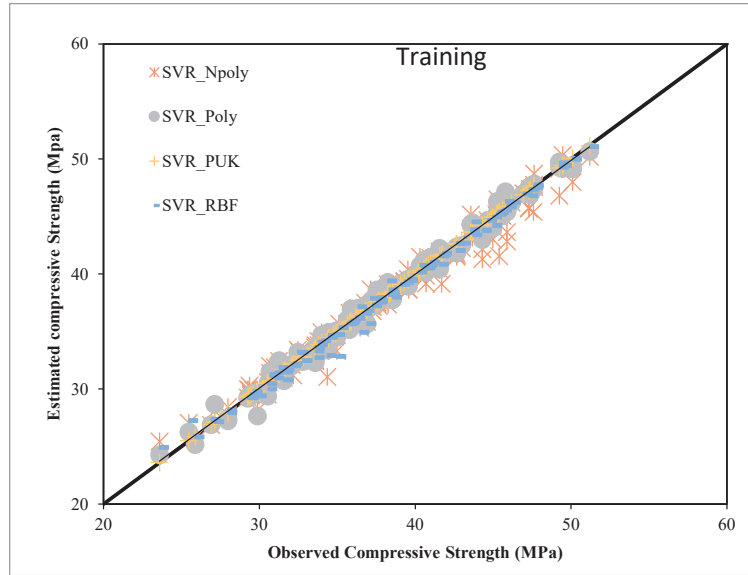


Fig 5.4 (a): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using various kernel function-based SVR models for training stage

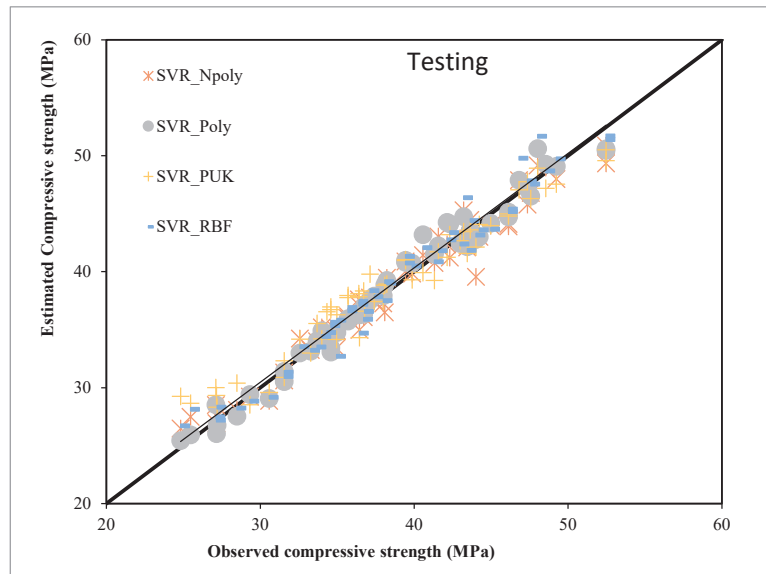


Fig 5.4 (b): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using various kernel function-based SVR models for the testing stage

5.7 Assessment of inter-comparison of MLR, RF, GPR, and SVR-based best-performing models:

Inter comparison of the machine learning techniques shows that the GPR_Poly model shows better results when compared to other techniques. As seen from **Fig 5.5(a) and 5.5(b)** for both training and testing results suggest that the GPR_Poly and SVR_Poly have similar patterns in the training phase whereas the GPR_Poly outperformed the SVR_Poly model in the testing phase with 0.9902 for CC, 0.7622 for MAE, 0.9509 for RMSE, SI for 0.0248 and NSE of 0.9805. The variation of the estimated and observed values of the compressive strength of rubberized slag-based GPC using LR, RF, GPR_Poly, and SVM_Poly are shown in **Fig 5.6(a)** both training and testing. From the figure, we can infer that the estimated values of GPR_Poly are very similar to the observed compressive strength of the rubberized slag-based GPC compared to other modeling techniques. Similarly, the variation of the residual error as shown in **Fig 5.6(b)** both training and testing depicts that the GPR_Poly shows minimal error compared to other modeling techniques. The Performance of the training and testing of MLR, RF, GPR, and SVR-based best-performing models in the estimation of compressive strength of rubberized slag-based GPC are shown in **Table 5.4**.

