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A Review of Experimental Study on the Effect of Curing Conditions on the Strength Development of Geo-Polymer Concrete

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Abstract - *This review will examine how the curing environment influences both the development of the strength properties in addition to the microstructural evolution of geo polymer concrete, specifically focusing on curing conditions such as temperature, time, and moisture control. Performance of geo polymer systems is highly dependent upon the curing environment which dictates the rate at which reactions occur as well as gelation. Studies have demonstrated that curing of geo polymer systems at higher temperatures (compared to ambient) leads to increased compressive strength during the early ages of a structure and results in denser microstructures. Additionally, studies have shown that optimal curing under ambient conditions or moisture controlled curing may be able to produce comparable long-term strengths with greater practicality when utilizing geo polymer materials for construction projects. This review also provides an overview of how curing conditions affect porosity; the interfacial transition zone between aggregate particles and cement paste; shrinkage of the geo polymer system; and the durability of geo polymer systems to various types of environmental stressors including chemical, thermal, and mechanical. In addition, this review identifies areas of future research that relate to implementing curing strategies in the field; evaluating the long-term durability of geo polymer systems; and developing scalable curing techniques for geo polymer systems.*

Key Words: **Geo polymer concrete, curing conditions, strength development, microstructure, temperature curing, moisture control, durability**

1. INTRODUCTION

1.1 Need for Sustainable Binder Systems

The increasing concern about the environment and the ever-increasing carbon footprint associated with the use of traditional Portland cement, have led to an increase in research on alternative binder systems that will contribute to reducing greenhouse gas emissions and supporting sustainable building methods. The manufacturing process for traditional cement requires a lot of energy and produces a significant amount of CO2 into the atmosphere; therefore, there has been a growing interest in using industrial by-product materials which require less energy to manufacture. In light of the above, geo polymer concrete has shown great promise as it can be made from waste alumina silicate materials, while also showing comparable performance in terms of mechanical and durability properties compared to other types of concrete.

1.2 Basics of Geo polymer Concrete and Its Chemistry

The development of geo polymer concrete occurs from the chemical reaction between materials rich in alumina silicates (fly ash; ground granulated blast furnace slag; meta kaolin) with an alkaline activating liquid. In the chemical development, dissolution of these precursor materials occur followed by polymerization and development of a 3-D inorganic framework predominantly comprised of N-A-S-H or C-A-S-H type gel networks. Geo polymer binder development has been demonstrated to be different than the hydration development of traditional cements in that geo polymer binder development can be affected by the availability of reactive species, temperature, alkalinity levels, and moisture conditions. Provided that proper curing conditions exist, this unique chemistry allows for the development of geo polymer binders exhibiting high early strength properties, enhanced chemical durability, and superior thermal stability properties.

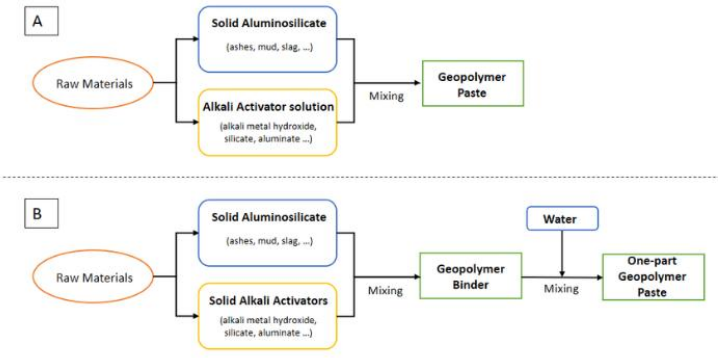

Figure-1: Processing flow chart of (A) traditional geo polymer; and (B) one-part geo polymer.

1.3 Curing Conditions Strongly Influence Geo polymer Strength

The curing process is the primary factor which determines how much the geo polymerization reaction occurs and how efficiently; therefore, curing is an extremely important parameter in determining the rate of strength development in geo polymer concrete. In order for the reaction to proceed

as desired, sufficient thermal energy must be provided, moisture levels must be adequately controlled, and ample time should be allowed for the geo polymer gel phase to form and then develop density. Increased temperatures will enhance the dissolution of the reactants and also encourage quicker gelation; conversely, proper humidity control will aid in preventing excessive moisture loss prior to curing, thereby reducing the potential for poor bonding and increased porosity. As such, varying the curing temperature, duration, or moisture content, can have significant effects upon the degree of microstructural development, which in turn may lead to significant differences in both the compressive strengths and long term performance of geo polymer concretes.

