STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc/

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Issue 5, 2025
DOI (Journal): 10.37591/JoPC

Review JoPC

Effect of Heat Exposure on Structural Integrity of Geopolymer Concrete Composites

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Abstract

The research evaluates the thermal degradation effects of high temperatures on Geo Polymer Concrete Composite (GPCC) by examining alccofine concrete, concrete made with alccofine and porcelain waste aggregates. Knowing how GPCC behaves under high temperatures proves essential for protecting buildings during fires as well as industrial applications. Each mix design received composite concrete samples that underwent increased heating conditions from 100°C to 700°C at 200°C intervals. Post-heating, various parameters were analyzed, including weight loss, compressive strength reduction, and visual assessment of surface cracking and spalling. The results revealed distinct degradation patterns among the different concrete types. Nominal concrete exhibited significant strength loss and increased cracking at higher temperatures. GPCC demonstrated improved thermal stability compared to the nominal mix, showing less weight loss and strength reduction, likely due to the pozzolanic reaction of alccofine enhancing the microstructure. The combined addition of alccofine and porcelain waste aggregate GPCC further enhanced the thermal performance, exhibiting the least degradation among the three mixes. This suggests that the combined effect of alccofine and porcelain composite creates a denser and more durable microstructure, leading to better resistance against thermal damage. The study highlights the beneficial role of alccofine and the synergistic effect of alccofine and porcelain in improving the high-temperature performance of concrete, along with the promising thermal resistance exhibited by Geo Polymer Concrete Composite (GPCC), providing valuable insights for designing more fire-resistant composite concrete structures.

Keywords: Alccofine (AL), Compressive strength, elevated temperature, porcelain waste aggregate (PWA), geo polymer concrete composites (GPCC)

INTRODUCTION

Concrete stands as an essential building material which people have recognized because of its exceptional strength along with its long-lasting properties. For concrete structures to remain safe throughout their lifespan, builders must follow all accredited fire safety guidelines in building standards. Fire poses significant threat to structures, as one of the most hazardous environmental conditions they can encounter. Consequently, implementing effective fire protection measures for structural elements has become a critical aspect of building design. There are rich sources to develop the geo-polymer concrete of the sources on alumino-silicates and the alkaline activators for the process of polymerization. [1, 2]. Exposing geo-polymer composites to temperatures that go over 600 °C leads to a big drop in both their compressive strength and modulus of elasticity. When temperatures became greater than 800 °C, the strength of geo-polymer concrete decreased a lot because of micro-cracks and damage [3]. The

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Received Date: June 20, 2025
Accepted Date: August 01, 2025
Published Date: September 04, 2025

Citation: Vikas, B.S Walia, Isha. Effect of Heat Exposure on Structural Integrity of Geopolymer Concrete Composites. Journal of Polymer & Composites. 2025; 13(5): 318–328p.