Table 5.4: Performance parameters of MLR, RF, GPR, and SVR-based best-performing models

Performance parameters	MLR	RF	SVR_Poly	GPR_Poly
	Training data set			
CC	0.8820	0.9958	0.9958	0.9965
MAE	2.6376	0.4618	0.4086	0.4408
RMSE	3.0453	0.6218	0.5914	0.5416
SI	0.0796	0.0163	0.0155	0.0142
NSE	0.7780	0.9907	0.9916	0.9930
	Testing data set			
CC	0.8641	0.9631	0.9878	0.9902
MAE	3.0412	1.4863	0.8335	0.7622
RMSE	3.5376	1.9364	1.0693	0.9509
SI	0.0921	0.0504	0.0278	0.0248
NSE	0.7304	0.9192	0.9754	0.9805

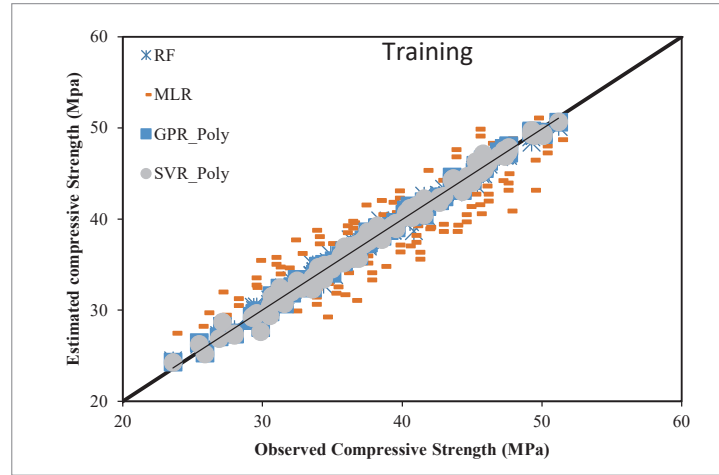


Fig 5.5 (a): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for training stage

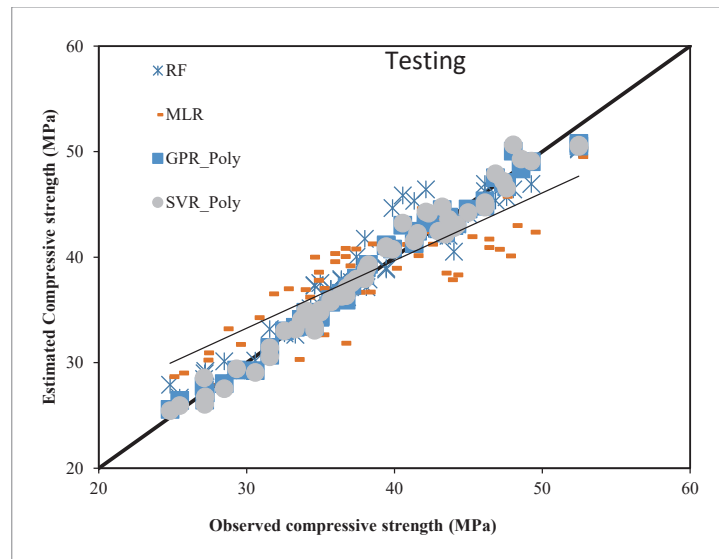


Fig 5.5 (b): Agreement plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for testing stage.

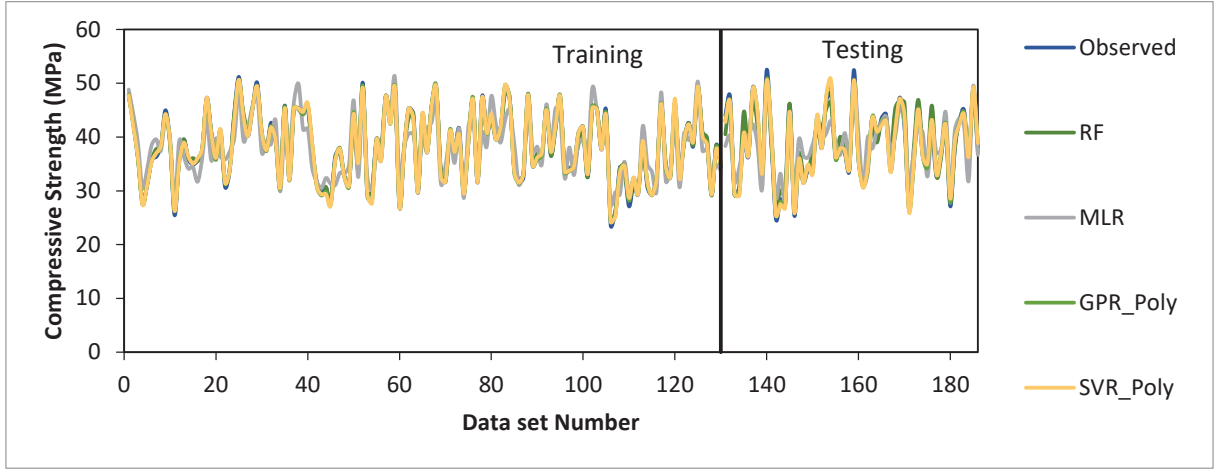


Fig 5.6 (a): Variation in estimated values of compressive strength of rubberized slag-based GPC using LR, RF, different kernel function-based GP, and SVM approach in comparison to the observed value