2. LITERATURE REVIEW

2.1 Overview of Research Trends in Geo polymer Concrete

Over the past twenty years there has been an explosion in research on geo polymer concrete primarily due to the need for sustainable building materials and the desire to recycle industrial waste. Researchers have investigated a wide variety of precursor materials (fly ash, slag, meta kaolin, etc.) that are rich in alumina-silicates and react differently based on their chemical composition and particle size. A large portion of the research in this field has focused on alkaline activators (sodium hydroxide, sodium silicate, and various alkali solution blends) as they determine the rate at which reactions occur and the ultimate properties of the geo polymer binder. As the field of geo polymer concrete has evolved, investigators have moved away from investigating the general physical properties of the binder and into more specific aspects of performance (compressive strength development, durability, optimal mixture designs, curing techniques). These investigations demonstrate a larger movement to understand how processing parameters affect the engineering performance of geo polymer concrete.

2.2 Historical Development of Curing Techniques in Geo polymers

The early research in geo polymers was carried out under conditions of high-heat curing, which was used extensively to achieve low-calcium fly ash-based systems with higher temperature to enable dissolution and polymerization. It was also demonstrated that there is a positive correlation between heat curing temperatures (both moderate and high) and the rate of early strength gain, such that it has become an almost default method of curing due to the speed of early strength development. However, subsequent limitations of heat curing (high energy consumption, poor practicability for site based construction etc.) prompted a move towards ambient curing techniques. Consequently, as researchers became interested in optimizing their work, they started to investigate how changes in mix design, blending precursors, increasing the concentration of the activating agent etc. would lead to improved early strength development at ambient temperatures. The recent focus of curing optimization techniques has been to develop optimal curing methods through manipulation of curing profile, altering humidity, employing combined curing methods and developing optimized curing procedures that will improve the properties of geo polymers without requiring additional external heating.

2.3 Summary of Experimental Studies on Curing Temperature

A substantial amount of literature has studied the effects of curing temperature (temperature during curing) on strength development; this body of work demonstrates that curing temperature is a major factor affecting the development of strength for geo polymer materials. The majority of studies have shown that curing at low temperatures impede the rate of dissolution of aluminum silicate particles; thus, low-temperature curing results in delayed increases in strength for geo polymer samples. Conversely, curing at moderate temperatures accelerates the gelation process and provides geo polymer samples with significant increases in early strength. In addition, higher curing temperatures promote rapid polymerization and provide benefits such as improved mechanical properties. However, high curing temperatures may also result in micro-cracks or uneven drying conditions, both of which are detrimental to long-term geo polymer performance. Overall, the temperature-dependent trends in reaction kinetics presented by these studies emphasize the importance of determining an optimum curing temperature for each combination of precursors and activators used in the production of geo polymer materials. The response of different geo polymer systems to their environment (thermal) varies.

2.4 Review of Studies on Curing Duration

The duration of curing (the amount of time the binder is exposed to heat) has also been well-studied. The research indicates that the duration of the heating process directly affects the completeness of the chemical reactions that occur during the curing process, and ultimately the level of mechanical property development exhibited by the cured binder. A short curing duration will generally result in higher early-age strength than a longer curing duration. However, it is possible that some of the reactants in the precursor binder system remain unreacted as a result of the short curing time. This can lead to reduced long-term strength and less dense matrix microstructures compared to a fully reacted binder. Conversely, an extended curing period will allow for nearly complete conversion of the reactants within the precursor binder into a stable, homogeneous polymer matrix. Although most research supports this position, there have been some studies indicating that after a specific optimal curing time, additional curing time results in only incremental increases in strength. Thus, curing time will need to be optimized based on the type of reactive precursor being used, the

concentration of the alkaline activator, and the temperature at which the curing process is conducted.

2.5 Studies on Moisture/Humidity-Controlled Curing

Research has demonstrated that curing temperature (and thus moisture/humidity) has a substantial effect on both the strength and structure of geo polymer products. Sealed versus unsealed curing conditions have been compared; research indicates that uncontrolled evaporation during the initial reactions may lead to partial or incomplete formation of the geo polymer gel and increased porosity within the product. Controlling the curing environment via sealed curing or other methods, thereby retaining internal moisture and providing a consistent source of moisture for continued gel formation, can provide improved mechanical properties. Curing in a controlled environment using a humidity chamber provides the ability to control not only the density of the geo polymer matrix, but also to minimize the number of defects formed as a result of drying. This research clearly illustrates the significance of maintaining adequate moisture levels during the geo polymer reaction process, particularly for mixes having low amounts of available free water or high percentages of fine precursor materials requiring considerable internal moisture to proceed through their respective chemical reactions.

