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A Review on the Mechanical and Microstructural Performance of Sustainable Geopolymer Concrete

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Abstract
With high levels of CO_2 emissions and resource depletion more attention has been paid to environmental aspects of ordinary Portland cement (OPC) production, especially in view of the need for better sustainable construction materials. The good news to the usage of waste product in GPC as an eco-friendly construction material through the use of fly ash, ground granulated blast furnace slag and Meta kaolin. These differences could be attributing to the lack of aluminosilicate rich substances which are required for GPC to occur using regular cement as well as better environmental advantages.
Past research results are reviewed on the basis of sustainable GPC performance at mechanical and micro scale. The paper examines the factors that influence the strength characteristics of GPC, which include solution molarity strength, manner of curing, the ratio of binders, binding micro structural effects on gelation behavior and the porosity and phase composition. SEM, TGA and FTIR and MIP evaluation methods are used in this section to demonstrate the importance of their use in microstructure performance demonstration.
GPC is equally as strong as or stronger than OPC in compressive tests and tensile tests, and is slightly better against environmental degradation, according to the experimental data. Obstacles still have to be overcome in standardization of mix designs and long term performance evaluation methods. Need for research is identified towards achieving industrial acceptance of geo polymer technology that the study highlights.

IndexTerms
Geopolymer concrete, microstructure, compressive strength, aluminosilicate, N-A-S-H, durability, green construction, SEM, sustainability, activators

I. INTRODUCTION

It is therefore the industry's transformation into a considerable source of global carbon dioxide (CO_2) emissions due to OPC cement production and its use in construction. Owing to global importance, one ton of ordinary Portland cement (OPC) production yields close to carbon dioxide emissions (7–8%) of approximately one ton, which total almost 8% of global greenhouse gas emissions. It also means there are a lot of energy that is required in the production of cement as well as a lot of non renewable resources such as limestone and clay to intensify damage to the environment. The increasing urbanization accompanied by population expansion outlays a need to find eco-friendly alternatives to OTP based concrete as there was rapid expansion of infrastructure of OPC based concrete [1].

Geopolymer concrete is a sustainable technological response to problems faced by the cement industry in the sense of operations. In the late 1970s, Joseph Davidovits first demonstrated the actuative base of the techno chemical concept behind Geopolymer Concrete by the activation of three aluminosilicate mineral bearing industrial by products by using alkaline solutions. Other than C-S-H gels, geopolymerization produces different binding gels, called sodium or calcium aluminosilicate hydrate (N-A-S-H or C-A-S-H) gels in geopolymer that results in better durability due to its distinct microstructure. GPC has lower CO_2 emission in its manufacturing process, better chemical resistance and the fast early strength development property as well as excellent performance under aggressive conditions than OPC.

This paper [2] examines sustainable geopolymer concrete through examination of material and structural microproperties. In this review synthesis research, which reviewed the studies are based on peer reviewed and looked into which mix parameter along with curing conditions with different concentration activators affect GPC strength and durability. To understand GPC, the roles of its microstructural features (the formation of gel phase and pores as well as their relation to additives and fibers) need to be analyzed.

The documents presented here come out in the format of an organizational structure with section II, which describes the problem definition of ultimate geopolymer concrete principles. Section III is devoted to mechanical properties, section IV is to micro structural behavior and analysis. The fifth section conducts a performance evaluation of GPC limited for short and long term purposes. Section VI brings the conclusion and forward-looking recommendations for planned GPC research for factory and industrial applications.

II. Problem statement and preliminaries

As GPC possesses several advantageous features for the environment and performance, the industry has been trying to adopt GPC but is essentially constrained. First primary obstacle of the widespread adoption of geopolymer concrete stems from researchers still not understanding its behavior under different environmental situations and loading conditions in long term use. Field of Geopolymer Concrete is a modern material due to short life span in the industry for deformation and long time resistance reason why there are no consistent data on studies of performance duration in this material. It cannot be accepted in large scale applications due to technical uncertainty.

The problem lies thus as there are no existence of standardized mix design procedures and quality control frameworks. The unpredictable mechanical and micro structural properties proven by the work are due to raw material type, namely various fly ash classes, and chemistry difference between slag and metakaolin. Since there are large variations in activator concentration, water to binder ratios, and curing procedures, complex formulation of universal design guidelines becomes physically challenging. Practitioners and engineers face problems when the way of trying to simultaneously ensure fault tolerance and repeatable performance are not standardized.