amount of Al_2O_3 in geo-polymer mortars affects how they behave and are structured when exposed to high temperatures. Al_2O_3 was included in the study and the results suggest that it helps geo-polymer composites last longer against heat and stay strong even up to 1000 °C. [4]. The number of the geo-polymer concrete has a great influence on its performance of such variables as concentration of sodium hydroxide, Al/bi ratio, workability, setting time and the amount of sources of binder alumino-silicats. [5]. High temperatures impose crucial modifications to both physical characteristics and mechanical strength of concrete materials. The concrete properties transform based on factors such as its material density and porosity together with initial strength characteristics as well as moisture percentage [6]. The various temperatures that occur in building fires directly impact the severity of damage which concrete buildings experience. Its response to elevated temperatures is more complex. When subjected to heat, concrete experiences a series of chemical and physical transformations that affect its structural integrity [6, 7]. As the temperature rises, the constituent materials of concrete expand at different rates, leading to internal stresses. These stresses can result in micro-cracking, which compromises the material's overall strength and durability. The extent of cracking depends on the rate of heating and type of aggregates used in concrete mix [8]. The Taguchi method allows fly ash-based geo-polymer concrete to maximize its strength and other mechanical properties. How well and how long geo-polymer concrete lasts is affected by the alkaline concentration, the ratio of liquid to fly ash and the way it is cured [9]. Calcium hydroxide, a primary hydration product, dissociates into calcium oxide and water at temperatures above 450°C. The deterioration process weakens cement-based material structures because it harms their binding properties and cement matrix strength [11]. Manufacturing healthy, sustainable, green concrete that does not require use of Ordinary Portland Cement (OPC). Geo-polymer composite concrete as construction material was invented a few years ago by Prof. Davidovits (1978) popularized with its uniqueness and method of making the concrete [10]. Using metakaolin and fly ash in geo-polymer composite concrete has made it capable of standing up to severe heat of around 900°C. It has been shown through studies that they suffer less cracking and raveling than OPC concrete after being exposed to elevated temperatures. The strong resistance to thermal decay by geo-polymer concrete is thanks to its ceramic-type structure. It was found that after being heated to 800°C, geo-polymer samples still retained over 40% of their compressive strength which is very important for fire resistance in structures [12]. Initial strength of concrete influences its ability to withstand high temperatures. High-strength concrete, while robust under normal conditions, may be more prone to spalling due to its dense microstructure, which restricts moisture migration. Conversely, normal-strength concrete, with its relatively porous structure, allows for better moisture release, reducing the risk of spalling [11]. Rapid heating causes a steep temperature gradient within the material, leading to higher internal stresses and increased risk of spalling. While slower heating rates allow for a more uniform temperature distribution, reducing the likelihood of explosive failure [12]. At temperatures below 300°C, the material generally retains most of its strength. However, as the temperature rises beyond this threshold, degradation of hydration products and thermal stresses become more pronounced. At temperatures exceeding 600°C, concrete experiences severe strength loss and may fail structurally [13]. Adding fly ash and slag to geo-polymer composite concrete increases both flexural strength and the elastic modulus while the material is cured naturally. Evidence has shown that using 50% fly ash and 50% ground granulated blast furnace slag (GGBFS) gives the concrete better early strength so no heat curing is required [14]. GPC composite, which is intrinsically less vulnerable to high temperatures because of its ceramic-like matrix content and low level of calcium materials, fire protection is improved further through the use of fibers. In the case of the GPC, where the polypropylene fibers are used, they play the same role of providing micro-channels for vapor expulsion that enhances the thermal stability. However, steel fibers are used to increase the post-cracking strength as well as to maintain the integrity of the structure when the temperatures are high [15]. Fire protection coatings of in-tumescent paints and insulating barriers, can be applied to concrete surfaces to shield them from direct exposure to heat. These coatings act as a thermal barrier, delaying the temperature rise within the concrete and providing additional time for evacuation and fire suppression efforts [13]. Slag mortars and composite concrete materials kept their structure intact after going through temperatures as high as

1000 °C. With increasing temperature, the strength of alkali-activated slag mortars slowly went down but was still better than that of ordinary Portland cement mortars and some conventional composite concretes under comparable conditions. It was found by microstructural examination that the alkali-activated matrix in the mortar and the stronger joints between binder and aggregate improved the ability of composite concrete to resist fire. Alkali-activated mortars are said to resist high temperatures well, since no micro-cracking was detected in their study below 800 °C [16].

MATERIALS BEHAVIOR OF HIGH TEMPERATURE CONCRETE

The analysis of supplementary cementitious materials, fibers and aggregates in GPCC, when exposed to high temperatures occurs during this chapter. Concrete's heterogeneous nature, resulting from the combination of cement gel, aggregate, and fibers, makes it challenging to predict its behavior at various high temperatures, as each component reacts independently to thermal conditions [17, 18]. Heating composite concrete triggers several physicochemical changes that alter its thermo-mechanical properties [19].