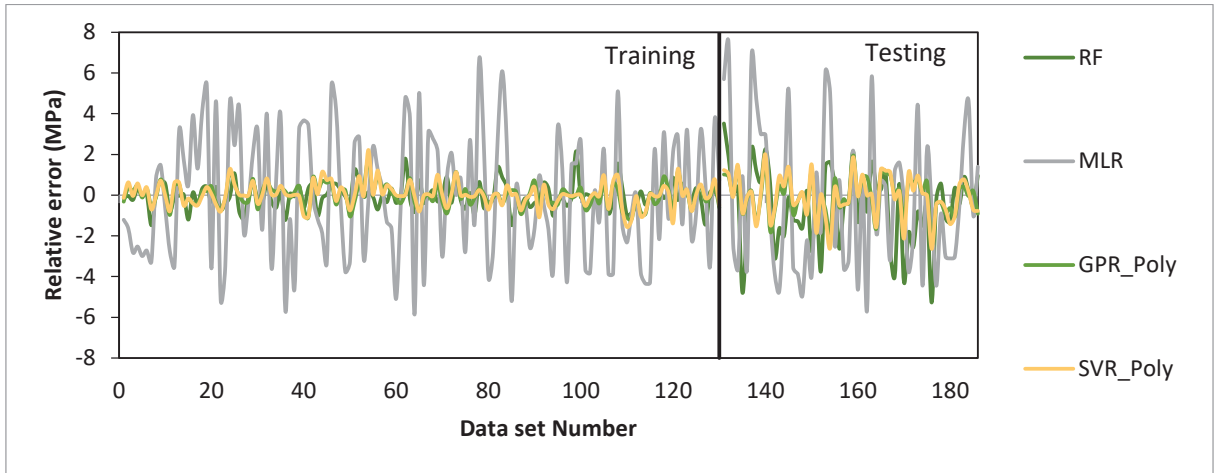


Fig 5.6(b): Variation of residual errors of compressive strength of rubberized slag-based GPC using LR, RF, different kernel function-based GP, and SVM approach

5.7.1 Single-factor ANOVA Results:

Results of single factor ANOVA listed in **Table 5.5** suggest that F- values of 0.047204 (LR), 0.186562 (RF), 0.002586 (SVR_Poly), and 0.000928 (GPR_Poly) were less than the F-critical value of 3.927393 and P values of 0.828404 (LR), 0.666639 (RF), 0.959531 (SVR_Poly) and 0.975757 (GPR_Poly) was greater than 0.05 which suggest that estimated and observed values for the soft computing models is insignificant (P).

Table 5.5: Single-factor ANOVA of MLR, RF, GPR, and SVR-based best-performing models

Variation among observed and applied models	P-value	F crit	F	Insignificant variation
LR	0.828404	3.927393	0.047204	P
RF	0.666639	3.927393	0.186562	P
SVR_Poly	0.959531	3.927393	0.002586	P
GPR_Poly	0.975757	3.927393	0.000928	P

5.7.2 Box plot results:

Box plots for observed and estimated values using applied models are shown in **Fig 5.7(a)** for training and **5.7 (b)** for testing respectively. These figures suggest that the width of SVR_Poly and GPR_Poly are similar to observed values. Whereas the width of the box is found smaller for the LR LR-based model for both training and testing stages these figures suggest that SVR_poly and GP_poly have comparable results as observed values in terms of 1st quartile, mean, and 3 quartile. The statistical performance of compressive strength of LR, RF, SVR_Poly, and GPR_Poly models are shown in **Table 5.6**

Table 5.6: Statistics of compressive strength of LR, RF, SVR_Poly and GPR_Poly models

	Observed	LR	RF	SVR_Poly	GPR_Poly
Statistic	Training data set				
Minimum	23.5900	27.4620	24.4870	24.2670	24.3040
Maximum	51.1800	51.0900	50.1090	50.6610	50.6240
1st Quartile	33.5700	33.5808	33.3770	33.1200	33.2883
Mean	38.2475	38.2475	38.2929	38.2191	38.2474
3rd Quartile	43.6800	42.0295	43.9493	43.9153	43.9350
IQR	10.1100	8.4488	10.5723	10.7953	10.6468
	Testing data set				

Minimum	24.8200	27.8640	26.6610	25.4570	25.5680
Maximum	52.4700	50.2850	50.3270	50.6370	50.7770
1st Quartile	34.2375	36.6273	34.8643	33.8953	33.5475
Mean	38.4119	38.6604	38.9503	38.4781	38.4513
3rd Quartile	43.5000	41.2425	44.2270	43.7330	43.4030
IQR	9.2625	4.6153	9.3628	9.8378	9.8555