Preliminaries:

Understanding GPC requires a delve into the various elements of GPC and their terms within the technical world. Geopolymer concrete production consists mainly of industrial waste materials composed of aluminosilicates such as fly ash and GGBS and metakaolin (MK). Si and Al in the right amount are necessary to initiate the geopolymerization process present in the materials.

The main gel products formed in the geopolymerization reaction include N-A-S-H (sodium aluminosilicate hydrate) gels and C-A-S-H (calcium aluminosilicate hydrate) gels. In GPC systems using fly ash as the main binder, the ratio between N-A-S-H gels is higher whereas C-A-S-H gels become the predominant in systems made with GGBS or MK. These gels that form throughout the reaction give hardness to Hardened GPC, from which we obtain the structural strength [3].

The alkaline activators (mainly sodium hydroxide) are used to initiate the geopolymer reaction through molarity; the higher the molarity, the geopolymer reaction will initiate. The activating of the molarity both activates the geopolymer formation speed and the total amount of formed geopolymer. Alkaline to binder (A/B) ratio has a very large impact on workability and setting time together with strength development of GPC. Overall behavior of concrete is regarded as depending upon the way concrete is cured for the period.

Heat during curing thus increases the speed of polymerization and helps to produce initial strength development, more so in compositions containing fly ash components. Although strength development occurs more slowly in this method, ambient curing methods are practical for the construction process. For complete understanding of the implications of these essential factors on geopolymer concrete performance evaluation and mechanical optimization, this paper aims to explain both the fabrication and performance of these cement alternatives [4].

III. Mechanical Performance of Geopolymer Concrete

For good quality as an ordinary Portland cement (OPC) concrete replacement, GPC needs to have excellent mechanical performance. The twenty years of research that has already been conducted over the last twenty years prove that when GPC is properly designed and cured you get compression and tensile strength and flexural strength that match or outperform OPC standards. This section will examine analysis of compressive strength testing and tensile responses, and activator concentration, curing methods, and additive examinations on GPC mechanical attributes due to the effects of essential parameters.

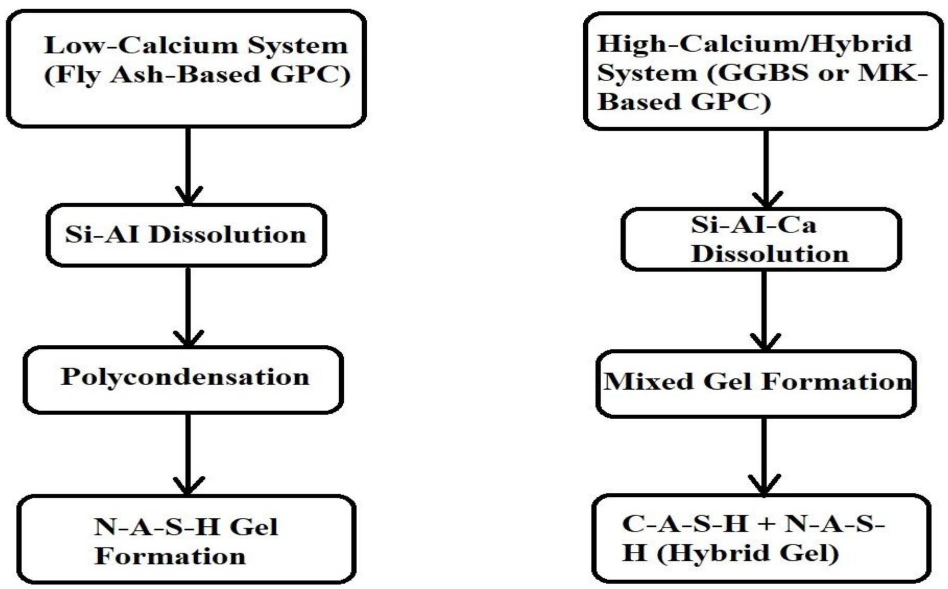

Fig.1. Schematic anof GPC Gel Phases [1] [3]

a. Compressive Strength across Different Binders and Activators:

The compressive strength properties are highly dependent of the material used for the precursor of GPC and using the proper activator chemicals. Fly ash GPC is NaOH and Na_2 SiO_3 activated and needs to be high temperature cured for its strength development to develop steadily during its polymerization. This is due to the rich calcium resources from GGBS used in GPC, which facilitate the developement of C-A-S-H gel and N-A-S-H and therefore aid the strengthening of the concrete structure.

