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**High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse
Aggregate as Partial Replacement**

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A Thesis in Structural Engineering

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Feb, 2025

Addis Ababa

**A Thesis Submitted in Partial Fulfillment of The Requirements for The Degree of Master
of Science in Structural Engineering.**

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UNDERTAKING STATEMENT

I, **Sarem Jezbu**, hereby declare that this thesis titled “**High-Temperature performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement**” is the result of my original research work and has been carried out under the guidance of **Dr. Esayas G.Youhannes**. I affirm that this work has not been submitted, either in whole or in part, for any other degree or diploma at this or any other university or institution.

To the best of my knowledge, all sources, references, and contributions used in this thesis have been duly acknowledged. Any material or content that is not my own has been appropriately cited and credited. I take full responsibility for the authenticity and accuracy of the information presented in this thesis.

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ABSTRACT

The increasing demand for sustainable construction materials, along with the growing need for improved fire resistance in structural elements, has accelerated research into alternative aggregate sources for concrete production. In this context, this study investigates the high-temperature performance of concrete in which waste ceramic coarse aggregate, sourced primarily from discarded tiles and sanitary ware, is used as a partial replacement for natural coarse aggregates. The core aim is to address two pressing challenges in modern construction: enhancing concrete's resistance to elevated temperatures and promoting the sustainable use of construction and industrial waste.

A series of concrete mixtures incorporating waste ceramic aggregate at replacement levels of 10%, 20%, 30%, 40%, and 50% by volume were prepared and subjected to both ambient conditions and elevated temperatures up to 600°C. After heating, specimens were cooled either gradually in a furnace or by immersion in a limited volume of water to simulate post-fire scenarios. Comprehensive tests were carried out to assess residual compressive strength, mass loss, and workability. The results demonstrated that concrete with 40% ceramic aggregate achieved the best overall performance, retaining more than 70% of its original compressive strength after thermal exposure. Water-quenched specimens consistently outperformed those cooled in the furnace due to shorter exposure to damaging high temperatures and the moderated thermal shock effects provided by steam and rising water temperatures.

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The superior performance of ceramic-modified concrete is attributed to several synergistic factors. The angular and irregular shapes of the ceramic particles contribute to improve internal packing, which reduces porosity and enhances strength. Moreover, the pozzolanic reactivity of ceramic materials due to their silica and alumina content supports secondary hydration reactions, thereby enhancing matrix cohesion and long-term durability. A stronger interfacial transition zone (ITZ) is formed, further improving the mechanical integrity of the concrete. Additionally, ceramic aggregates exhibit low thermal conductivity and high heat resistance, properties that significantly enhance the thermal stability of concrete under high-temperature exposure. Workability is also improved due to the smooth surface texture and lower water absorption rate of the ceramic aggregates, simplifying the mixing and placing process.

In Ethiopia, where construction activity is rapidly expanding and ceramic waste is increasingly abundant but underutilized, the application of ceramic aggregates offers a dual advantage: reducing environmental waste while supporting infrastructure development. The findings of this study suggest that up to 40% replacement of natural coarse aggregate with waste ceramic aggregate provides an optimal balance between mechanical strength, thermal resistance, and sustainability. This position's ceramic-modified concrete as a viable solution for fire-resistant construction in hot or fire-prone environments.

In conclusion, this research demonstrates that waste ceramic materials can be effectively repurposed into durable and thermally resilient concrete, offering an eco-friendly and cost-effective alternative to conventional aggregates. The use of waste ceramic in concrete not only enhances mechanical and thermal properties but also aligns with circular economy principles by minimizing industrial waste and promoting resource efficiency. These findings contribute

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meaningful insights into sustainable construction practices, particularly in regions where exposure to high temperatures is expected, and encourage the development of policies and recycling infrastructure to support broader implementation.

Keywords: concrete; waste ceramic; workability; compressive strength; durable; Pozzolanic activity; Fire-resistant concrete; Interfacial transition zone (ITZ); high temperature; circular economy.

ACKNOWLEDGMENT

First and foremost, I want to sincerely thank **Allah (SWT)**, the Most Merciful and the most beneficent, for giving me the courage, endurance, and direction I needed to finish this thesis. This accomplishment would not have been achieved without His incalculable blessings and steadfast support.

My supervisor, **Dr. Esayas G. Youhannes**, has provided me with tremendous advice, support, and knowledge over my research journey, for which I am incredibly grateful. His commitment and helpful criticism have been essential in forming this work.

I would also like to acknowledge the support of **College of Technology and Built Environment construction materials testing laboratory, Lideta Manufacturing College and Addis Ababa Institution of Technology** for providing me with the resources and opportunities necessary to conduct this research. My sincere thanks go to my colleagues, peers, and friends for their encouragement and meaningful discussions, which have greatly enriched my academic experience.

Lastly, I extend my heartfelt appreciation to my family, especially my parents, for their endless love, prayers, and sacrifices. Their unwavering support has been my greatest source of motivation.

May Allah (SWT) reward everyone who has supported me in this journey and accept this effort as a humble contribution to knowledge.

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1. INTRODUCTION

Concrete is one of the most widely used materials in the construction industry due to its ease of fabrication, robustness, and adaptability. High temperatures are among the most significant environmental factors that can greatly affect the performance of concrete. Numerous research papers have examined how concrete deteriorates under high temperatures, raising concerns about the material's loss of strength, durability, and integrity. This phenomenon is quite significant, particularly in areas with frequent extreme temperatures or in applications where fire resistance is crucial. Research into enhancing concrete's performance under these conditions has been prompted by the growing need for more durable and environmentally friendly building materials as a result of urbanization and industrialization.

During their operation, infrastructure such as residential complexes, industrial buildings, and nuclear power stations is susceptible to fire damage. The mechanical, thermal, and physical properties of concrete structural members are all affected by exposure to high temperatures. High temperatures cause severe deterioration due to the nanoscale collapse of cement gel structure. When exposed to high temperatures on a micro-scale, the cement mix dehydrates, porosity increases, pore pressure varies, and the moisture content in the concrete changes. Loss of strength, reduced durability, structural cracking, increased drying shrinkage, changes in aggregate color, thermal expansion, cracking, creep, and spalling are all signs of inadequate pore pressure at the macro level. The mechanical properties of concrete influence its loss of strength and deterioration, while its thermal characteristics, which are temperature-dependent, control how much heat is transferred through the material.

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The use of waste materials as partial substitutes for traditional materials in concrete manufacturing has also evolved in the building sector in recent years. This change aids in creating sustainable building methods while addressing the growing waste disposal problem. Waste ceramics, a result of discarded ceramic products like tiles, sanitary ware, and pottery, is one such material that has garnered attention. It has been demonstrated that waste ceramics, when finely ground, possess certain advantageous properties that could improve the mechanical and durability characteristics of concrete. However, its behavior in concrete subjected to high temperatures has not been fully studied and remains a crucial aspect of future research.

By investigating how concrete performs at high temperatures when coarse particles are partially substituted with waste ceramic coarse aggregate, this study aims to fill this gap. The goal is to ascertain how waste ceramic affects concrete's mechanical and thermal characteristics, with an emphasis on its behavior at high temperatures. The results of this study may have significant ramifications for creating more environmentally friendly and fire-resistant concrete mixes, which would enhance the durability and safety of concrete structures subjected to extreme environments.

1.1 Background

At temperatures exceeding 300°C, factors such as the porosity of the mix and the materials used for binding and aggregates in concrete determine its ability to endure heat effectively. High temperatures lead to chemical changes in concrete that ultimately weaken its integrity. Concrete is commonly affected by heat through issues like cracking, spalling, increased porosity, reduced strength, and loss of mass as the hydrated cement paste loses water content.

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Concrete's thermal behavior is greatly influenced by the type of aggregate that is utilized. Conventional coarse aggregates, such as crushed stone or gravel, usually undergo thermal expansion, which can cause internal strains and cracking when temperatures are high. On the other hand, when used as a partial replacement, waste materials such as ceramic aggregates may offer specific benefits. Concrete's thermal stability under fire or heat stress conditions may be improved with ceramics, which are known for their relatively low thermal expansion and high-temperature resistance.