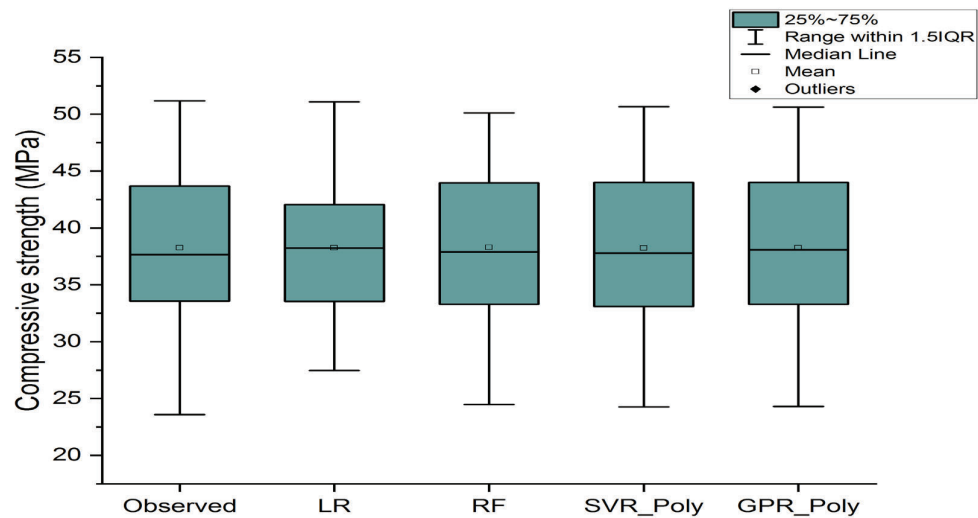


Fig 5.7 (a): Agreement box plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for training stage

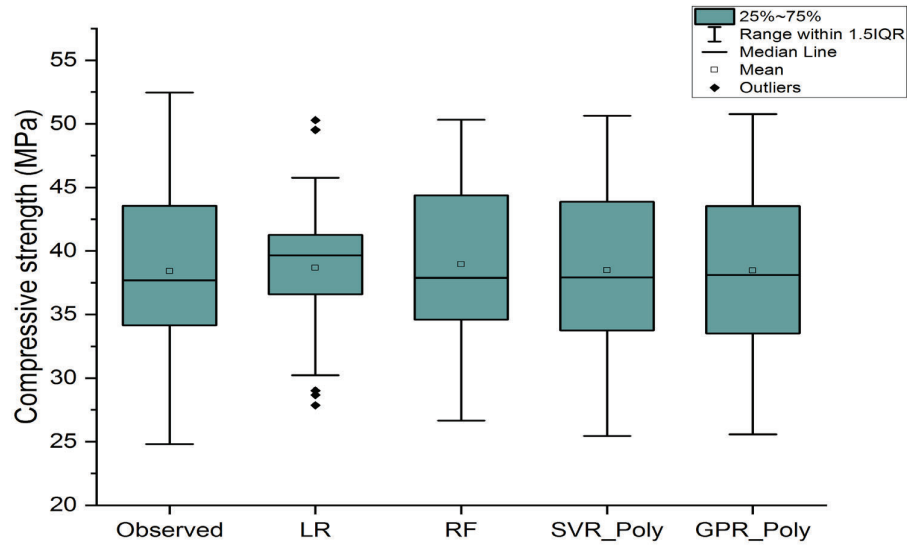


Fig 5.7 (b): Agreement box plot among observed vs estimated values of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for testing stage

Box plots for the error distribution of the various models are shown in **Figure 5.8 (a)** for training and **5.8 (b)** for testing respectively. These figures suggest that the width of SVR_Poly and GPR_Poly shows the least error band among the various models. Whereas the width of the box is found larger for the LR LR-based model for both training and testing stages these figures suggest that SVR_poly and GP_poly have comparable results as observed values in terms of 1st quartile, mean, and 3 quartile. The statistical performance of error distribution of LR, RF, SVR_Poly, and GPR_Poly models are shown in **Table 5.7**.

Table 5.7: Statistics of error distribution of LR, RF, SVR_Poly and GPR_Poly models

	LR	RF	SVR_Poly	GPR_Poly
Statistic	Training data set			
Minimum	-5.8660	-1.4809	-1.5620	-1.1820
Maximum	6.6940	2.1622	2.2220	1.7740
1st Quartile	-2.7558	-0.3760	-0.1550	-0.3808

Mean	0.0000	-0.0454	0.0284	0.0000
3rd Quartile	2.6289	0.3185	0.3828	0.3407
	Testing data set			
Minimum	-5.6610	-5.2750	-2.6420	-2.4660
Maximum	7.4710	3.5213	1.9880	1.9550
1st Quartile	-3.3048	-1.5323	-0.7025	-0.7194
Mean	-0.2486	-0.5384	-0.0662	-0.0394
3rd Quartile	2.2185	0.6148	0.8210	0.7413