Metakaolin (MK) is a highly pozzolanic substance that improves the strength properties of fly ash or slag mixtures. When fly ash is mixed with GGBS or MK, then they of course have reached a compressive strength higher than 70 MPa due to thermal accelerated curing [5]. Performance stability is sensitive to the presence of the inconsistent industrial waste in changing the materials sources.

b. Role of Molarity, A/B, and SS/SH Ratios:

The strength development of this system depends very much on the molarity of sodium hydroxide solution used. Rising the molarity leads to faster dissolution of aluminosilicate species that enhances both polymerization and strength outcomes up to its optimal range (10–16 M). Greater than the recommended concentrations of sodium hydroxide solution cause very rapid setting and substantially reduced workability with resultant reduction in total strength by rapidly setting highly concentrated alkali salts.

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One of the important parameters to be managed correctly is A/B ratio. The increase of the A/B ratios leads to intensification of activators concentration by strengthening but causing disadvantages in workability. The ideal ratio of 0.4 to 0.6 A/B ratios is achieved to guarantee some strength with the required level of workability.

Such SS/SH ratio has an influence on performance compared to sodium hydroxide and sodium silicate. The research has shown that the maximum compressive strength occurs with an SS/SH ratio of 2.0 to 2.5 because the quality of silica used for complete gel formation is maxed. The properties of this range can only be utilized thereby achieving the desired strength with good setting performance when the specifications of this range are maintained. If these variations are not within this range then the weakness will occur [6].

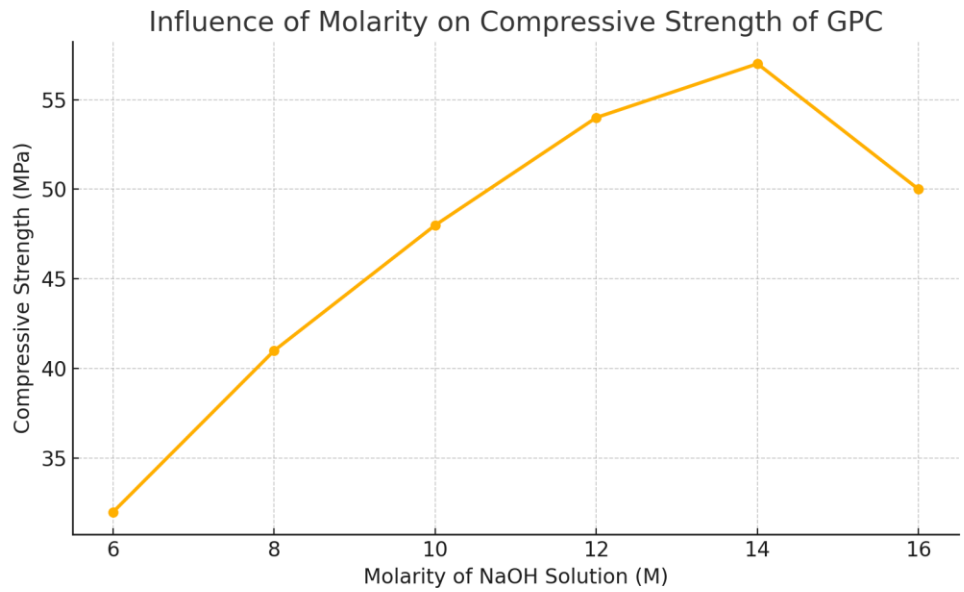

Fig.2. Influence of Molarity on Compressive Strength of GPC

c. Flexural and Tensile Performance:

Compressive strength is the main indicator of performance though flexural and tensile strength largely provides important properties required of structural members including beams, slabs and pavement layers. For GPC, flexural strength varies from 3 to 7 MPa whereas tensile strength from 2 to 5 MPa depending on the precursors mix used for making and the curing procedures after curing [7].