Table 1 demonstrates elevated temperature effects on concrete at different stages. During the temperature range of 20 to 80 °C concrete loses capillary water because of water expansion processes. At temperatures between 80 to 100 °C, ettringite decomposes, the cement matrix and aggregate lose their physically bound water so micro-cracking occurs because of capillary porosity. Concrete dehydration together with gel decomposition takes place between 100 °C and 200 °C while losing both water and C–H–S gel [20, 21]. Concrete strength reaches stability and sometimes even improves at 300 °C because of the densification process affecting the cement gel layers. Stiffness and strength values in concrete decrease beyond 300 °C according to findings from [22, 23]. Micro-cracking in the cement paste from CH decomposition takes place within the temperature range of 400 to 600 °C. During the second stage of C–H–S breakdown from 600 to 800 °C compressive strength experiences a significant reduction. The temperature interval of 800 to 1200 °C leads to vast micro-cracking phenomena because of dehydration processes [24, 25].

Supplementary Cementitious Material

Alccofine 1203 (AF) is a microfine product of low calcium silicate slag basis. Alccofine regulates high reactivity due to controlled granulation as well as it enhances workability at a reduced demand for water. Because of its ultrafine particle size, concrete strength increased [18]. The use of SCM such as alccofine, natural pozzolans and industrial by-products as portland cement substitutes helps to decrease emissions during cement production. This also helps lower costs and reduce industrial waste. To mitigate costs, cement consumption, industrial waste, and significant CO_2 emissions [19]. Table 2 presents examples of SCMs used as partial cement replacements in concrete subjected to the high temperatures.

Table 1. Elevated temperature effects on concrete at different stages.

Temperature	Effect	Remarks
27°C - 100°C	Hydrothermal reactions occur, leading to loss of physically bound water within the concrete.	No Structurally Change
200°C	Water within the concrete begins to convert to vapor.	Explosive Spalling
300°C	Siliceous concrete begins to experience a loss of strength.	
400°C	Dissociation of calcium hydroxide takes place, potentially leading to explosive spalling (where surface layers of the concrete break off).	
500°C - 800°C	◆ Expansive quartz conversion (α to β quartz) ◆ A marked increase in basic creep (deformation under sustained load) ◆ Dissociation of calcium carbonate (calcination) ◆ Total loss of the water of hydration (chemically bound water)	Concrete Structurally not Useful
1000°C - 1200°C	Concrete is no longer structurally useful.	
1200°C	The melting of concrete begins.	
1400°C	Concrete completely melts down.	

Table 2. SCM partially replaced with cement exposed to high temperatures.

SCM	W/C ratio	Temperature exposed	Replacement levels
Alccofine	0.41	100 °C, 300 °C,500 °C,700 °C	14%
Alccofine	0.41	100 °C, 300 °C,500 °C,700 °C	16%
Alccofine	0.41	100 °C, 300 °C,500 °C,700 °C	18%

Table 3. The stone aggregates were partially replaced with porcelain waste aggregates exposed to the high temperatures.

Aggregate	W/C ratio	Temperatures exposed	Replacement levels
Porcelain Waste	0.41	100 °C, 300 °C,500 °C,700 °C	1%
Porcelain Waste	0.41	100 °C, 300 °C,500 °C,700 °C	2%
Porcelain Waste	0.41	100 °C, 300 °C,500 °C,700 °C	3%

Composite concrete performance improves significantly when these SCMs (fly ash (FA), ground granulated blast-furnace slag (S), metakaolin (K), and silica fume (SF)) are added to concrete mixes according to research [20]. Table 3 presents examples of the stone aggregates were partially replaced with porcelain waste aggregates concrete subjected to high temperatures.

Behavior of Aggregates at Elevated Temperature

The artificial construction material of composite concrete stands as a fundamental industry component which generates significant environmental influence. Thermal differentiation occurs at high temperature levels because aggregates expand and cement paste contracts which create micro-cracks in the interfacial transition zone (ITZ) and cement paste that degrades mechanical performance [26]. The thermal characteristics of aggregates react to their chemical mixture as well as their mineral composition and the details of rock structure. Heating produces physical alterations and chemical transformations in minerals which lead to expansion changes across concrete materials. Limestone together with dolomite show stability levels until 600°C before decomposing into CaO and CO_2 at 700°C. The melting points of different aggregates vary, igneous rock withstands temperatures higher than 1000°C but granite requires heat between 1200 and 1250°C for melting and basalt’s melting point exceeds 1050°C due to their mineral composition [27]. Figure 1 shows the differential thermal analysis (DTA) of aggregates at a heating rate of 10°C per minute. All key properties of CM composite concrete improved when changing the morphology of the binders. Enhancing the temperature and amount of time allowed for curing made the geo-polymer composite concrete stronger [28].