Although research on waste ceramics in concrete is still in its infancy, initial findings indicate that adding waste ceramics to concrete may improve its mechanical properties, including workability, compressive strength, and shrinkage control. However, comprehensive studies on the behavior of waste ceramics, particularly at high temperatures, are lacking. There is a strong case for further research into this knowledge gap, especially as the building sector increasingly moves toward sustainable options.

1.2 Statement of the problem

Concrete, a widely used construction material, is highly regarded for its durability, versatility, and ease of production. Nevertheless, one of its most significant weaknesses is its vulnerability to degradation at high temperatures. Exposure to high temperatures, for example, due to fires and extreme weather, can result in the loss of durability, strength, and integrity in concrete structures. Concrete's thermal behavior is influenced by the behavior of its constituent materials, such as the types of coarse aggregates used. Traditional aggregates, for instance, gravels and stones, expand when subjected to high temperatures, producing internal stresses, spalling, and cracks in concrete structures. This issue becomes particularly critical in high-

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temperature and high-fire susceptibility structures, such as residential buildings, factories, and buildings with a heightened level of fire resistance.

Recent construction activity has transitioned toward becoming cleaner and greener, with growing momentum for utilizing waste materials as partial substitutes for conventional aggregates in concrete. One such material that has gained prominence is waste ceramic, a by-product of discarded ceramic materials, including sanitary ware, tiles, and pottery. Waste ceramic aggregates, when reduced to a fine state, possess beneficial properties such as low thermal expansion and high durability, which can potentially enhance concrete performance, especially in high-temperature conditions. However, despite numerous studies discussing the mechanical and durability behaviors of concrete with waste ceramic aggregates, little research has focused on their behavior under high-temperature conditions.

The lack of such information presents a challenge in determining whether high-temperature resistivity and integrity can be improved in concrete with the incorporation of waste ceramic aggregates and their durability at these temperatures. In the absence of a critical analysis of waste ceramic aggregates' behavior with concrete under thermal stress, it is difficult to confidently assert whether this resource can serve as a valuable tool in producing heat-resistant concrete mixtures for high-temperature applications. Therefore, a critical analysis of concrete performance at high temperatures when a portion of coarse aggregates is replaced with waste ceramic, its suitability for high-temperature use, and its viability as a sustainable construction material is in demand.

The objective of this work is to fill this gap by studying the effects of replacing a portion of coarse aggregates with waste ceramic on concrete's thermal, mechanical, and durability performance at high temperatures. Such an impact will contribute to the development of a

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durable concrete mixture that is not only environmentally friendly but also resistant to high temperatures, subsequently enhancing the durability and safety of concrete structures under high-temperature conditions.

1.3 Research objective

1.3.1 General objective:

The general objective is to investigate high-temperature performance of concrete with a portion of conventional coarse aggregates replaced with waste ceramic, with a view to investigating thermal and mechanical performance of such concrete.

1.3.2 Specific objectives:

1. To compare the high-temperature performance and room-temperature mechanical strength of concrete containing waste ceramic aggregates (at 10%, 20%, 30%, 40%, and 50% replacement levels) with conventional concrete.
2. To evaluate the effect of replacing a portion of coarse aggregates with waste ceramic in concrete's compressive strength at high temperature.
3. To assess the effectiveness of waste ceramic replacement (10%, 20%, 30%, 40% and 50%) in concrete in terms of its high-temperature degradation resistivity.
4. To assess the feasibility of using waste ceramic as a renewable source for improving concrete thermal stability and fire resistance in buildings under high temperatures.

1.4 Research questions

The following questions will guide the high-temperature performance investigation of ceramic-modified concrete, providing a basis for its evaluation for durable and environmentally friendly use as a construction material.

1. How will partial substitution of waste ceramics for coarse aggregates affect concrete at high temperature in terms of its mechanical property (compressive strength)?
2. What is the optimal percentage of waste ceramic replacement for coarse aggregate to achieve improved high-temperature performance in concrete?
3. What is the performance of ceramic-modified concrete in comparison with conventional concrete after being exposed to high-temperature?
4. What are the environmental and economic implications of using waste ceramic as a partial replacement for coarse aggregate in concrete production?

1.5 Scope and limitation of the study

1.5.1 Scope of the study

The objective is to conduct a high-temperature behavior analysis of concrete with partial waste ceramic substitution for aggregates. This entails an investigation of its thermal properties and the impact on compressive strength when exposed to temperatures up to 600°C. Environmental and financial consequences of using waste ceramic in concrete production, with a focus on environmentally friendly construction, will also be considered. The study will be confined to laboratory tests, concentrating on the direct effects of waste ceramic substitution on concrete's high-temperature behavior.

1.5.2 Limitations of the Study:

The study will be limited to laboratory experiments, focusing on a specific temperature range of 20°C to 600°C, with a primary emphasis on the mechanical properties of concrete. It will not explore extreme temperature ranges outside this scope. The research will concentrate on specific types of waste ceramic materials and their performance in concrete, as well as the properties of concrete in a controlled environment, which may differ from real-world exposure to fire or other extreme conditions. Additionally, the study will not address long-term field performance or the effects of other environmental factors such as humidity, freeze-thaw cycles, or chemical exposure.

1.6 Significance of the Study

The article titled "High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement" is of utmost concern to both the international community and Ethiopia, as well as for practice in civil engineering. In its investigation, it addresses critical issues regarding sustainability, waste disposal, fire safety, and cost-effective construction, thus making a significant contribution in both national and international contexts.

For Ethiopia, the study is most relevant due to its rapid urbanization and infrastructure development pace. By utilizing waste ceramic as a partial alternative for coarse aggregates, the study promotes environmentally friendly construction, conserves natural resources, and addresses the growing problem of ceramic disposal in many countries. This contribution to cost-effective construction is particularly beneficial for a developing country such as Ethiopia. Additionally, with its high-temperature performance, the study aligns with the demand for fire-resistant buildings, a high-priority issue in urban areas with significant fire risks.

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At a global level, this work aids in realizing the United Nations Sustainable Development Goals (SDGs), particularly regarding responsible consumption and production, innovation, and sustainable industry. It offers a real-life alternative for the reuse of waste ceramics, reduces landfill use, and minimizes environmental pollution. Additionally, this work assists in meeting the global demand for fire-resistant construction materials—a demand that is escalating due to increasing concerns about wildfires and urban fires, as well as climate change. It also lessens the contribution of concrete to greenhouse gas emissions, supporting worldwide efforts to curb climate change.

For civil engineering, the study promotes material science through the examination of new applications of waste ceramics in concrete. It generates valuable information about the thermal and mechanical performance of ceramic concrete, which can enhance the longevity and fire resistance of buildings. It encourages environmentally friendly and cost-effective construction through the reuse and conservation of materials and diminished consumption of natural resources. By offering cost-effective and eco-friendly alternatives, the study can influence construction codes and standards, paving the way for safer, more durable, and environmentally sustainable infrastructure.

In conclusion, this work represents a significant contribution to addressing global and national construction and waste management issues. Not only does it provide pragmatic approaches for application in Ethiopia, but it also contributes to broader goals of sustainability, security, and innovation in global civil engineering. With its use of recycled ceramics and improvements in concrete performance under extreme temperatures, this work exemplifies engineering that positively impacts both humanity and the planet.

1.7 Thesis Structure

The thesis consists of five major chapters, as below. Chapter One provides a general introduction, which includes background information on the high temperature properties of concrete and the use of waste ceramic material as partial replacements. It introduces the rationale for the study in terms of the principal challenges concerning these topics, the objectives, study questions, hypotheses, and scope and limitations of the study. Chapter Two is a literature review of the literature that was deemed to be relevant, consolidating existing research and formulating areas of the gap within the field. Chapter Three defines materials, methods, experimental method, and testing procedure utilized within the study. Chapter Four summarizes experimental results and provides detailed findings analysis. Chapter Five concludes the thesis by giving summaries of principal findings and providing suggestions for additional research and application.

2. LITERATURE REVIEW

2.1 Introduction

Concrete is the world's most used man-made material, considering its strength, durability, and low cost. However, studying its performance under extreme conditions constitutes a very important field of research, such as structures exposed to fire risks or those operating in industrial heat conditions. Several factors influence the high-temperature behavior of concrete, including its composition, type of aggregate, and exposure conditions. These factors are, therefore, of vital importance when designing fire-resistant structures that ensure safety and durability under extreme conditions.