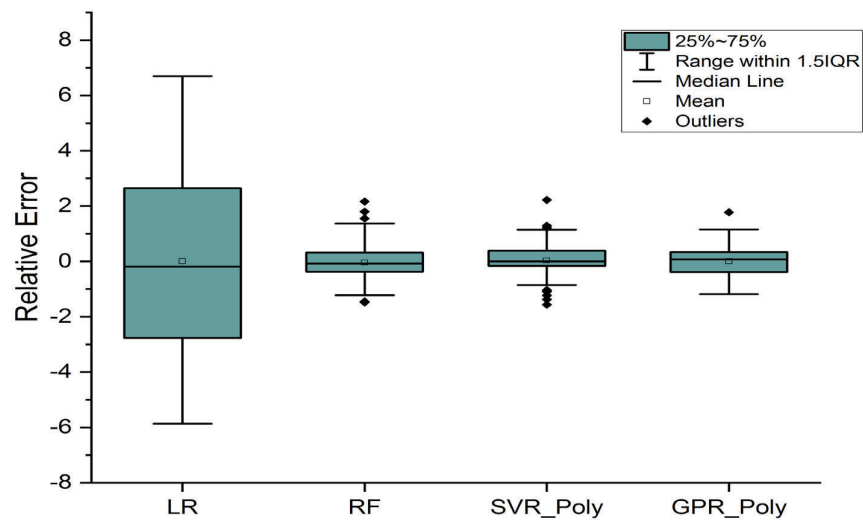


Fig 5.8 (a): Agreement box plot for relative error of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for training stage

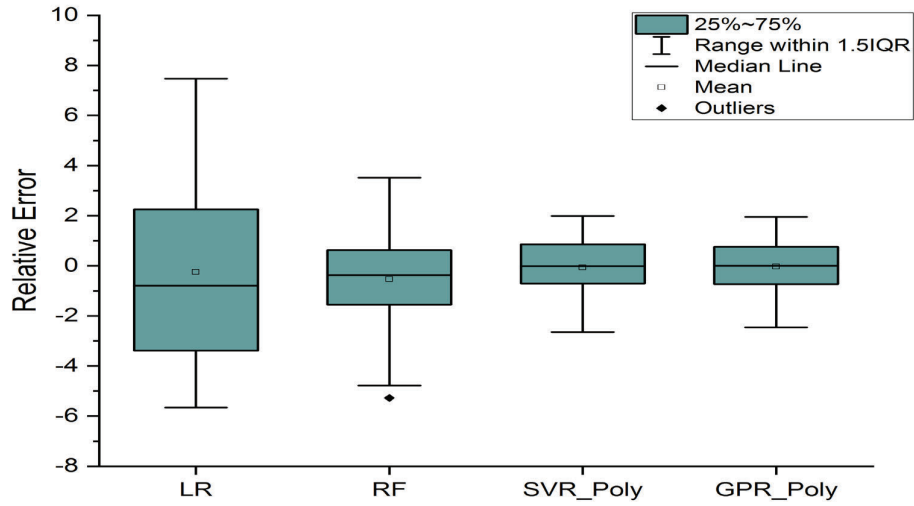


Fig 5.8 (b): Agreement box plot for relative error of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for the testing stage

5.7.3 Taylor's diagram results:

In this investigation a graphical method Taylor diagram to evaluate the performance of all applied models. Taylor's diagram for the training stage is listed in **Figure 5.9(a)** and for the testing stage in **Figure 5.9(b)**. Taylor diagram expresses standard deviation in the x and y axis and CC on curvature. The best model is determined by comparing the distance between observed (hollow black circle) and model values (solid circles). The results of these figures indicate that the GPR_Poly --based model has the highest accuracy than the other applied models for the prediction of the compressive strength of rubberized slag-based GPC. SVR_Poly has also very good performance except for GP_poly among all applied models. LR models (Solid yellow circle) have the lowest performance among all applied models due to their larger distance from the observed circle in both the training and testing stages.