MECHANICAL CHARACTERISTICS OF CONCRETE AT ELEVATED TEMPERATURE

The Geo-polymer concrete composite fire resistance depends on materials' high-temperature resistance properties including compression force, flexure strength and tension strength as well as elastic modulus, stress-strain interaction graphs and P-M curves. [25]. Mechanical tests on geo-polymer concrete composite (GPCC) at elevated temperatures are typically conducted on cubical or cylindrical samples of various sizes, differing from room-temperature specimen measurements. Due to the lack of standardized test methods for high-temperature mechanical characterization, range of specimen sizes is used in these tests [26].

Mix Design

The concrete mix design was carried out in accordance with the provisions of IS 10262:2019. Mix IDs M1, M2, and M3 were formulated by replacing Ordinary Portland Cement with alccofine 1203 at 14%, 16%, and 18%, respectively, by weight of cement. For Mix IDs M4, M5, and M6, a fixed 16% alccofine replacement was used, while porcelain waste aggregate (PWA) was introduced as a partial replacement for coarse aggregate at 1%, 2%, and 3% by weight, respectively. The coarse aggregate used in the mixes was tested for grading and crushing value as per IS 383:2016. A constant water cementitious ratio (w/cm) was maintained across all mix designs to ensure uniformity. Table 4 presents the detailed mix proportions for both alccofine concrete and GPCC mixes.

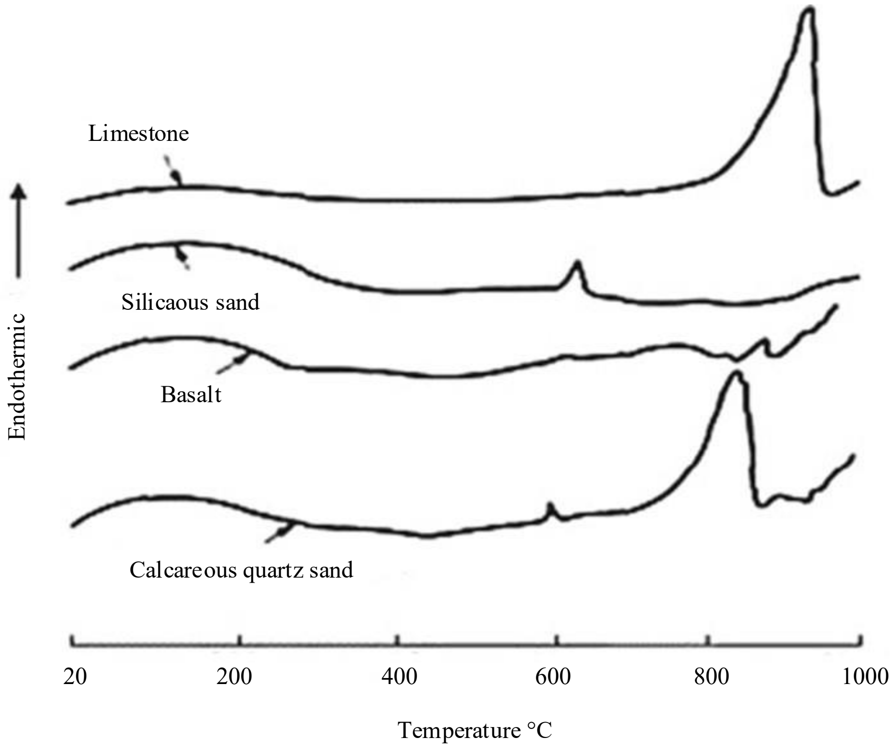

Figure 1. Differential thermal analysis of aggregates at heating rate of 10°C/min.

Table 4. Represents the mix design of alccofine concrete (M1 to M3) and GPCC (M4 to M6).