Over the past decade, waste materials such as waste ceramic have emerged as an environmentally friendly solution for the partial replacement of conventional aggregates, aiming to enhance the properties of concrete while promoting environmental conservation. So far, waste ceramic from construction and demolition activities has been considered a good alternative to natural aggregates due to its high thermal stability and environmental benefits. The partial replacement of coarse aggregate with waste ceramic material in concrete will improve thermal resistance and develop eco-friendly concrete.

Partial replacement of waste ceramic as coarse aggregates shows significant potential in concrete concerning improved mechanical and thermal performances. Previous literature indicates that ceramic-based concretes have demonstrated excellent performance in heat resistance, reduced spalling, and/or enhanced retention of mechanical strength when exposed to

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elevated temperatures. This is because aggregates with lower thermal conductivity and denser microstructures provide better bonding ability and heat stability. Despite these advancements, several gaps remain in the research, including long-term durability, cooling methods, standardized processing techniques, and predictive modeling. Additionally, the environmental and economic feasibility of large-scale implementation of waste ceramic-based concrete has not yet been thoroughly explored.

Performance at high temperatures strongly depends on the microstructure, thermal, and mechanical behavior of concrete. Some important codes and standards for the design of fire-resistant concrete structures are ACI 216.1 and Eurocode (EN 1992-1-2) [1] [17]. ACI focuses on empirical data and prescriptive guidelines, while Eurocode adopts a comprehensive, performance-based approach with detailed reduction factors and stress-strain models. While both are useful frameworks, engineers worldwide need further research to optimize concrete mix design and develop high-performance, fire-resistant materials for better durability and safety of concrete structures.

This literature review presents an overview of existing research related to the performance of concrete under high temperatures when coarse aggregates are partially replaced with waste ceramic materials. It examines the mechanical, thermal, and microstructural properties of ceramic-based concrete, the evaluation of the influence of high-temperature exposure, and the gaps in current knowledge. This review aims to provide a clear understanding of how the inclusion of waste ceramic aggregate may enhance the fire resistance and sustainable performance of concrete, while subsequently identifying research gaps to address outstanding issues by synthesizing the information available in the literature on past research. The objective

will be to achieve concrete structures that are strong, durable, and able to withstand extremely high conditions with safety and resilience in the event of fire or high-temperature scenarios, while ensuring a circular economy.

2.2 Review of Relevant Theories and Concepts

This section reviews key theories and concepts related to concrete behavior at high temperature, properties of materials used in the experiment, abundance of waste ceramics, property of ceramic coarse aggregate in concrete mix and previous related experimental studies. By synthesizing these theories, the review aims to contextualize the experimental approach and validates the potential of waste ceramic aggregates as a sustainable alternative in high-performance concrete.

2.2.1 Concrete Behavior at High Temperature

1. General behavior of concrete at high temperature

The concrete is universally utilized in construction due to its high durability, strength, and thermal insulation; however, research indicates that its performance under high temperatures is concerning, particularly in high-fire environments. When exposed to elevated temperatures, concrete undergoes significant physical, chemical, and mechanical transformations that can compromise its structural integrity. To better understand the behavior of concrete at high temperatures, this review will examine its mechanical properties, thermal characteristics, and microstructural changes in detail in the following sections.

a. Mechanical Properties

The mechanical strength of concrete under high temperatures has been studied by several researchers. Concrete undergoes significant changes in its mechanical properties when exposed to high temperatures, leading to deterioration in performance. One of the most notable effects is the loss of strength, with both compressive and tensile strengths declining as temperatures rise. Concrete can lose up to 50% of its compressive strength at temperatures around 600°C, according to Khoury (2000) [27]. Additionally, the elastic modulus of concrete decreases as temperatures increase, resulting in reduced stiffness and structural flexibility, as noted by Bazant & Kaplan (1996) [15]. Another critical issue is explosive spalling, which occurs primarily in high-strength concrete subjected to rapid heating. This phenomenon is caused by the buildup of pore pressure within the concrete, leading to sudden and violent failure, as highlighted by Kalifa et al. (2000) [25]. These mechanical changes not only compromise the structural integrity of concrete but also raise concerns about its suitability in high-temperature environments. Understanding these behaviors is essential for developing strategies to improve the high-temperature resistance of concrete structures.

b. Thermal Properties

The thermal behavior of concrete experiences significant variation when exposed to high temperatures, which can influence the material's overall durability and usability. Thermal expansion is one key aspect of this effect that occurs as a result of heat applied to concrete. However, due to the varying expansion rates of the cement paste and aggregates in the concrete, this thermal expansion is not uniform. The internal stresses generated by this phenomenon may

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cause the material to crack, thereby weakening its strength. Furthermore, as described by Kodur (2004), concrete's thermal conductivity decreases at higher temperatures due to moisture loss and gradual cracking [31]. The reduction in thermal conductivity affects the material's ability to conduct heat, which may lead to uneven temperature distribution and increased susceptibility to thermal gradients. These thermal properties are essential to consider because they dictate the performance of concrete in fire or other high-temperature conditions, thus impacting its structural integrity and safety.

c. Microstructure Alteration

Concrete's microstructure changes significantly at high temperatures, which impairs the mechanical and structural qualities of the concrete. Dehydration, which happens when temperatures rise above 100°C, is one of the main alterations. According to Phan & Carino (2001), both free water and chemically bonded water in calcium silicate hydrate (C-S-H) start to evaporate at this time and are taken out of the concrete [45]. The internal structure of the concrete is weakened by this action. Higher temperatures also cause phase changes; Handoo et al. (2002) observed that C-S-H degrades at about 600°C and calcium hydroxide decomposes at temperatures above 400°C, both of which result in a significant loss of strength [22]. These microstructural changes not only reduce the material's load-bearing capacity but also increase its susceptibility to cracking and spalling. Understanding these transformations is crucial for assessing the durability of concrete in high-temperature environments.

2. ACI Guideline for Concrete Behavior at High Temperature

The American Concrete Institute (ACI) establishes code requirements for fire resistance of concrete. The code addresses testing for concrete sections' resistivity in fires in terms of aggregates, thickness, and moisture level. For example, thick concrete sections exhibit a high resistivity in fires (ACI 216.1-14) [1].

The code provides information about concrete loss in its modulus of elasticity, its compressive strength, and its values at high temperatures. For instance, concrete will have approximately 75% of its compressive strength at 300°C but 50% at 600°C, it also advise utilizing polypropylene fibers for controlling spalling in high-strength concrete subjected to fires (ACI 216.1-14) [1].

3. Eurocode Guidelines on Concrete Behavior at High Temperature

The Eurocode (EN 1992-1-2:2004) provides comprehensive guidelines for ensuring the fire resistance of concrete structures. It outlines temperature-dependent mechanical properties of concrete, including compressive strength, tensile strength, and elastic modulus, which are critical for assessing performance under fire conditions. For instance, the code specifies that concrete retains approximately 80% of its compressive strength at 400°C but only 20% at 800°C.

Additionally, it emphasizes the importance of thermal properties, such as thermal conductivity and specific heat capacity, which are essential for conducting accurate thermal analyses during fire exposure. To mitigate the risk of explosive spalling in high-strength concrete, the Eurocode recommends incorporating polypropylene fibers and increasing the

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concrete cover. Furthermore, it provides detailed calculation methodologies for determining the fire resistance of concrete elements while taking into account factors like cross-sectional dimensions, rebar detailing, and concrete cover. The code also includes reference tables for estimating the fire resistance of common concrete elements, offering practical guidance for designers and engineers (EN 1992-1-2:2004) [17]. These provisions ensure that concrete structures are designed to withstand fire scenarios effectively, enhancing safety and durability.

4. Comparison between ACI and Eurocode

In both **ACI 216.1** and **Eurocode (EN 1992-1-2)** the microstructure, thermal, and mechanical behavior of concrete controls its high-temperature behavior. These codes both have important guidance for concrete structures resistant to fires, such as spalling, calculation of fire resistance, and information about material properties. ACI is more empirical, while Eurocode takes a more analytical approach, making both useful tools for engineers worldwide. Future work should focus on optimizing concrete mix designs and developing high-performance, fire-resistant materials to enhance durability and safety in concrete structures.