2.6 Review of Alternative and Advanced Curing Methods

In addition to traditional heat and curing by ambient temperature, there are several other, advanced curing techniques presented in literature. One of the most commonly discussed alternatives is the curing by solar radiation (solar curing) which was tested as an environmentally friendly method of curing in areas with high levels of solar irradiation. This research demonstrated that, under specific circumstances, solar radiation may be used as a supplementary source of heat to support the curing process. Microwave curing was researched for its potential to rapidly and uniformly heat geo polymeric materials; however, controlling microwave curing to prevent overheating at local points is required. In addition to microwave curing, steam curing and hot air curing were researched in order to increase strength of the geo polymer by increasing the amount of thermal energy available for curing. The research of hybrid curing techniques that use combinations of various thermal and/or moisture curing techniques has shown great promise as a means to achieve consistent results with minimal energy consumption. The development of these alternative curing techniques is indicative of the on-going efforts to improve and develop curing techniques that are suitable for both varying climates and building environments.

2.7 Comparative Analysis of Ambient vs Heat Curing in Literature

The use of ambient-cured (room temperature) versus heat-cured geo polymer systems has been one of the most disputed aspects of geo polymer research. While heat curing tends to yield greater initial strengths (particularly when using low-calcium precursors such as fly ash) primarily by accelerating polymerization processes with increased temperatures; ambient curing can offer numerous benefits including greater ease of application, lower costs, and better field applications. Researchers have reported several methods that can be used to enhance the performance of ambient cured systems. Some of the methods include finer grinds of the precursors (in order to create a larger surface area), addition of calcium rich materials (such as blast furnace slag) and modification of the activator composition. Although researchers have made significant progress in developing improved ambient curing systems, there remains considerable variability in the results obtained from ambient curing systems across various studies. The variability in results has primarily occurred due to the differences in the characteristics of the precursors and the environmental conditions under which the curing process occurs. This variability clearly indicates a need for a further understanding of the mechanisms controlling the behavior of ambient curing systems.

3. FUNDAMENTALS OF GEOPOLYMER CONCRETE

3.1 Chemistry of Geo polymerization

Geo polymers are formed when alumina silicates react with an alkaline activator to create a three-dimensional inorganic polymer matrix through multiple poly condensation reactions. The first step in the geo polymer synthesis process is the dissolution of alumina and silica from the alumino silicate source material into solution with hydroxide (OH-) ions. Once dissolved, the two primary gel-forming species undergo poly condensation to produce various forms of gel, such as N-A-S-H in low-Ca systems or C-A-S-H in Ca-rich systems. Geo polymerization differs significantly from Portland cement hydration; while Portland cement hydration results in the formation of calcium-silicate-hydrates (C-S-H) through a hydration reaction, geo polymerization is a direct chemical transformation that occurs due to the effects of alkalinity, temperature and moisture content of the system. It is this gel-forming reaction that provides geo polymers their high mechanical strength, thermal stability and durable performance characteristics.

3.2 Materials Used in Geo polymer Binders

Different alumino silicate materials can be used as sources for synthesis of geo polymer concrete; the three most commonly utilized are fly ash, ground granulated blast furnace slag (GGBS), and meta kaolin. The contribution of each material is varied based on chemical compositions,

particle size distributions, and the degree of amorp hosity present in the material. Fly ash-based mixtures generally need high temperature curing to produce high-strength geo polymers, while GGBS-based mixtures often show improved early age reactivity at room temperature as they have higher calcium contents than fly ash. Ultimately, the choice of source material impacts both the rate of the overall reaction and the types of gel that are formed as well as the properties of the fully cured geo polymer binder.

3.3 Role of Alkaline Activators

Alkaline activators which normally include alkali hydroxides (NaOH), alkaline metal hydroxides (KOH), and/or alkaline silicates (Na2SiO3) or a combination thereof are key for the preparation of geo polymer concrete since they facilitate the dissolution of precursors and the formation of the gel phase. In addition, the molarity of hydroxide solution; silicate modulus; and activator to binder ratio control the rate and degree of polymerization. Although higher molarities of the activator typically increase the dissolution rate it may also produce some detrimental effects such as high heat evolution and efflorescence. Therefore the correct activator system should be developed based on the characteristics of the particular precursor to ensure that the concrete has good workability, develops adequate strength over time, and is durable.