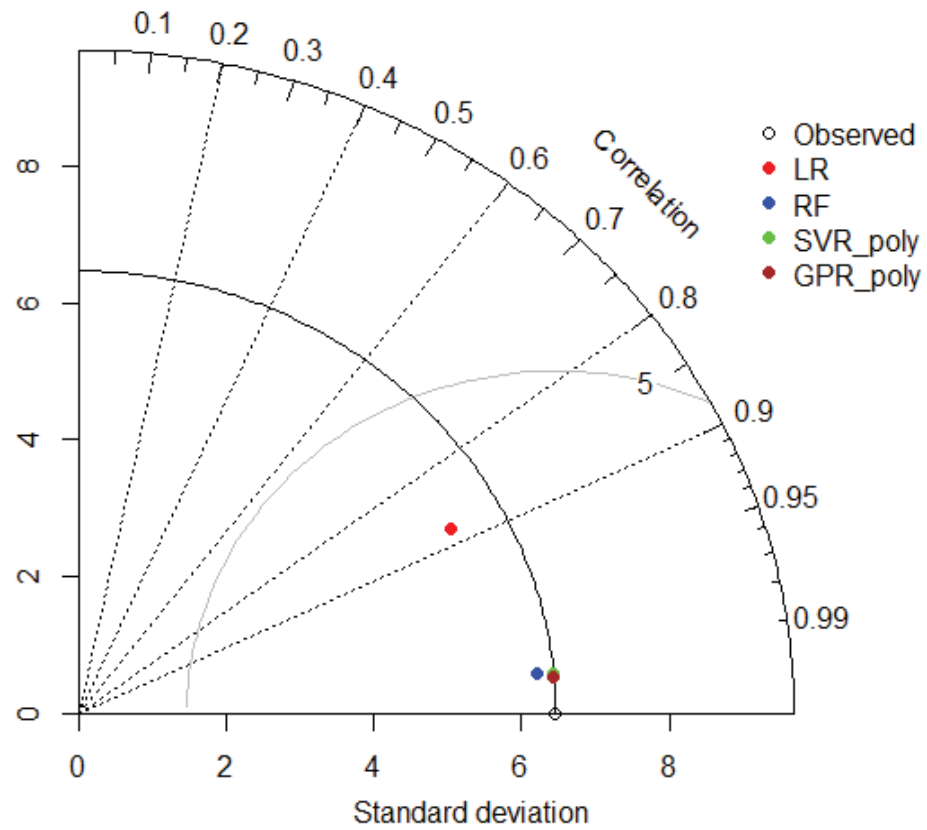


Fig 5.9 (a): Taylor diagram of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for training stage

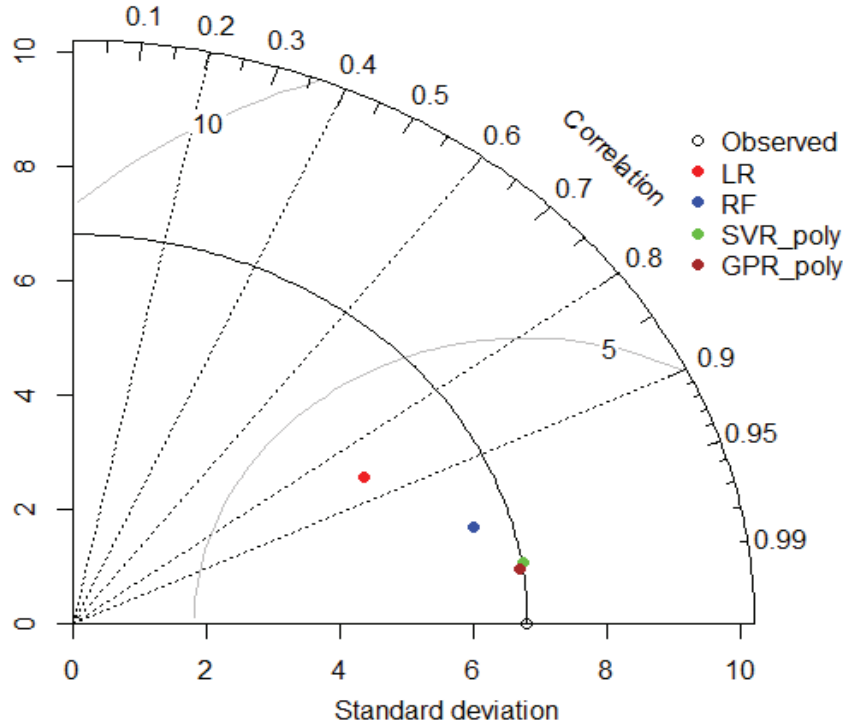


Fig 5.9 (b): Taylor diagram of compressive strength of rubberized slag-based geo polymer concrete using LR, SVM, and best-performed kernel function for GPR and SVR models for the testing stage

5.8 Sensitivity analysis:

The sensitivity analysis was conducted to evaluate the most significant input variables in the prediction of the compressive strength of rubberized slag-based geopolymer using the GPR-Poly model. Several factors such as fly ash quantity, Molarity of NaOH, Na_2SiO_3 quantity, NaOH quantity, sand, copper slag, rubber aggregate, coarse aggregate, and curing period affect the compressive strength of rubberized GPC. The testing datasets were created by removing at a time for analysis as presented in **Table 5.8**. The significance of various input variables on the output variable (CS) was stated in terms of CC, MAE, and RMSE. The results from **Table 5.8** suggest that the input parameter curing period plays the most significant role in predicting the compressive strength of rubberized slag-based geopolymer using this data set.

Table 5.8: Sensitivity analysis using GPR-Poly-based model for the testing stage.

Input combination									Target	GPR_Poly (Testing data set)		
FA	M	q	Naq	S	CoS	CA	RA	D	CS	CC	MAE (MPa)	RMSE (MPa)
										0.9902	0.7621	0.9508
										0.9902	0.7621	0.9508
										0.9689	1.4117	1.7488
										0.9902	0.7620	0.9514
										0.9901	0.7655	0.9561
										0.9902	0.7621	0.9508
										0.9902	0.7621	0.9507
										0.9902	0.7617	0.9503
										0.9902	0.7621	0.9508
										0.6020	4.8400	5.5677

Where FA= Fly ash quantity, M= Molarity of NaOH, q= Na₂SiO₃ quantity, Naq= NaOH quantity, S= sand, CoS= copper slag, CA= Coarse aggregate, RA= rubber aggregate, D= curing period