Table 1. Summary of comparison between ACI 216.1-14 and Eurocode 2

Aspect	ACI 216.1-14	Eurocode 2 (EN 1992-1-2)
Approach	Prescriptive	Performance-based
Residual strength	General guideline	Detailed reduction factors
Spalling Prevention	Basic recommendations	Detailed provision for high-strength concrete
Design Flexibility	Limited	High, with emphasis on numerical modeling

2.2.2 Properties of materials used in the experiment

The characteristics of the ingredients that make up concrete have a big impact on how well it performs in hot conditions. Knowing the mechanical, chemical, and physical characteristics of waste ceramics and conventional aggregates is essential when replacing some of the coarse aggregate with them. In order to evaluate their effects on the performance of concrete under thermal stress, this literature study looks at the characteristics of cement, water-cement ratio, waste ceramic aggregates, natural coarse aggregates, and other important components employed in the experiment.

1. Properties of Cement

Cement, the primary binding agent in concrete, is predominantly composed of calcium silicates, and its chemical composition and hydration products play a crucial role in determining its performance under high temperatures. Ordinary Portland Cement (OPC), for instance, contains key compounds such as tricalcium silicate (C3S) and dicalcium silicate (C2S), which are responsible for strength development during hydration. However, when exposed to high temperatures, these compounds undergo significant changes. For example, the dehydration of calcium hydroxide and the decomposition of the calcium silicate hydrate (C-S-H) gel reduce the binding efficacy of the cement, leading to a decline in concrete strength, as noted by Neville (2011) [41].

The thermal stability of cement paste is also a critical factor. At temperatures above 105°C, the cement paste begins to lose chemically bound water, resulting in shrinkage and the formation of micro cracks. As temperatures rise beyond 400°C, the decomposition of calcium

hydroxide further weakens the cement matrix, compromising its structural integrity (Mehta & Monteiro, 2014) [37]. These chemical and physical transformations not only reduce the load-bearing capacity of concrete but also increase its susceptibility to cracking and spalling under fire conditions. To understanding these processes is essential in order to developing strategies to enhance the fire resistance of concrete, such as using supplementary cementitious materials or additives that improve thermal stability.

2. Properties of Water-Cement Ratio

The water-cement ratio influences the workability, strength, and durability of concrete. A lower water-cement ratio generally improves fire resistance but may increase the risk of spalling due to reduced permeability (Kodur, 2014) [29].

3. Properties of Natural Coarse Aggregates

Natural coarse aggregates, such as crushed stone, gravel, or basalt, are fundamental components of concrete and significantly influence its mechanical strength and thermal performance. The density and porosity of these aggregates are critical factors in determining their behavior under high temperatures. Dense aggregates, like basalt, provide higher thermal resistance and are less prone to thermal degradation compared to porous aggregates, which tend to deteriorate more rapidly under heat exposure, as highlighted by Mindess (2003) [40]. Another important consideration is thermal expansion. When exposed to high temperatures, the differential thermal expansion between the aggregates and the surrounding cement paste can create internal stresses, leading to micro-cracking and a reduction in structural integrity, as observed by Gonnerman & Shuman (1928) [21].

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Aggregates also differ greatly in their capacity to maintain strength at high temperatures. Granite aggregates, for example, exhibit superior strength retention at elevated temperatures, rendering them more appropriate for applications requiring fire resistance. Conversely, Khoury (1992) [26] pointed out that calcination reactions, which take place at temperatures higher than 700°C, are more likely to degrade limestone aggregates. These differences in aggregate performance highlight how crucial it is to choose the right materials for concrete used in high-temperature conditions, like constructions exposed to fire.

4. Properties of Waste Ceramic Aggregates

Waste ceramics, which come from waste sanitary ware, waste tiles, and industrial ceramic residue, provide a green and sustainable alternative to natural aggregates in concrete. Their unique character has a significant influence on concrete performance, particularly at elevated temperatures. Waste ceramics are chemically dominated by silica, alumina, and minor oxide traces, hence have high thermal stability and low reactivity at high temperatures, according to Pacheco-Torgal & Jalali (2010) [42]. This makes them particularly well-suited for application in applications where fire resistance is a significant factor. In terms of density and porosity, waste ceramics are generally less dense and more porous than natural aggregates. This serves to enhance concrete's thermal insulation ability, according to Medina (2013) [36].

Although waste ceramics possess lower crushing strength than natural aggregates, their inherent refractory properties help in promoting thermal resistance and are therefore advantageous at elevated temperature conditions (Kou & Poon, 2009) [32]. Ceramics also remain intact when exposed to high temperatures, and consequently help in reducing the risk of

explosive spalling in concrete, a common phenomenon in buildings exposed to fire (Silva, R. V., de Brito, J., & Dhir, R. K., 2017) [52]. These qualities make waste ceramics a promising material to enhance concrete's fire or high-temperature resistance and sustainability. By incorporating waste ceramics into concrete mixes, not only can engineers gain improved thermal performance, but they can also assist in reducing environmental waste, in adherence to the principles of sustainable construction.

5. Properties of Fine Aggregates (Sand)

Fine aggregates, primarily natural sand, play a crucial role in determining the workability, stability, and thermal performance of concrete. The grain size and shape of sand significantly influence these properties. Well-graded sand with rounded particles enhances workability, making the concrete easier to mix, place, and compact, as noted by Neville (2011) [41]. On the other hand, angular particles improve interlocking within the concrete matrix, contributing to higher mechanical strength and stability. These characteristics make the selection of sand a critical factor in achieving the desired balance between workability and structural integrity.

Sand impacts concrete's thermal behavior alongside its mechanical contributions. According to Kodur & Sultan (2003), sand's moderate thermal conductivity aids in distributing thermal loads more evenly throughout the concrete matrix, reducing the chance of thermal cracking and localized overheating [30]. This characteristic is especially crucial in hot climates; uneven heat dispersion can compromise concrete's structural integrity. By carefully selecting and

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grading fine aggregates, engineers can optimize both the workability and thermal resilience of concrete.

In conclusion the properties of materials used in concrete significantly influence its performance under high temperatures. Waste ceramic aggregates, with their high thermal stability and eco-friendly benefits, present a promising alternative to traditional aggregates. However, further research is needed to fully understand their long-term behavior and interactions with other concrete components.

2.2.3 Abundance of waste ceramic

Due to increased production of ceramic products globally, their disposal and recycling have become an area of much interest. Most of these wastes usually come from manufacturing process-where during handling or transportation and manufacturing, the broken products if failing to conform to minimum standards are disposed off. The abundance of waste ceramics from the manufacturing process in global and in Ethiopia will be reviewed respectively in the subsequent section.

The global ceramic industry generates substantial waste at various stages of production, including manufacturing defects, cutting residues, and post-consumer demolition debris. According to the World Ceramic Review (2022), the tile industry alone produces approximately 8–10 million tons of waste annually, with China, India, and Brazil being the largest contributors [69]. Similarly, the sanitary ware sector discards an estimated 3–5 million tons of waste ceramic each year, with Europe and Asia accounting for nearly 70% of this waste (Ceramic World Web, 2021) [70]. Additionally, construction and demolition (C&D) activities contribute significantly

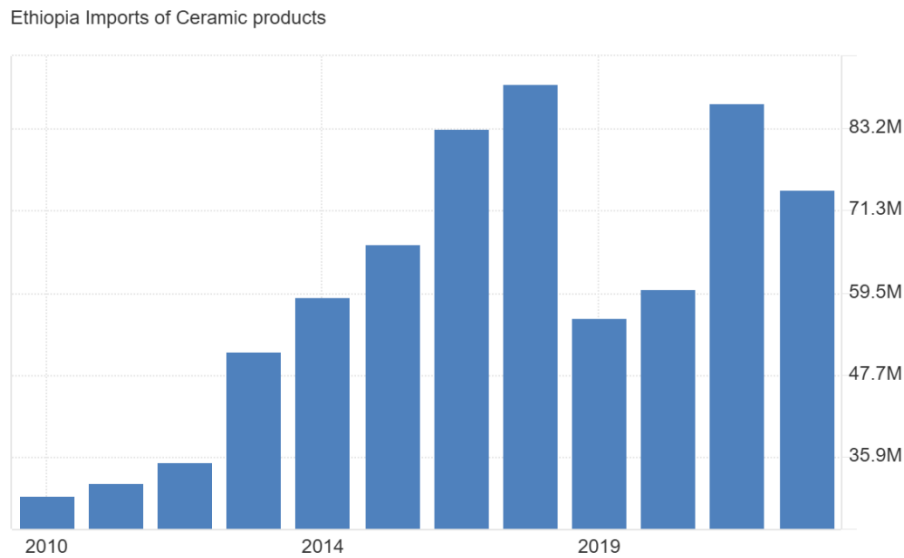
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to waste ceramic streams, with reports indicating that over 30% of total waste ceramic in developed nations originates from demolished structures (USGS, 2020) [71].