Mix ID	Cement	Alccofine	Fine aggregate	Coarse aggregate	PWA	Water
M1	361.20	58.80	1062.50	767.13	0	163.80
M2	352.80	67.20	1062.50	763.97	0	163.80
M3	344.40	75.60	1062.50	760.82	0	163.80
M4	352.80	67.20	1057.93	741.14	18.28	163.80
M5	352.80	67.20	1053.36	717.26	36.55	163.80
M6	352.80	67.20	1048.79	693.36	54.83	163.80

Compressive Strength

Fire-resistant composite concrete is designed to remain strong under high temperatures. In regular concrete, fire performance depends on water-cement ratio, curing, aggregates, and additives. Geo-polymer concrete composites (GPCC), with low calcium and a stable matrix, offer better fire resistance, though strength varies with materials, activators, and curing methods [28]. Composite concrete loses significant compressive strength at high temperatures. Factors like mix design, testing method, specimen size, and applied stress influence its mechanical behavior. In stress-free conditions, residual strength of cube specimens decreases steadily as temperature rises [27]. At temperatures rising from ambient to 300 °C the initial compressive strength decreases by 20% of its original measurement. The material strength decreases at an accelerated rate from 300 °C to 800 °C [29]. Table 5 represents the compressive strength of alccofine concrete and GPCC.

The residual compressive strength of Alccofine concrete (M2) at 100°C, 300°C, 500°C, and 700°C remains higher compared to conventional concrete (M1) and another modified mix (M3), indicating better thermal resistance. However, the geopolymer concrete composite (M6) outperforms all mixes across all temperature ranges, demonstrating superior thermal stability and mechanical retention under elevated temperature exposure. Figure 2 presents a comparison of the residual compressive strength of Mixes M1 to M6 at elevated temperatures of 100°C, 300°C, 500°C, and 700°C.

Table 5. Represents the compressive strength (N/mm^2) of alccofine concrete and GPCC at various temperature.

Mix ID	Compressive strength at 100 °C	Compressive strength at 300 °C	Compressive strength at 500 °C	Compressive strength at 700 °C
M1	41.10	37.46	26.95	13.75
M2	41.97	38.02	27.57	14.88
M3	41.33	37.80	27.16	14.21
M4	42.15	39.00	28.35	15.47
M5	42.42	39.63	28.74	15.83
M6	43.00	39.90	29.07	16.23

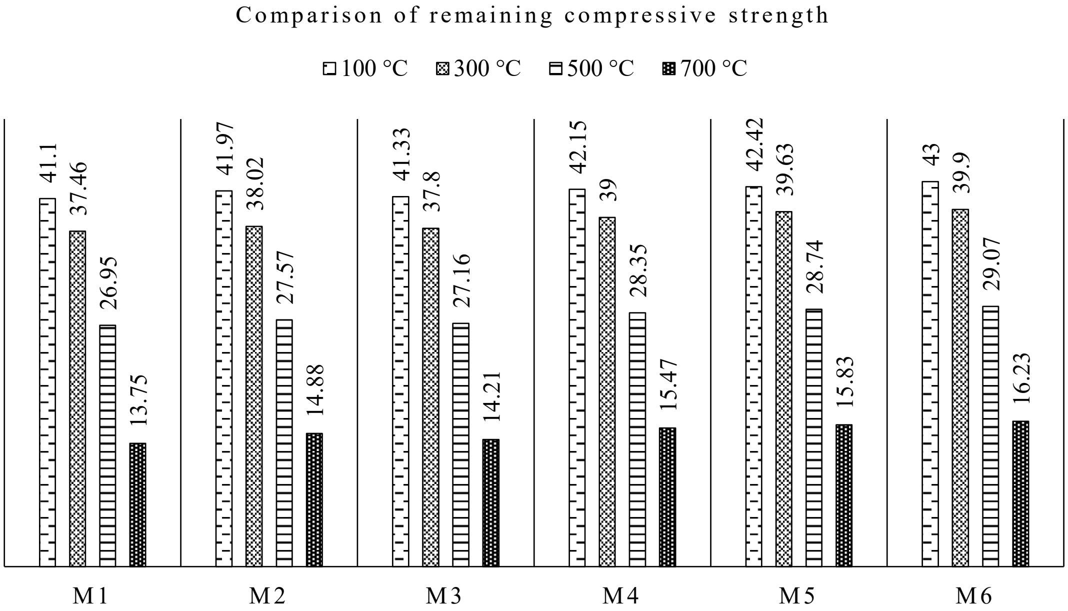

Figure 2. Shows the comparison of remaining compressive strength of mix M1 to M6 at temperature 100°C, 300°C, 500°C & 700°C.