5.9 Summary:

The conclusion of this study states the application of various soft computing techniques such as LR, RF, different kernel functions based on SVM, and GPR for predicting the compressive strength of rubberized slag-based GPC. This study was employed to show the successful application of soft computing techniques alongside indistinctness, inaccuracy, and irregular predictions in the field of civil engineering. The hypothesis formulated for this study of compressive strength of rubberized slag-based GPC has shown satisfactory results for both training and testing datasets, but the outcome suggests that GPR_Poly shows better results than the other computing techniques. The results also show that the polynomial kernel function works better than the other kernel functions for the prediction of compressive strength of rubberized slag-based GPC on GPR and SVM models. The present computational modeling is a precise and very simple technique defining the compressive strength of rubberized slag-based GPC which is better than time-consuming conventional techniques and high-performance dynamic systems. The sensitive analysis on best performed soft computing technique

(GPR_Poly) to predict the compressive strength of rubberized slag-based GPC for input variables such as fly ash quantity, Molarity of NaOH, Na_2SiO_3 quantity, NaOH quantity, sand, copper slag, rubber aggregate, coarse aggregate and curing period shows that the curing period was the most significant variable. The results of techniques LR, RF, GPR, and SVM show that are supposed to be capable of potential studies such as group method of data handling (GMDH), adaptive neuro-fuzzy inference system (ANFIS), particle swarm optimization (PSO), etc with sizable data sets. Moreover, the use of these predictive models helps in determining the accurate optimum compressive strength of GPC without conducting many trial mixes which will save time, energy, and money.

CHAPTER 6

CONCLUSIONS

Geopolymer concrete is a cement less eco-friendly material where its production leads to reduction of the carbon footprint. The reduction of carbon footprint is mainly due to use of industrial waste by-products such as fly ash, GGBS, Copper slag as the binder materials. In this study the fresh properties such as initial and final setting time, flow value, and workability, Mechanical properties such as compressive strength, flexural strength and split tensile strength, Durability properties such as density, water absorption, acid attack, RCPT and sorptivity are provided for geopolymer mortar and concrete where fine aggregate is replaced by 10, 20, 30, 40 and 50% of copper slag and coarse aggregate is replaced by 5, 10 and 15 % of crumb rubber. The study of bond strength of rubber and slag based geopolymer concrete with steel and GFRP bars are also provided to determine the structural performance. Various soft computing techniques such are also studied to minimize the mix design experiments and achieve the target strength of the rubberized slag-based concrete.

6.1 Summary of Key Findings:

This research investigated the effects of varying NaOH molarities, SS/SH ratios, and the incorporation of copper slag and crumb rubber on the properties of fly ash-based geopolymer mortar and concrete. The primary findings are as follows:

- **Setting Times:** The initial and final setting times of geopolymer mortar decreased with increasing NaOH molarity and SS/SH ratio. Specifically, the initial setting time decreased from 425 minutes to 215 minutes, and the final setting time decreased from 670 minutes to 442 minutes as the SS/SH ratio increased. Similarly, increasing NaOH molarity reduced the initial setting time from 425 minutes to 305 minutes and the final setting time from 670 minutes to 456 minutes. The addition of copper slag further reduced setting times, with initial setting times decreasing from 382 minutes (10% copper slag) to 63 minutes (50% copper slag) and final setting times from 548 minutes to 132 minutes.
- **Flow Values:** The flow values of geopolymer mortar decreased with increasing NaOH molarity and SS/SH ratio. The flow value decreased from 142 mm to 81 mm as the SS/SH ratio increased from 1 to 3 and NaOH molarity from 8 to 12 M. The substitution of fine aggregates with copper slag and crumb rubber also reduced flow values, with

copper slag reducing flow values from 123 mm to 58 mm and crumb rubber from 87 mm to 58 mm.

- **Compressive Strength:** The compressive strength of geopolymer mortar and concrete was influenced by NaOH molarity, SS/SH ratio, and the incorporation of copper slag and crumb rubber. Higher NaOH molarities and SS/SH ratios generally increased compressive strength, with optimal results observed at 10 M and 12 M NaOH concentrations. The addition of copper slag enhanced compressive strength, with 50% copper slag replacement yielding the highest strength. Conversely, the inclusion of crumb rubber reduced compressive strength, although pre-treatment of rubber improved strength outcomes.
- **Flexural and Split Tensile Strength:** Both flexural and split tensile strengths increased with higher NaOH molarities and SS/SH ratios. The incorporation of copper slag improved these strengths, while crumb rubber had a detrimental effect. However, pre-treatment of crumb rubber mitigated some of the negative impacts on strength.
- **Sorptivity and RCPT:** The sorptivity of geopolymer concrete increased with higher crumb rubber content, indicating greater water absorption. However, the inclusion of copper slag reduced sorptivity, enhancing the material's resistance to water ingress. The RCPT values indicated that copper slag improved chloride ion resistance, while crumb rubber had a mixed effect depending on the treatment duration.
- **Durability:** The study also assessed the durability of geopolymer concrete under acidic conditions. The inclusion of copper slag and crumb rubber influenced weight loss and compressive strength loss. Copper slag increased the mass of specimens initially but led to mass loss over time due to its solubility in acidic media. Crumb rubber enhanced acid resistance, reducing weight loss and maintaining compressive strength better than mixes without rubber.
- **Bond Properties:** The comparative study between GPC and OPC concrete specimens indicates that GFRP-reinforced GPC exhibits higher bond strength than OPC under similar conditions. The GPC specimens achieved an average bond strength of 18 MPa, compared to 16.8 MPa for OPC, despite exhibiting splitting failure while OPC showed pullout failure. The higher bond strength in GPC is likely responsible for increased radial stresses leading to splitting failure. These findings highlight the potential of GPC as a strong and reliable alternative to conventional OPC in reinforced concrete applications.