Tensile and flexural strengths are enhanced by the steel fibers' ability to arrest propagation of cracks and also by polypropylene and basalt fibers' ability to arrest cracks and to produce the behavior after cracks develop. The fact that FRGPC exhibits strengthened toughness features in addition to the ductility functions and resistance against thermal and impact damage makes it useful for demanding structural uses.

d. Effect of Temperature, Curing, and Additives:

Fly ash based systems are highly reactive to thermally controlled environments, and for this reason strength development depends on curing temperature. Accelerated geopolymerisation occurs when geopolymer is exposed to thermal temperatures ranging from 60–90°C for 24 h [3]. For practical applicability, the cure is preferred to take place in ambient curing. Under normal conditions, GGBS and GGBS-fly ash blended systems have excellent curing capacity and GPC projects can be made suitable for site installation.

Good packing densities and pozzolanic reactivity (in functions of compressive and flexural reactions) are obtained from the combination of nano silica and rice husk ash with the matrix. The fine inclusion of these particles into the matrix facilitates closing of the microvoids and hence enhances the mechanical strength as well as the durability performance.

e. Comparative Analysis with OPC Concrete:

The results of research indicate that GPC outperforms OPC concrete in compressive strength mining and chemical resistance properties. For OPC hydration is the basis of the strength development that, in contrast, is polymerization based in GPC which provides the flexibility for the optimization potential of material selection as well as curing conditions. The GPC material characteristics such as lower drying shrinkage and stronger performance to thermal and chemical attacks elevate durability in aggressive environment.

Despite this, GPC is not yet implemented in a systematic and satisfactory way for the purpose of obtaining uniform strength development among different raw materials and environmental conditions. One reason for the specific control over chemical activators required in GPC is that the hydration behaviour of OPC is understood.

Table 1: Mechanical Property Comparison – OPC vs GPC

Property	**OPC Concrete**	**GPC (Fly Ash + GGBS)**
Compressive Strength	40 MPa	50–65 MPa
Tensile Strength	3.5 MPa	4.5–6 MPa
Flexural Strength	4–5 MPa	5–7 MPa
Acid Resistance	Low	High
Chloride Permeability	High	Low

Sources: [2], [4], [5]

IV. Micro structural Behavior and Analysis:

The microstructure of geopolymer concrete influences very much its mechanical properties, durability and long term stability. Geopolymer Concrete (GPC) reverses the geological process in which sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H) gels are used to bind, as in ordinary Portland cement concrete (OPCC) where C-S-H gel binding is produced by calcium silicate hydration. The gel structure and morphology development are conditioned by selecting a precursor material and activator content in the cure conditions ranging from quality of cure as well those that may or may not contain calcium. This leads to study [2] of gel phase development and the resulting micro structural consequences to enhance GPC performance outcome.

a. Gel Phase Development: N-A-S-H, C-A-S-H, and Hybrid Systems:

When polymerization of alumina and silica is combined, the main binding phase of fly ash based GPC is N-A-S-H gel with low-calcium solutions. This gel gives density to both GPC and its enhanced durability, due to the cross-linked network of this gel. The early age strength behavior of gas based mixtures does not show calcium based strength characteristics.

The products of GGBS or MK precursors are C-A-S-H gels in which they structurally link to OPC C-S-H gels and aluminum and sodium are brought into the composition. These results in introduction of hybrid GPC structures that can make such analytical N-A-S-H materials and synthetic C-A-S-H gels combined to achieve excellent early age strength development with extended durability. In terms of concrete structures, the rounded and strengthened C-A-S-H and N-A-S-H gel systems link with reduced open spaces and benefit from reduced internal strains and brittleness leading to slower water absorption [5].

b. Techniques Used for Microstructural Characterization:

For proper understanding, microstructure of the GPC requires using different advanced testing methods.

- **Scanning Electron Microscopy (SEM):** SEM analysis was performed to observe surface level of the geopolymer matrix and reveals bond patterns as well as cracking patterns. SEM images of GGBS-based systems routinely show saturated matrices and meanwhile, those based on fly ash are usually porous after ambient curing [3].
- **Fourier Transform Infrared Spectroscopy (FTIR):** The development of N-A-S-H or C-A-S-H gels is verified using Fourth Transform Infrared Spectroscopy (FTIR) vibrating bands in Si–O–T (T = Si or Al). Peak position shifts display the polymerization level and the maturity level of gel formation.
- **Thermogravimetric Analysis (TGA):** That which traces weight loss events in gel dehydration and decomposition processes) is used to evaluate thermal stability of GPC. The weight loss of GPC during analysis is less than OPC; hence it gives the higher thermal resistance than OPC.