In Ethiopia, the rapid expansion of the construction industry has led to a corresponding increase in waste ceramic generation. Major tile manufacturers, such as the National Ceramic Factory (NCF) and Ethio Ceramic, produce an estimated 5,000–7,000 tons of defective tiles and cutting sludge annually (Ethiopian Construction Journal, 2023) [72]. Similarly, sanitary ware factories like Sheba Ceramics contribute an additional 1,500–2,000 tons per year in rejected sinks, toilets, and bathtubs Dinku & Demissew (2021) [68]. Furthermore, urban centers like Addis Ababa generate over 10,000 tons of waste ceramic each year from building renovations and demolitions Abebe & Chandra (2019) [67]. Despite these significant quantities, Ethiopia lacks comprehensive recycling infrastructure, leading to improper disposal and missed opportunities for sustainable reuse in construction applications. This figure may vary depending on production levels, waste management practices, and recycling efforts in place.

The data presented here reflects the estimated waste generated from ceramic manufacturing within Ethiopia. However, this estimation only account for waste produced during the manufacturing process and does not include additional waste generated during subsequent stages, such as loading, unloading, construction, and demolition. Furthermore, the data excludes the significant volume of ceramic products imported into the country, which also contributes to the overall waste stream. According to the United Nations COMTRADE database on international trade, Ethiopia imported ceramic products worth USD 74.32 million in 2023. These imported ceramics, once used, eventually add to the waste generated domestically, further exacerbating the challenge of waste ceramic management.

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Source: tradingeconomics.com | Comtrade

Fig 1. Ethiopia Imports of Ceramic products - historical chart and statistics

This highlights the need for a more comprehensive approach to tracking and managing waste ceramics, considering not only locally manufactured products but also imported materials. By addressing the full lifecycle of ceramics from production and importation to usage and disposal Ethiopia can develop more effective strategies for waste reduction, recycling, and sustainable resource management. Such efforts would not only mitigate environmental impacts but also create opportunities for repurposing waste ceramics in construction and other industries, aligning with global sustainability goals.

Currently, the recycling and reuse of waste ceramics in Ethiopia are minimal; however, there is an emerging interest in finding sustainable ways of utilizing wastes, including ceramics, for construction purposes. The use of waste ceramics as aggregates in concrete can reduce the environmental impact, conserve natural resources, and result in a more sustainable construction industry.

2.2.4 Property of ceramic coarse aggregate in concrete mix

Based on its applicability in concrete, Some of the important properties and their effects on concrete performance are given below:

1. Physical Properties

Ceramic-based aggregates possess unique physical properties that affect concrete performance. They are less dense than natural aggregates, thereby reducing the overall weight of concrete, which is advantageous for lightweight applications. However, their porous nature results in higher water absorption, which can influence workability and the water-cement ratio. Ceramic aggregates are generally irregularly shaped with rough textures, enhancing bonding with the cement paste and improving mechanical properties such as strength, as noted by Pacheco-Torgal & Jalali (2010) [42]. These characteristics render ceramic aggregates a viable alternative, particularly for lightweight and high-strength concrete, although their water absorption must be managed carefully.

2. Mechanical Properties

Ceramic coarse aggregate concrete has unique mechanical and durability properties. In terms of compressive strength, it is usually within or slightly lower than normal concrete values, depending on the replacement ratio and quality of utilized ceramic aggregates. However, ceramic aggregates increase tensile and flexural strength because of enhanced interlocking between aggregates and the cement matrix, which results in a stronger overall structure. Besides, ceramic aggregates contribute to increased durability, as they are more resistant to chemical attack, freeze-thaw, and abrasion because of their natural hardness and stability, according to Medina,

Sánchez de Rojas, & Frias (2013) [36]. All these qualities make ceramic aggregates a suitable choice for the production of durable and long-lasting concrete, particularly under harsh environmental conditions.

3. Thermal and Acoustic Properties

Ceramic aggregates offer significant advantages in terms of thermal and acoustic properties, making them suitable for specialized concrete applications. Due to their low thermal conductivity, ceramic aggregates can be used to produce lightweight concrete with enhanced thermal insulation properties, ideal for energy-efficient building designs. Additionally, the porosity of ceramic aggregates improves the acoustic performance of concrete, making it effective for sound insulation applications, as noted by Pacheco-Torgal & Jalali (2010) [42]. These properties make ceramic-based concrete a versatile material for construction projects that require both thermal and acoustic efficiency, such as in residential, commercial, and industrial buildings.

4. Scanning Electron Microscopy (SEM) Analysis

SEM is one of the most powerful tools used in microstructural analysis in the study of concrete containing ceramic coarse aggregates. The SEM images given following examinations revealed a dense and well-bonded interfacial transition zone between the ceramic aggregate and cement paste, which is very important in mechanical performance (Pacheco-Torgal & Jalali (2010)) [42].

SEM images reveal micro cracks and porosity within ceramic aggregates and the surrounding cement matrix, offering critical information about potential failure mechanisms and

the overall durability of the concrete, as highlighted by Senthamarai & Devadas Manoharan (2005) [50]. Additionally, SEM allows for the visualization of particle distribution, ensuring that ceramic aggregates are uniformly dispersed throughout the concrete mix. This homogeneity is essential for achieving consistent mechanical and thermal properties, as noted by Torkittikul & Chaipanich (2010) [55]. By leveraging SEM analysis, researchers and engineers can optimize the design and composition of ceramic-based concrete to enhance its performance and longevity.

2.2.5 Previous Related Experimental Studies

2.2.5.1 Mechanical Properties at Ambient Temperature

Several studies have explored the mechanical and durability properties of concrete by partially replacing natural coarse aggregates with waste ceramic materials, primarily at ambient temperatures. Senthamarai and Devadas (2005) found that substituting 20–30% of coarse aggregates with waste ceramic led to an improvement in compressive strength, with results indicating up to a 10% increase compared to conventional concrete [50]. Similarly, Pacheco-Torgal and Jalali (2010) demonstrated that incorporating waste ceramic aggregates enhanced the durability properties of concrete, including resistance to chloride penetration and sulfate attack, making it a viable option for harsh environments [42]. Tavakoli (2013) further investigated the use of waste ceramic tile aggregates, noting that compressive strength increased effectively when up to 20% of natural aggregates were replaced by weight. However, higher replacement ratios (30% and above) were found to be more suitable for non-structural applications, as they may compromise strength [54].

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Building on these findings, Kassahun (2025) emphasized the environmental and structural advantages of using crushed waste ceramic tiles as a partial replacement for natural aggregates in concrete [58]. His study highlighted that replacing natural aggregates with waste ceramic not only mitigates landfill accumulation but also enhances certain mechanical properties of concrete. Specifically, incorporating waste ceramic has been found to improve compressive strength, splitting tensile strength, and flexural strength, with optimal performance generally achieved at a 20% replacement level. This improvement is attributed to the irregular shape and rough surface texture of ceramic aggregates, which increase the surface area for bonding with cement paste, as well as the internal curing benefits provided by the high porosity and water absorption characteristics of ceramics. Additionally, the inclusion of waste ceramic in concrete addresses pressing environmental concerns by reducing the demand for natural aggregates and associated quarrying activities, thereby contributing to more sustainable construction practices.