3.4 Reaction Mechanism and Microstructural Development

During the geo polymerization process (which is comprised of a series of interdependent processes) the initial stages involve the dissolution of amorphous alumino silicates; diffusion of the dissolved ions; nucleation; and ultimately polymerization of gel structures. The early stages of geo polymerization are significantly influenced by both temperature and moisture conditions as these two variables will affect the rate at which dissolution occurs and the mobility of the ions being dissolved and consequently affect the density and uniformity of the gel that is being developed as it forms. Eventually, as polymerization proceeds the gel structure that develops becomes increasingly dense as it begins to occupy the voids present within the structure. This development of the gel structure results in a highly ordered microstructure with reduced porosity and increased stiffness. Therefore, the microstructural development is directly related to the curing conditions, therefore the thermal and moisture conditions present during the curing process are critical for achieving desired mechanical properties and long term durability.

4. TYPES OF CURING METHODS

4.1 Heat Curing

The use of heat curing is a common method in the creation of geo polymer concrete using many different types of precursors, particularly those with lower levels of calcium in fly ash. Heat curing allows the newly created geo polymer concrete to be cured at elevated temperatures (moderate to high) within an oven or steam curing chamber to promote the effective curing of the geo polymer. Through the use of elevated temperatures, the rate of gelation of the geo polymer increases through the increased dissolution of alumino silicate particles, thus increasing the early age strength of the geo polymer. Additionally, through the application of heat curing, the development of a denser and more continuous gel network is enhanced. Although the process of heat curing has proven to be successful in the laboratory environment, there are still some challenges associated with this type of curing such as the high amount of energy required and limitations in its practicality for use in larger scale construction projects.

4.2 Ambient Curing

Due to its potential for use in the field with less equipment, and less energy consumption; Ambient Curing has gained increased interest as an alternative to heat curing. Ambient curing allows geo polymer concrete to be cured at room temperature, eliminating the need for supplemental heat.

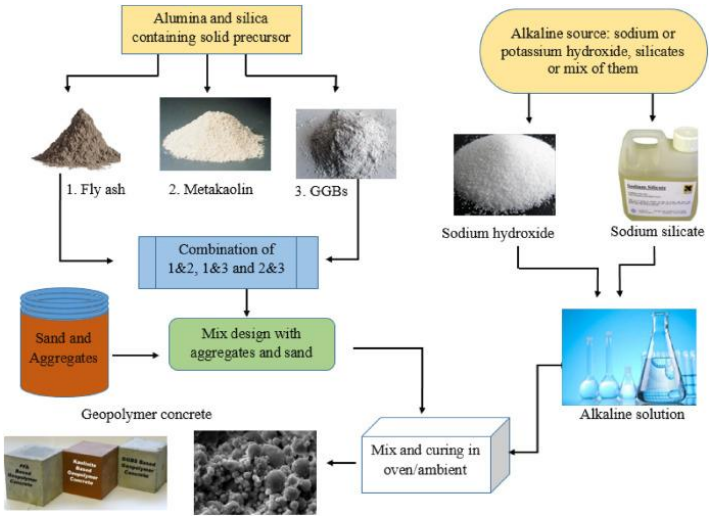

Figure-2: lassie fictions of Curing Methods (Heat, Ambient, Moisture-Controlled, Advanced)

4.3 Moisture-Controlled Curing

Moisture-controlled curing aims to regulate the availability of water during the geo polymerization process, preventing premature drying and ensuring that sufficient moisture remains for continued gel formation. This method often involves sealed curing, the use of plastic wrapping, or controlled humidity chambers that maintain a stable moisture environment around the specimen. Moisture retention has been shown to improve the density and uniformity of the geo polymer matrix by allowing uninterrupted polymerization reactions and reducing the risk of shrinkage-induced micro cracking. Studies

consistently demonstrate that moisture-controlled curing enhances both strength and durability, especially in systems with low water-to-solid ratios or fine precursors that rely on internal moisture for reaction progression. This curing approach plays a crucial role where environmental conditions fluctuate or where extended curing time is needed.