THERMAL PROPERTIES OF CONCRETE AT ELEVATED TEMPERATURE

The outcome of composite concrete materials exposed to high temperatures depends greatly on their thermal characteristics consisting of thermal conductivity alongside specific thermal diffusivity and heat along with spalling and mass loss. A material demonstrates its heat conducting capability through its thermal conductivity property [30]. The transfer of heat through materials takes place under two basic forms namely steady-state and transient heat conditions. The heat flow remains unchanged from one-time interval to another when the system exists in steady-state conditions. The heat flow under transient conditions shows a dependency on time since temperatures fluctuate during this period. Transient methods have higher preference than steady-state methods when measuring the thermal conductivity of composite concrete. Conventional concrete demonstrates an ambient temperature thermal conductivity between 1.4 W/m°C and 3.6 W/m°C. The high specific heat capability of concrete helps maintains structural temperature stability because it requires larger amounts of heat to rise in temperature per unit mass [31]. Fig. 3 demonstrated that thermal conductivity of normal weight concrete at varying temperatures: Insights from ASTM STP 882. Specific heat levels of concrete are strongly impacted by its density and aggregate composition and moisture levels. High-temperature measurements of specific heat require differential thermal analysis through DTA equipment which functions effectively beyond 600°C. Research demonstrates that polypropylene fiber augmentation in ultra-high-performance concrete minimizes spalling severity within 20 to 750°C but it does not result in substantial modifications to material properties.

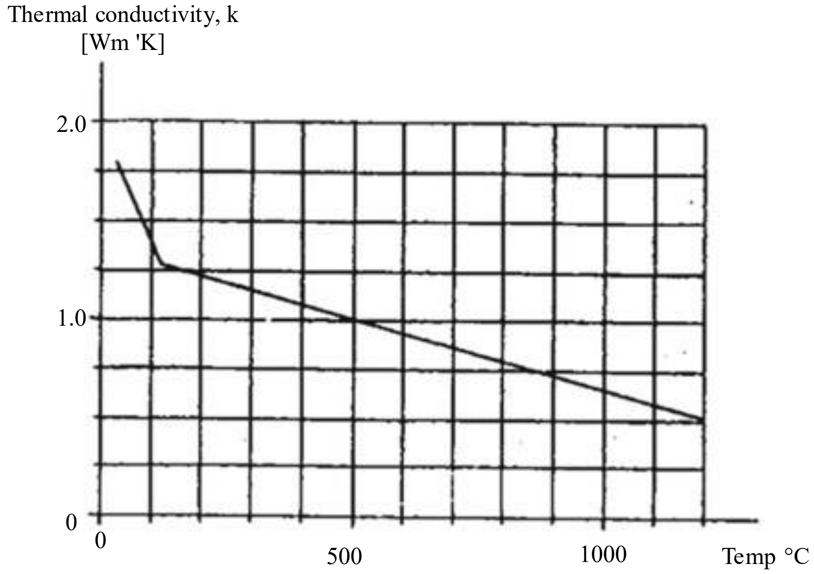

Figure 3. Thermal Conductivity of normal weight concrete at varying temperatures: insights from ASTM STP 882.

Mass Loss

Heat exposure causes composite concrete to evaporate moisture which reduces its density level. Natural concrete density forms the basis for determining between normal and lightweight among concrete materials. The aggregate type influences strongly how much concrete weighs when exposed to increased temperature conditions [31]. The mass difference between concrete mixed with siliceous or carbonate aggregates extends from room temperature up to 1000 °C. The mass of geo-polymer composite concrete made with siliceous and carbonate aggregates remains stable below 600 °C according to existing research [32].