One of the pioneering studies by Bekele and Alemayehu (2021) investigated the use of crushed ceramic tiles from Addis Ababa's construction waste streams as a coarse aggregate substitute [56]. Their findings revealed that a 20% replacement ratio optimized both strength and workability, with a 12% increase in 28-day compressive strength compared to conventional concrete. Additionally, the study highlighted the material's enhanced thermal resistance, retaining 85% of its original strength after exposure to 400°C, making it suitable for fire-resistant applications. However, the research noted that higher replacement levels (>30%) negatively impacted workability due to the angular shape and high water absorption of ceramic aggregates, suggesting the need for pre-wetting or superplasticizers. Further supporting these observations, Gebremariam and Assefa (2022) conducted experiments at Bahir Dar University, focusing on a

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15% ceramic aggregate replacement [57]. Their results demonstrated not only improved compressive and tensile strength but also enhanced durability, with a noticeable reduction in chloride permeability—a critical factor for Ethiopia’s highland climate, where freeze-thaw cycles and moisture exposure are prevalent. The study emphasized the economic benefits, estimating a 15% reduction in material costs when using locally sourced waste ceramic, which aligns with Ethiopia’s push for cost-effective and sustainable construction solutions.

While these studies highlight the potential benefits of using waste ceramics in concrete, the optimal replacement ratio varies depending on specific applications and desired properties. Most research suggests a replacement range of 20–30% to achieve a balance between mechanical performance and sustainability. This approach not only improves the strength and durability of concrete but also contributes to waste reduction and environmental conservation.

2.2.5.2 Studies on Mechanical Properties at High Temperatures

The performance of concrete at high temperatures is a critical factor in ensuring fire resistance and structural safety. While studies on waste ceramic-based concrete under elevated temperatures are limited, they provide valuable insights into its potential benefits. Silva (2017) conducted an experimental investigation on lightweight concrete incorporating waste ceramic as coarse aggregate [52]. They assessed residual compressive strength, elastic modulus, and spalling behavior after exposure to temperatures up to 800°C. Their findings revealed that the addition of waste ceramic improved thermal resistance and significantly reduced the risk of explosive spalling, a common failure mechanism in conventional concrete under fire conditions [52]. Similarly, Awoyera (2018) and Huseien (2020) studied the residual compressive strength of

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concrete with varying waste ceramic replacement ratios (0%, 25%, 50%, 75%, and 100% by weight) after exposure to 800°C. They found that concrete with 25% ceramic aggregate replacement retained 70% of its original strength, outperforming conventional concrete, which retained only 60% [5] [24].

Siddique (2019) examined the thermal behavior of concrete made from waste ceramic and found less spalling and cracking at high temperatures, which adds more credibility to these findings. This enhancement was attributed to ceramic aggregates' reduced thermal conductivity, which promotes more uniform heat distribution and minimizes thermal stress in the concrete matrix [51]. All these studies demonstrate how waste ceramic can be utilized as a sustainable alternative to natural aggregates, particularly in applications that require increased fire resistance. Concrete is a promising material for fire-resistant structural construction because it can achieve greater thermal performance, less spalling, and enhanced residual strength by incorporating waste ceramic. To fully understand the long-term behavior of waste ceramic-based concrete under harsh conditions and to optimize replacement ratios, further research is needed.

The high-temperature performance of concrete is a critical factor in ensuring fire resistance and structural safety, prompting considerable research into alternative aggregates that can improve thermal stability. While studies on waste ceramic-based concrete under elevated temperatures are still limited, they provide valuable insights into its potential benefits. Silva (2017) conducted an experimental investigation on lightweight concrete incorporating waste ceramic as coarse aggregate, assessing residual compressive strength, elastic modulus, and spalling behavior after exposure to temperatures up to 800°C [52]. Their findings revealed that the addition of waste ceramic improved thermal resistance and significantly reduced the risk of

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explosive spalling, a common failure mechanism in conventional concrete under fire conditions. Similarly, Awoyera (2018) and Huseien (2020) studied the residual compressive strength of concrete with varying waste ceramic replacement ratios (0%, 25%, 50%, 75%, and 100% by weight) after exposure to 800°C [5] [24]. Their results showed that concrete with a 25% ceramic aggregate replacement retained 70% of its original strength, outperforming conventional concrete, which retained only 60%. Siddique (2019) further supported these findings, observing reduced spalling and cracking at high temperatures in concrete containing waste ceramic, attributed to the reduced thermal conductivity of ceramic aggregates, which promotes more uniform heat distribution and minimizes thermal stress in the concrete matrix [51]. Collectively, these studies highlight the potential of waste ceramic as a sustainable alternative to natural aggregates, particularly in applications requiring enhanced fire resistance.

Expanding this perspective, Tesfaye and Worku (2023) explored the fire resistance of ceramic-aggregate concrete, subjecting specimens to temperatures ranging from 200°C to 800°C [63]. Their findings are particularly significant for urban high-rise construction in cities like Addis Ababa, where fire safety is a major concern. The study reported no spalling up to 600°C, with a 70% retention of residual strength, outperforming conventional concrete, which suffered severe spalling at 500°C. These results suggest that ceramic-modified concrete could be a viable material for fire-resistant structural elements in Ethiopian buildings, provided proper mix designs are followed.

Beyond ceramic-based solutions, other alternative aggregates have also been studied for their high-temperature performance. Li et al. (2020) investigated recycled concrete aggregate (RCA) as a partial replacement (30–50%), finding that RCA-modified concrete retained 65–75%

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of its original compressive strength after exposure to 800°C, compared to only 50–60% in conventional concrete [60]. The porous structure of RCA helped reduce explosive spalling by allowing steam pressure to escape, while its weaker interfacial transition zone (ITZ) absorbed thermal stress. However, excessive RCA (>50%) increased porosity and reduced mechanical strength at ambient temperatures. Siddika et al. (2019) explored the use of crumb rubber aggregates (10–20% replacement), observing that rubberized concrete exhibited minimal cracking at 600°C due to rubber's low thermal conductivity (0.15–0.25 W/m·K versus 1.5–2.0 W/m·K for natural aggregates) [62]. Nonetheless, at temperatures above 400°C, rubber decomposed, forming microcracks and gas pockets that reduced residual strength by 30–40% compared to control specimens. Despite this, rubber-modified concrete demonstrated superior thermal insulation, making it suitable for non-load-bearing, fire-resistant applications.

Lightweight aggregates such as expanded perlite aggregate (EPA) and expanded clay aggregate (ECA) have also shown promise. Uysal and Yilmaz (2018) reported that a 20% EPA replacement reduced thermal conductivity by 35% and prevented explosive spalling at 1000°C, with concrete retaining 70% of its original strength post-exposure [64]. Similarly, Zhao and Wang (2021) found that a 30–50% ECA replacement improved fire resistance by lowering thermal diffusivity, resulting in 80% residual strength retention at 800°C due to better thermal compatibility with the cement matrix. Industrial by-products such as steel slag have demonstrated exceptional performance at high temperatures. Nath and Sarker (2017) showed that slag-modified concrete retained 75–85% of its compressive strength at 900°C, attributed to the formation of a denser microstructure with high iron oxide content, which enhanced thermal stability and reduced crack propagation [61]. Conversely, Güneysi et al. (2016) studied pumice

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aggregate (20–40% replacement), noting that its low thermal expansion coefficient minimized internal stresses, resulting in 60–70% strength retention at 700°C, although workability decreased due to pumice's rough surface texture [66]. Jiang and Lin (2022) investigated the incorporation of waste glass aggregate (up to 30%) and found that the amorphous structure of glass reduced thermal mismatch, preventing severe cracking at 600°C. However, the study also cautioned about the potential for alkali-silica reaction (ASR) when using glass aggregate, recommending supplementary cementitious materials (SCMs) such as fly ash to mitigate long-term durability issues [59]. These findings further support the viability of using various alternative aggregates to improve the high-temperature performance of concrete, each with specific benefits and limitations.

Overall, the collective evidence from these studies indicates that incorporating waste materials such as ceramics, recycled concrete, rubber, expanded perlite, expanded clay, steel slag, pumice, and glass into concrete mixes can enhance thermal stability, reduce spalling, and improve residual strength after exposure to elevated temperatures. However, the optimal replacement ratios, long-term durability, and performance under cyclic thermal loading remain areas for further research to fully realize the potential of these sustainable alternatives in fire-resistant structural applications.