- **Mercury Intrusion Porosimetry (MIP):** It gives information regarding pore dimensions along with total porosity evaluation. Based on its mixture design and curing solutions, OPC has higher medium sized pore concentration between two and fifty nanometers and has less total pore volume than GPC [6].

c. Porosity and Micro cracks:

The functionality of porosity in concrete becomes very important to determine its durability as well as strength. GPC porosity is a function of the type of precursors, of the reactivity level of the precursors, of the concentration of activator and curing conditions. The capillary porosity reduction of heat curing is better than unregulated ambient curing due to resulting faster polymerisation to completion while unregulated ambient curing of GPC give unfused reaction end products, especially in fly ash based GPC.

Normally, making concrete stops making micro cracks when there is a problem the concrete was not cured properly, such as because there is an insufficient mixing process or due to stress of shrinkage. Micro cracking is formed to less extent in GPC due to its naturally low shrinkage and microstructure is very dense. Other benefits come from adding nano silica or fibers since they are beyond micro structural defects by filling anything but then building barriers from where there was a possible cracking route [7].

d. Influence of Microstructure on Durability and Strength:

The mechanical and durability of GPC are directly related to how it is structured at the micro level. Compressive strength and permeability, and resistance to sulfates, chlorides and acids, are better from a dense matrix plus well developed N-A-S-H or C-A-S-H gels [1]. Both the mechanisms of ion movement pathways and the freeze-thaw durability mechanisms depend on the precise arrangement of pores and on their connectivity levels.

A unique aluminosilicate network crosslinking gives [5] the N-A-S-H and C-A-S-H gel systems excellent performance because linked properties of strength enhancing properties, particularly rapid initial strength development and extension of gel stability, are provided through the combination of N-A-S-H and C-A-S-H gel systems. Proper optimization of microstructure is necessary for the development of durable high performance GPC.

Table 2: Durability Assessment of GPC in Aggressive Environments

Environment	Performance Metric	GPC Behavior
Sulfate Exposure	Expansion (%) after 120 days	Negligible (0–0.01%)
Acid Attack	Strength loss after 28 days	<10%
Chloride Penetration	RCPT Value (Coulombs)	800–1200
Freeze-Thaw Cycles	Mass loss (%)	<1%

Sources: [2], [4], [6]

e. Case Comparisons from Literature:

[2] Found in their research that UHPGPC with silica fume along with fine quartz powder implementation had the dense microstructure with decreased porosity and increased interconnecting bonds. It was also demonstrated that the binder material has a largely tightly packed structure, with very few particles left behind in the SEM results after reaction. Their research reported that when creating improved compressive strength and thermal stability materials, the N-A-S-H to C-A-S-H gel transition occurred at different levels of calcium as it increased.

According to the results of [1] slag based GPC shows that total porosity decreased while more mesopores were present as compared to OPC. The enhanced interfacial transition zones (ITZ) enhanced the elasticity modulus of the material as well as decreased the material permeability.

Table 3: Case Comparisons from Literature

Study	Binder System	Key Microstructural Observation	Strength Performance
[1] Influence of Microstructure of Geopolymer Concrete on Its Mechanical Properties—A Review	Slag-based GPC	More mesopores, lower porosity than OPC	Higher elasticity, good resistance
[2] A state-of-the-art review of the physical and durability characteristics and microstructure behavior of ultra-high-performance geopolymer concrete	UHPGPC with silica fume + quartz powder	Dense matrix, minimal unreacted particles	High early strength (70+ MPa)
[3] Molarity activity effect on mechanical and microstructure properties of geopolymer concrete: A review	Fly ash with increasing calcium content	Transition from N-A-S-H to C-A-S-H gels	Increased strength with calcium
[4] Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties	Fly ash and GGBS blended	Improved ITZ, reduced permeability	Enhanced mechanical and durability