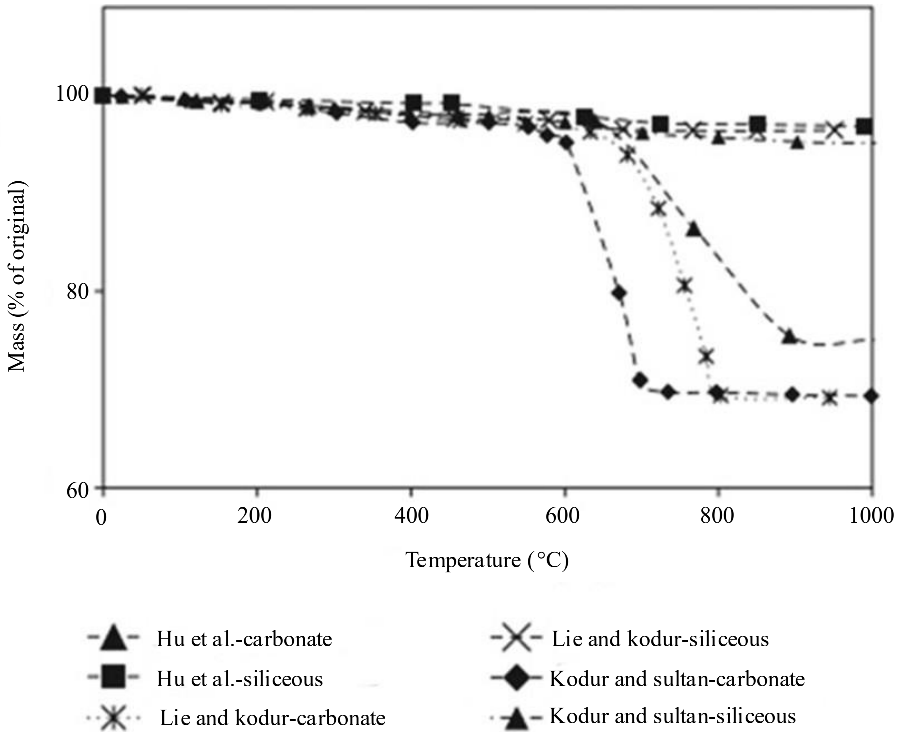

Figure 4. Effects of aggregate types on concrete mass variations at elevated temperatures.

Spalling of Concrete

High pore pressure in combination with thermal stresses together with their interaction serve as main triggers of explosive spalling in concrete exposed to high temperatures. Heating transforms water in cement paste and pores into vapor, creating a temperature gradient that drives moisture movement [33]. Fig. 4 shows effects of aggregate types on concrete mass variations at elevated temperatures. This increases pore pressure, especially away from the surface, depending on concrete permeability, leading to spalling. Simultaneously, temperature differences between the surface and core generate thermal strains, causing tensile and compressive stresses. Together, these factors result in explosive spalling.

MICROSTRUCTURAL PROPERTIES

Porosity Analysis of Concrete

The evaluation of geo-polymer composite concrete porosity coupled with pore network analysis at high temperature uses HRCT with micro tomography as reliable investigation tools at meso- and micro-scale levels. The figure displays micro tomography scans of concrete samples that underwent heating treatments at five temperature levels from 27°C up to 800°C. The micro tomography images in Fig. 5 represent concrete specimens at five different elevated temperature levels starting from 27 to 100, 400, 500 and 700 °C. The porosity values measured at the meso-scale rise up to 800°C and the micro-scale shows growth until 1400°C. The substantial rise in porosity results in developing a pore network that degrades the concrete specimen progressively [34, 35].