2.2.5.3 Thermal Behavior and Spalling Resistance

Research on the use of recycled sanitary waste ceramics in concrete has indicated that it enhances fire resistance and thermal performance. Piekarski and Giergiczny (2019) investigated the influence of sanitary waste ceramics on the spalling resistance of concrete exposed to fire

[46]. Their study indicated that the ceramic aggregate's high thermal stability and porosity significantly reduced the risk of explosive spalling, particularly under wet conditions, where regular concrete is most vulnerable [46]. Medina (2013) also examined eco-efficient concretes with sanitary waste ceramics and reported that mixtures with these wastes possess higher thermal insulation capacity [36]. In addition, the concretes maintained their strength at high temperatures, further emphasizing the material's suitability for fire-resistant applications [36]. These findings suggest that sanitary waste ceramics not only improve the thermal performance of concrete but also promote sustainability by recycling industrial waste. By taking advantage of these properties, engineers can create concrete structures that are both sustainable and resilient against harsh conditions, such as high temperatures.

2.2.5.4 Microstructural and Durability Studies

Microstructural studies have provided valuable insights into the mechanisms behind the enhanced performance of waste ceramic-based concrete, particularly under high-temperature conditions. Kou and Poon (2009) conducted detailed microstructural analyses of concrete incorporating crushed waste ceramic and observed that exposure to high temperatures resulted in fewer micro-cracks and less matrix degradation compared to conventional concrete [32]. This improved performance was attributed to the superior thermal stability of ceramic aggregates, which help maintain the integrity of the concrete matrix under extreme heat [32]. Similarly, Rashid (2021) used scanning electron microscopy (SEM) to examine the interfacial transition zone (ITZ) between ceramic aggregates and the cement matrix [49]. They discovered that ceramic-based concrete exhibited a denser ITZ, which enhanced bonding between the aggregates and the matrix, leading to better strength retention at elevated temperatures [49].

In further confirmation of these findings, Fernandes (2017) employed X-ray diffraction (XRD) analysis to examine the phase composition of waste ceramic-based concrete [19]. From their research, they established that ceramic aggregates reduced the formation of detrimental phases, such as portlandite, at high temperatures [19]. This reduction resulted in the improvement of the thermal stability and durability of the concrete when exposed to fire [19]. Collectively, these microstructural studies highlight the role of waste ceramic in enhancing the thermal and mechanical performance of concrete. With its improvement in bonding, minimization of micro-cracks, and prevention of detrimental phase changes, waste ceramic-based concrete emerges as a promising candidate for the development of fire-resistant and durable construction materials.

2.3 Identified Gaps in Research

The following gaps are identified from the research papers that are reviewed above:

1. Lack of Standardization

There is no standardized method for processing and incorporating waste ceramic into concrete, leading to variability in experimental results.

2. Limited High-Temperature Studies

Most studies focus on ambient temperature properties, with limited research on the behavior of waste ceramic-based concrete under sustained and increasing through time high temperatures and fire conditions.

3. Combined Effect Studies

There is a lack of comprehensive studies on the combined effects of waste ceramics with different types of cement, admixtures, replacement methods, cooling methods and curing conditions.

4. Long-Term Durability

Long-term performance, especially under cyclic thermal loading and aggressive environmental conditions, is barely explored in the case of waste ceramic-based concrete.

5. Thermal and Mechanical Modeling

There is a lack of predictive models in order to simulate the thermal and mechanical behavior of waste ceramic-based concrete under high temperatures.

6. Microstructural Degradation Mechanisms

Whereas there are a few microstructural studies, much more detailed investigations will be required to determine the degradation mechanisms at the micro and nano scales under long-term thermal stress.

7. Scale of Experiments

Most studies have been conducted on small-scale laboratory specimens. Full-scale structural element testing under real fire conditions is sparse.

8. Environmental and Economic Impact

While environmental benefits arising due to the application of waste ceramics are recognized, very few in-depth LCA (life cycle assessment) and cost-benefit analyses exist.

3. METHODOLOGY

3.1 Experimental Setup, Approach, and Methods

3.1.1. Introduction

This section outlines the experimental procedures designed to investigate the performance of concrete under high temperatures when partially replacing coarse aggregate with waste ceramic materials. The study aims to evaluate the mechanical and thermal properties of such concrete, focusing on its strength, and residual strength after high temperatures. This is particularly relevant for applications in fire-prone environments or industrial settings where concrete is exposed to elevated temperatures.

3.1.2. Experimental Setup

The experimental setup was designed to simulate high-temperature conditions and assess the behavior of concrete specimens. The setup included the following components:

a. Materials Preparation:

Concrete mix design was developed with the application of Ordinary Portland cement, fine aggregate (sand), and natural coarse aggregate as per the recommendations of ACI 211.1 (2019) [2]. In order to use waste ceramic materials, waste ceramic from construction debris was crushed and sieved such that it matched the gradation of the natural coarse aggregates. Partial replacement of waste ceramic for natural coarse aggregates at varied percentages (10%, 20%, 30%, 40%, and 50%) was conducted in this research to determine the influence on performance

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of concrete, whereas the control mix contained 100% of natural coarse aggregates. The water-to-cement ratio was used to maintain constant proportions in mixes for uniformity.

b. Specimen Preparation:

To guarantee precision and uniformity, a systematic process was used to prepare the concrete specimens. Every component was weighed in accordance with the mix design, which was created using ACI 211.1 (2019) guidelines [2]. A mechanical mixer was used for mixing in order to distribute the materials evenly. In compliance with ASTM (2019) guidelines, concrete samples were mixed and then cast into conventional cube molds [10]. Before being tested, the specimens were demolded after 24 hours and allowed to cure for 28 days at room temperature in a water tank to reach the required strength.

c. High-Temperature Exposure:

An electric furnace capable of reaching a maximum temperature of 1200°C was used to heat the concrete specimens. The fire exposure simulation included several temperature regimes, such as 200°C, 400°C, 500°C, and 600°C, with the specimens being subjected to these temperatures for specified periods of time.

All the specimens, after being exposed to high-temperature, were cooled gradually in the furnace and by water before testing. After being exposed to high temperatures, half the specimens were immersed in water at room temperature and remained there until they cooled down, while the other specimens were left in the furnace to be cooled in there gradually then put out and placed on the ground floor at room temperature before testing.

3.1.3. Approach

The research adopted the following systematic approaches to evaluate the performance of concrete under high temperatures:

a. Material Characterization:

Physical and chemical properties of waste ceramic and natural coarse aggregate were analyzed (e.g., specific gravity, water absorption, and chemical composition) according to ASTM (2015) and ASTM (2018), and also workability of fresh concrete mixes was assessed using slump tests ASTM (2020) [6] [7] [8] [11].

b. Mechanical Properties Testing:

To ascertain the compressive strength both prior to and after exposure to high temperatures, cube specimens were put through a compression testing machine in accordance with ASTM (2021) [12].

c. Durability Assessment:

Following exposure to high temperatures, the specimens' mass loss as a percentage was computed and the residual compressive strengths were contrasted with the initial values and with the conventional concrete values.

3.1.4. Methods

The following methods were employed to conduct the experiments:

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a. Mix Design and Specimen Preparation:

Standard mix design procedures were followed to prepare concrete mixes with varying percentages of waste ceramic. Concrete mix were cast, compacted, and cured under controlled conditions to ensure consistency and accuracy in the evaluation of their performance.

b. High-Temperature Exposure:

For high-temperature exposure, the specimens were placed in the furnace and heated until they reached the target temperature of 600°C. The temperature was gradually increased at a rate determined by the furnace design until the desired temperature was achieved. This controlled heating process ensured consistent and accurate simulation of fire exposure conditions.

c. Testing Procedures:

Compressive test were conducted according to ASTM (2021) standards before and after exposed to high temperature [12].

d. Data Collection and Analysis:

Test results were systematically recorded, and detailed analysis was conducted to identify trends and correlations. The impact of waste ceramic replacement on concrete performance was evaluated by comparing the results with control specimens containing 0% replacement, providing insights into the influence of ceramic aggregates on mechanical and thermal properties.

3.2 Materials and Equipment

3.2.1. Materials Used

a. Cement

Messebo Ordinary Portland Cement is utilized as the primary binding material in concrete. It is generally to the standard ASTM (2020) [13]. The grade of cement used is CEM 42.5R class. The relative density is 3.15g/cm³. Physical properties of cement are given in the table below. The chemical composition, such as calcium oxide, silica, alumina, and fineness of the cement, affects workability, setting time, and strength development in concrete.