5. INFLUENCE OF CURING TEMPERATURE

5.1 Peak Strength Development under Various Temperature Regimes

Geo polymer concrete curing temperatures are crucial for the amount and rate of time it takes for geo polymer concrete to develop its strength. Increased curing temperature results in a faster breakdown of alumino silicate precursor materials which increases the rate of reaction of forming the binding gel of geo polymer concrete. Consequently, geo polymer concrete cured at higher temperatures than ambient temperatures typically exhibit significantly greater strength immediately after casting (early age) than those cured under ambient conditions. Experimental studies have demonstrated that increasing the curing temperature within a reasonable temperature range produces an increase in compressive strength through a more complete geo polymerization process. Additionally, excessive curing temperatures may produce micro-cracks within the geo polymer matrix through thermal stresses, evaporation of pore water, or producing less stable gel phases. While curing at elevated temperatures generally improves properties of the geo polymer matrix, there must be a balance to achieve the maximum strength at the optimum curing temperature to avoid undesirable effects.

5.2 Optimal Temperature Ranges for Different Geo polymer Systems

The appropriate temperature for curing geo polymer concrete depends upon a number of parameters including the type of precursor (i.e., low-calcium vs. calcium-rich), the specific formulation of the alkaline activator and the ratio of all of the components in the mixture. Low-calcium precursors, e.g., Class F fly ash, generally are required to be cured at relatively elevated temperatures in order to fully react; optimum curing conditions for these types of precursors have been reported to exist in the temperature range of 60°C to 90°C. However, because of their inherently greater reactivity than low-calcium precursors, calcium-rich precursors (e.g., slag, fly ash–slag blends) will typically develop sufficient strength at relatively lower temperatures. To determine the "optimum" curing temperature for a particular geo polymer concrete mixture requires consideration of both the chemical properties of the individual constituents of the mixture, as well as several other practical considerations, including the desired curing duration, energy consumption and/or field applications. There is consistent evidence in research indicating that curing temperatures within a certain "window," defined by the specific geo polymer concrete mixture being evaluated, enhance reaction kinetics while maintaining structural integrity, thus temperature is considered one of the most significant variables affecting the performance of geo polymer concrete.

6. INFLUENCE OF HUMIDITY AND MOISTURE

6.1 Moisture Availability and Its Impact on Porosity

The amount of moisture available during curing has a substantial impact on the internal pore-structure formed within the curing environment of geo polymer concrete. Maintaining adequate levels of moisture will allow for continued progress in the geo polymerization reaction process so that it can continue to form uniform and dense networks of gels. Typically when samples are placed into sealed or high-humidity environments during curing the retained moisture allows for the dissolution of alumino-silicate particles which allows for a higher degree of poly condensation. The higher degrees of poly condensation tend to result in a matrix with less total porosity and greater structural integrity. Conversely, if samples are exposed to low-humidity conditions during curing (or even unsealed), then there will be an excessive loss of moisture and this could lead to the occurrence of limited reaction processes and also the creation of large capillary pores. These types of environments could negatively affect both the early age properties of geo polymer concrete and its long term performance. As such, controlling the level of humidity is important for determining the quality and durability of the final microstructure of geo polymer concrete.

6.2 Influence of Moisture Conditions on Shrinkage Behavior

The degree of shrinkage in geo polymer concrete is primarily influenced by the amount of moisture migrating into and out of the developing gel throughout its initial development stages. Shrinkage can occur due to rapid loss of moisture resulting in tensile stress within the matrix causing it to shrink, and further cause micro-cracking to form. The effect of shrinkage on geo polymer concrete can be substantially diminished through the maintenance of a high humidity environment which will reduce the rate of evaporation and minimize the potential for differential shrinkage; this results in a less variable material with respect to dimensional stability. Research has demonstrated that establishing an optimal moisture level for curing can both minimize shrinkage and diminish the likelihood of cracks that may result in reduced long term durability. Therefore, effective management of humidity can act as a means of protecting against shrinkage-related damage.

7. COMBINED EFFECTS AND INTERACTION BEHAVIOUR

7.1 Multifactor Interactions among Temperature, Duration, and Moisture

The curing process of geo polymer concrete is typically controlled by multiple, interacting factors, including temperature, curing time (duration) and moisture content (curing environment). As such, these curing factors frequently act in conjunction with each other to create combined influences on reaction progression and final strength development. For example, the enhanced reaction rates associated with elevated curing temperatures are significantly dependent on sufficient available moisture. Likewise, extended curing periods can provide additional benefits depending upon whether continued polymerization will occur within an environmentally favorable condition. A thorough understanding of these multi-factorial relationships will enable accurate prediction of future performance and selection of curing procedures to produce desired mechanical and microstructural properties. This multi-faceted behavior also underscores the need for a comprehensive or integrated approach to evaluate all curing factors simultaneously.