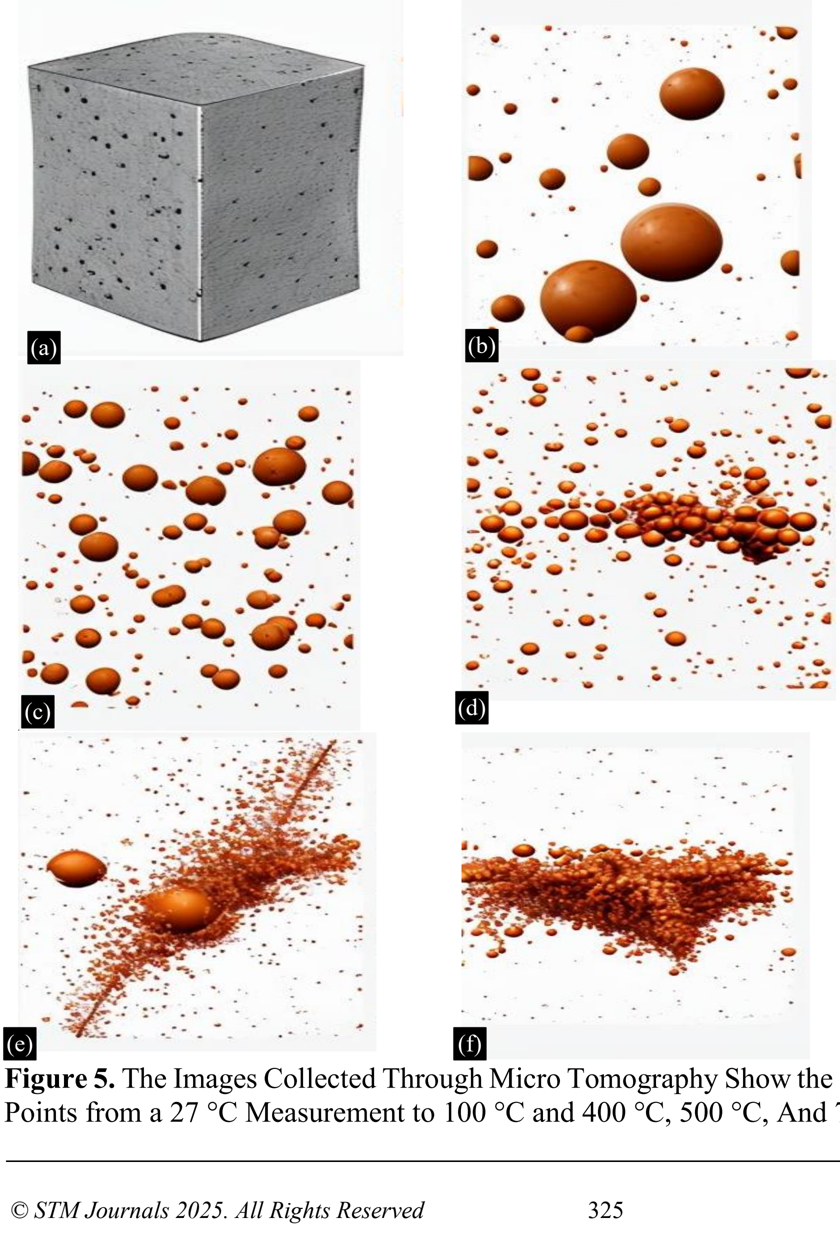

Figure 5. The Images Collected Through Micro Tomography Show the Sample at Various Temperature Points from a 27 °C Measurement to 100 °C and 400 °C, 500 °C, And 700 °C.

CONCLUSION/SUMMARY

1. Alccofine concrete (M1 & M3) showed significant strength loss, surface cracking, and spalling at elevated temperatures, highlighting its vulnerability to thermal damage.
2. Alccofine concrete (M2) demonstrated enhanced thermal stability, with reduced weight loss and compressive strength degradation, attributed to the pozzolanic reaction improving the microstructure.
3. The Geo-Polymer Composite Concrete (M6) of alccofine 16% and porcelain waste aggregates 3% yielded the best thermal performance, exhibiting minimal degradation and superior resistance to high-temperature.
4. The study underscores the potential of alccofine and porcelain as supplementary materials for designing GPCC with enhanced thermal stability, contributing to safer and more durable structures in fire-prone or high-temperature environments.
5. GPCC's (M4 to M6) mechanical properties, such as compressive strength decline with rising temperatures, with significant strength loss beyond 400°C but performed better than alccofine concrete (M1 to M3).
6. The thermal conductivity of materials depends on mix proportions, aggregate type and moisture content, permeability and density but specific heat is mainly affected by moisture content.
7. Concrete loses mass due to moisture loss, with significant density reduction occurring above 600°C.

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