- **Soft computing techniques:** This study demonstrates that soft computing techniques such as Linear Regression, Random Forest, Support Vector Machine, and Gaussian Process Regression can effectively predict the compressive strength of rubberized slag-based geopolymer concrete. Among the models evaluated, the polynomial-based GPR approach provided the most accurate predictions, with the curing period identified as the most influential input parameter. The results highlight that polynomial kernel functions perform better than other kernels in both GPR and SVM models. Overall, the developed models offer a reliable and efficient alternative to conventional experimental methods, reducing the need for extensive trial mixes and saving time and resources.

6.2 Implications of the Research:

The findings of this research have significant implications for the construction industry, particularly in the development of sustainable and durable building materials. The use of industrial by-products such as fly ash, copper slag, and crumb rubber in geopolymer concrete not only addresses waste management issues but also enhances the mechanical and durability properties of the material. The reduction in setting times and flow values with higher NaOH molarities and SS/SH ratios suggests that these parameters can be optimized to achieve desired workability and strength characteristics. The improved compressive, flexural, and split tensile strengths with copper slag incorporation highlight its potential as a valuable replacement for conventional aggregates. However, the negative impact of crumb rubber on strength necessitates further research into pre-treatment methods to enhance its compatibility with the geopolymer matrix.

6.3 Recommendations for Future Research:

Future research should focus on the following areas to build on the findings of this study:

Optimization of Mix Design: Further studies should explore the optimal mix design for geopolymer concrete incorporating varying percentages of copper slag and crumb rubber. This includes investigating the effects of different curing conditions and durations on the mechanical properties and durability of the material.

Long-term Durability: Long-term durability studies are essential to understand the performance of geopolymer concrete under various environmental conditions, including exposure to aggressive chemicals, freeze-thaw cycles, and high temperatures.

Pre-treatment of Aggregates: Research should continue to explore effective pre-treatment methods for crumb rubber to enhance its bonding with the geopolymer matrix and mitigate its negative impact on strength.

Field Applications: Pilot projects and field applications of geopolymer concrete incorporating industrial by-products should be conducted to evaluate its performance in real-world conditions and identify any practical challenges in its use.

Environmental Impact Assessment: Comprehensive life cycle assessments should be conducted to evaluate the environmental benefits of using geopolymer concrete with industrial by-products compared to conventional concrete.

This research has demonstrated the potential of fly ash-based geopolymer mortar and concrete incorporating copper slag and crumb rubber as sustainable construction materials. The findings highlight the importance of optimizing NaOH molarity, SS/SH ratio, and aggregate replacement levels to achieve desired mechanical properties and durability. The use of industrial by-products not only enhances the performance of geopolymer concrete but also contributes to waste management and environmental sustainability. Future research should continue to explore the optimization and practical applications of these materials to fully realize their potential in the construction industry.

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LIST OF PUBLICATIONS

1. Choudary, Y. S., Singh, K., Babu, T. S., & Deepthi, G. (2023). Impact on Mechanical and Durable Properties of Rubber and Copper Slag-based Geo-polymer Mortar using Various Sodium Hydroxide Molarities and Proportions of Alkali Activator Solutions. *Journal of Mining and Environment*, 14(3), 853-870. (SCOPUS)
2. Yeluri, S. C., & Yadav, N. (2020, November). Mechanical properties of rubber aggregates based geopolymer concrete-A review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 989, No. 1, p. 012014). IOP Publishing. (SCOPUS)
3. Yeluri, S. C., Singh, K., Babu, T. R., & Garikapati, D. (2023). Durability properties of rubber aggregates based geopolymer concrete-a review. *Materials Today: Proceedings*. (SCOPUS)

LIST OF CONFERENCES

1. Presented a paper titled “Mechanical properties of rubber aggregates based geopolymer concrete-A review” in Virtual International Conference on Emerging Research trends in Structural Engineering (ERTSE 2020) organised by Vellore Institute of Technology, Chennai during 16-17 July, 2020.
2. Presented a paper titled “Durability properties of rubber aggregates based geopolymer concrete-a review” in International UKIERI Concrete Congress Sustainable Concrete Infrastructure, Hosted by Dr B R Ambedkar National Institute of Technology Jalandhar, India and Guru Nanak Dev Engineering College Ludhiana, India, held on 14 - 17 March 2023.