7.2 Insights from Response Surface Analysis and Experimental Optimization

Response Surface Analysis (RSA) is becoming an increasingly important method to study the interaction between curing parameters, as RSA allows researchers to evaluate non-linear relations and optimal curing conditions for Geo polymer formation. The use of Response Surface Models, through systematic variation of Temperature, Time and Moisture Levels allow researchers to determine areas in which Curing Parameters will interact to produce maximum Strength and/or minimum Porosity. The use of RSA will give a more complete understanding of how Curing Variables affect one another and what are the Threshold Limits at which Performance begins to decrease. Optimization techniques using RSA are particularly beneficial for the development of Field Applicable Curing Strategies, which can optimize Efficiency and Practicality while achieving Optimal Performance.

8. DURABILITY UNDER VARIOUS CURING CONDITIONS

8.1 Chemical Durability and Resistance to Aggressive Environments

The relationship between chemical durability in geo polymer concrete and curing can be explained by the effects on the density and connectivity of the gel phase which will influence how well a geo polymer concrete resists chemical attacks. Systems with a good curing history (especially systems cured at elevated temperatures or in a sealed environment) tend to have higher-density micro structures that provide effective protection from sulfate attack, chloride ion penetration, and acidic attack. On the other hand, poorly cured systems tend to produce pore networks that are highly susceptible to damage caused by ions penetrating through them. The formation of continuous stable alumino silicate gels during a successful curing process has a significant impact on the durability of geo polymer concrete, showing that curing does not only affect early strength but also the long term chemical resistance of a geo polymer concrete system.

8.2 Thermal Durability and High-Temperature Stability

Curing has an important influence on the formation of thermally resistant gel structures in geo polymer concrete, which can help preserve the thermal stability benefits of geo polymer concrete over OPC (ordinary Portland cement) based systems. The effective curing of geo polymer concrete provides thermally stable gel structures that will continue to provide load bearing properties at high temperature. Typically, samples that have been cured with heat are more resistant to thermal degradation than samples that have not received adequate heat curing due to their higher density and improved interfacial bond development, both of which are less likely to fail from cracks or mass loss. On the other hand, poorly cured materials will typically exhibit defects that are exacerbated by thermal stresses; thus, curing affects not only the amount of heat resistant phase that forms in the geo polymer concrete, but it also determines how much of the original material properties remain post-thermal exposure.

9. CONCLUSION

Strength development, Microstructure refinement, Long-term durability are all impacted by curing conditions in the production of geo polymer concrete. Each of Temperature (duration), Duration, and Moisture availability contribute to the geo polymerization reaction to form different gel phases, Porosity distributions, and Matrix Quality. High temperature curing enhances reaction rate and creates High Strength Densities at Early Age, Ambient curing when properly optimized is an Energy Efficient Alternative to Field Applications. Moisture controlled curing is a significant factor in Maintaining Reaction Continuity and Reducing Shrinkage Induced Defects. The interactions between the three curing factors emphasize the Need for Design Considerations that account for the Interactions between Curing Parameters and Both Early and Long Term Performance. Overall, the Study indicates that Developing Curing Protocols based on Precursor Reactivity, Mix Designs, and Application will Improve Mechanical Behavior, Stability of Microstructure, and Environmental Sustainability of Geo polymers. Overall this study reinforces that Curing is an Essential Design Variable to Advance Geo polymer Technology into Wider Use in Civil Engineering Practice.

10. LIMITATIONS

Though a substantial amount of research has been conducted on curing of geo polymer, there are still a number of constraints limiting the ability to generalize the results from those studies. The majority of the studies have used controlled laboratory conditions which fail to reflect the complexity and variability of actual site construction conditions; therefore, translating an optimum laboratory curing regime to a practical application is challenging. Additionally, the variation in precursor materials, specifically the heterogeneity of industrial by-product such as fly ash, introduces additional uncertainty as differences in chemical composition and fineness significantly affect curing sensitivity and reaction rate. Most studies provide information on early age strength and micro-structure with very little long-term data on durability performance under various environmental conditions. While advanced curing techniques show promise, they are typically evaluated on a small scale and, thus, leave open questions concerning their cost effectiveness and scalability. Lastly, the collective effect of curing variables are not fully understood and many models oversimplify the complex kinetics involved in the geo polymerization process. These limitations demonstrate the need for further systematic, field oriented, and long term investigation to establish universally applicable curing practices.

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