V. Durability and Long-Term Properties:

In order to assess the suitability of geopolymer concrete (GPC) for structural applications, durability assessment of it is necessary, as it defines its long term lifetime potential. Geopolymer cement (GPC) also exhibits significantly increased resistance to the action of various chemical agents which is superior to that of ordinary Portland cement concrete (OPCC) and also has characteristics of reduced permeability. These characteristics suggest that GPC is a suitable material choice for the extreme conditions involved in coastal environments as well as wastewater structures and various industrial products [4].

a. Performance under Chloride, Sulfate, and Acid Attack:

GPC has better strength and durability than chloride or sulfate damage compared to what OPC is able to offer. GPC does not have the calcium hydroxide that is needed for sulfate ions to create expansive ettringite in OPC products so GPC is less sensitive to sulfate based damage. GPCs from fly ash and slag maintain well the resistance properties by resisting the surface deterioration and not experiencing loss of mass during these tests, when immersed in $MgSO_4$ and Na_2SO_4 solutions [5].

GPC is highly resistant to acids since its calcium material is minimum and it is dense granular in structure. Through the geopolymerization process, N-A-S-H, C-A-S-H gels form [4] a stable matrix structure that is least influence by aggressive ions. It appears that the strength properties of GPC are better and erosional damage is less in 5% sulfuric acid, as opposed to OPC concrete under similar exposure tests.

b. Shrinkage, Permeability, and Weather Resistance:

The most attractive feature of GPC [1] is the absence of the need to shrink when dried. Low drying shrinkage is mostly a result of low drying shrinkage of the curing, which leads to a dense matrix with low-water content, and with very few micro cracks. Effectively, thermally cured Hyperplastic GPC has much reduced permeability because its pore structures are more refined. Through restricting capabilities exhibited in the GPC by mercury intrusion porosimetry tests, resistance to freeze thaw damage and carbonation has been shown to improve.

It is known that GPC has good weather resistance during various temperature changes. When used with good curing practices using appropriate additives, GPC mechanical quality is still at present relatively unaffected by hot conditions and temperature fluctuations.

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c. Role of Fibers and Secondary Binders:

The combination of steel and polypropylene and basalt fibers with GPC leads to significant improvements in its lasting durability and resistance against cracks. Under stretching forces as well as ecological stress, fibers are micro crack bridges to impede crack expansion. The properties of these secondary binders to fill micro voids and to increase gel density were found to be effective in durability improvement [3].

e. Long-Term Field Applicability:

Available field data about performance durability requires additional accumulation while laboratory findings show promise. Initial analysis and an evaluation of bridge deck, marine structure, and precast elements with GPC show that it produces appropriate structural performance as well as durability over long periods of time that will ensure developers properly design and cure using appropriate method. More extensive studies will also help validate whether GPC works in actual building durations and provide critical directions to building codes.

VI. Conclusion:

Among those advanced solutions for sustainable construction, Geopolymer concrete (GPC) competes favorably to the conventional ordinary Portland cement concrete (OPCC). Although mechanical capabilities with compression and tensile strength, as well as flexural resistance, are demonstrated, the implementations differ dependent upon appropriate formation and curing. The proportions of A and B together with molarity, SS/SH ratios and A/B ratios and the choice of precursor and activator depend highly on the GPC of the resulting cured material under specific curing procedures. GPC mechanical values are improved by fibers and nano-materials both that enable it to fulfill requirements for structural applications with different specific requirements.

GPC is a dense matrix of N-A-S-H and C-A-S-H gels and which resists deterioration and heat features. SEM, FTIR and TGA and MIP analyses indicate that blended systems that contain slag but largely manifest refined pore microstructure and reduced porosity.

However, GPC is currently a poor engineering material because there are multiple barriers to expansive use of it. GPC acceptance is limited solely due to inconsistent raw material characteristics and nonstandard mix design protocol as well as a lack of short availability of actual performance data from actual applications. Further studies are needed to facilitate commercial exploitation of GPC by means of increased workability and improved quality consistency as well as specifications in support of current construction operations.

Future investigation in this field, however, will be required to develop standardized guidelines and increased durability testing under real world environments and optimal mix design development for ambient curing. There is a possibility of Globally Proactive Construction to transform the building sector through its affordable low carbon building material construction solution.

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