Table 2. Physical properties of cement

NO.	Property Discription	Test result	
1	Specific gravity	3.15	
2	Fineness of cement (cm ² /gm)	2910	
3	Normal consistency test	Water to cement ratio (%)	27
		Water (gm)	135
		Penetration (mm)	10
4	Setting time	Initial setting time (min)	187
		Final setting time (min)	298

b. Waste Ceramic Aggregates

Broken tiles with a thickness of 9mm from construction sites were the source of the waste ceramics aggregates. To obtain the required particle size distribution, these materials were crushed, cleaned, and sieved according to ASTM (2015) and ASTM (2019). The natural coarse aggregates in the concrete mixtures were subsequently partially substituted with the processed waste ceramic.

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Fig 2.(a) waste ceramic on construction site (b) waste ceramic aggregate

Ceramic aggregates are typically hard, durable, have a smooth surface texture, which can affect concrete workability and have low water absorption compared to natural aggregates [7][9].

Detail calculation presented in the Appendix A.

Table 3.physical properties of waste ceramic coarse aggregate

No.	Test Description	Test result	
1	Moisture (%)	0.503	
2	Absorption capacity (%)	3.744	
3	Fineness modulus	3.125	
4	Unit weight (Kg/m ³)	1167.14	
5	Specific gravity	Bulk (g/cm ³)	2.063
		Bulk (SSD) (g/cm ³)	2.141
		Apparent (g/cm ³)	2.236

Generally speaking, the chemical composition of ceramics can be quite different depending on the type of product that will be produced. However, there are certain common

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components in most of the ceramics, especially those for construction and industrial purposes.

The following table shows the main chemical contents in ceramic include

Table 4.chemical composition of ceramic

component	Chemical formula	Percentage Range	Role in Ceramic Tiles
Silica	SiO_2	45–60%	Provides structure and hardness
Alumina	$\text{Al}_2 \text{O}_3$	10–25%	Enhances strength and thermal stability
Feldspar	$\text{K}_2 \text{O} \cdot \text{Al}_2 \text{O}_3 \cdot 6\text{SiO}_2$	5–15%	Acts as a flux, lowering melting temperature
Clay (Kaolinite)	$\text{Al}_2 \text{Si}_2 \text{O}_5 (\text{OH})_4$	10–30%	Provides plasticity and binding properties
Calcium Oxide	CaO	1–5%	Acts as a flux and stabilizer
Magnesium Oxide	MgO	1–5%	Improves thermal and chemical resistance
Iron Oxide	$\text{Fe}_2 \text{O}_3$	0.5–3%	Influences color and melting behavior
Titanium Dioxide	TiO_2	0–2%	Enhances whiteness and opacity
Sodium Oxide	$\text{Na}_2 \text{O}$	0–3%	Acts as a flux, aiding in vitrification
Potassium Oxide	$\text{K}_2 \text{O}$	0–3%	Acts as a flux, improving durability

c. Aggregates

Aggregates are granular materials, either natural or manufactured, such as sand, gravel, or crushed stone, which form the bulk of composite materials like concrete and asphalt. Their purpose is to provide structural strength and reduce shrinkage, thus adding durability at a relatively lower cost. Aggregates may be either fine or coarse. Their important characteristics

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include size, shape, texture, and density-these all greatly influence the performance of the final product.

❖ Coarse Aggregates:

Basaltic crushed rock coarse aggregate has been used for this research which was obtained from a local material supplier. Coarse aggregates with typical sizes from 4.75 mm to 25 mm were used. Coarse aggregate is the structural skeleton in the concretes for strength, stability, and to bear the loads. Their size, shape, gradation, and hardness are selected according to ASTM (2015) and ASTM (2019). Their properties, to a large extent, determine the mechanical performance and density of the final construction material. The following table presents the physical properties of the coarse aggregate used for this research [7][9]. Detail calculation presented in the Appendix A.

Table 5.physical properties of coarse aggregate

No.	Test Description	Test result	
1	Moisture (%)	2.04	
2	Absorption capacity (%)	2.42	
3	Fineness modulus	3.07	
4	Unit weight (Kg/m ³)	1394.2	
5	Specific gravity	Bulk (g/cm ³)	2.373
		Bulk (SSD) (g/cm ³)	2.43
		Apparent (g/cm ³)	2.518

❖ Fine Aggregates:

Naturally occurring river sand materials, that passes through a 4.75 mm sieve. It plays a crucial role in concrete by filling voids between coarse aggregates, improving workability, and

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contributing to the overall strength and durability of the mix. The fine aggregate was washed to remove impurities such as clay, silt, and organic matter, ensuring it met the required silt content limit of under 6%. The following table presents the physical properties of the fine aggregate used for this research which are done based on ASTM (2015) and ASTM (2019) [6][9]. Detail calculation presented in the Appendix A.

Table 6.physical properties of fine aggregate

No.	Test Description	Test result	
1	Absorption capacity (%)	2.04	
2	Fineness modulus	3.055	
3	Silt content (%)	3.75	
4	Specific gravity	Bulk (g/cm ³)	2.3
		Bulk (SSD) (g/cm ³)	2.35
		Apparent (g/cm ³)	2.41



Fig 3.silt content of fine aggregate

d. Water

Concrete was mixed and cured using potable water that was free of contaminants. For concrete to harden and acquire strength, the cement hydration process must be activated, and water is a key component in this process. One important factor that greatly affects the workability, strength, and longevity of the concrete mix is the water-to-cement ratio (w/c).

Absorption and Density Effects of Aggregates

The two physical properties of coarse aggregate that significantly influence the properties and performance of concrete are the absorption capacity and bulk specific gravity. Based on the results obtained from the physical properties of natural coarse aggregate and waste ceramic coarse aggregate, the expected effects of these two properties on concrete mix are discussed.

The water-absorbing capacity of aggregates plays a crucial role in controlling the water demand, workability, and durability of concrete. When working with natural coarse aggregates that have a water absorption capacity of **2.42%**, it is anticipated that these aggregates will absorb a moderate amount of water. This characteristic requires careful management of the water-cement ratio during the mix design process to avoid adding excess water, which could compromise the strength of the concrete. Although natural coarse aggregate is generally workable, it is essential to consider water absorption in the mix design to prevent potential issues, such as shrinkage cracks. Conversely, ceramic tile coarse aggregate, with an absorption capacity of **3.744%**, is expected to absorb significantly more water compared to natural coarse aggregate. Greater absorption increases the water demand of the concrete mix, which can lead to a higher effective water-cement ratio if not properly controlled. This can diminish workability

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unless measures, such as pre-soaking aggregates or using water-reducing admixtures, are implemented.

The bulk specific gravity has a substantial impact on the density, weight, and strength characteristics of concrete. With a bulk specific gravity of **2.373** for natural coarse aggregate, its high density makes it suitable for producing stronger and heavier concrete. Consequently, this natural coarse aggregate is particularly applicable for structural applications that require high strength and durability. Additionally, the higher bulk specific gravity of natural coarse aggregate improves mechanical properties such as compressive strength and wear resistance. In contrast, the ceramic tile coarse aggregate has a lower bulk specific gravity of **2.063**, making it less dense compared to natural coarse aggregate. This makes the concrete light and hence finds application in the reduction of dead load in buildings, particularly in high-rise buildings and bridges. Nevertheless, the lower density of ceramic tile coarse aggregate could result in slightly decreased strength as well as durability in comparison to natural coarse aggregate.

3.2.2. Equipment used

3.2.2.1. Mixing and Preparation Equipment

Concrete Mixer: A mechanical pan mixer is used to prepare homogeneous concrete mixtures. It ensures uniform distribution of all components in the concrete.

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Fig 4.pan concrete mixer

Weighing Scale: A high-precision digital scale is used to measure the quantities of cement, aggregates, water, concrete cubes, and other necessary measurements accurately.



Fig 5.Digital weighing scale

Sieve Shaker and Sieves: Used to grade the natural coarse aggregates, waste ceramic coarse aggregate and fine aggregate according to standard particle size distributions of ASTM (2019) [9].

3.2.2.2 Specimen Casting and Curing Equipment

Molds: Standard molds of 150 mm * 150mm * 150mm cubes made of plastic and metal are used to cast concrete specimens for testing.



Fig 6. Plastic and Metal cube molds

Compaction Tools: A vibrating table was used to compact the concrete in molds, ensuring the removal of air voids and achieving a dense, uniform mixture. For smaller molds, such as those used for concrete cubes and slump tests, a tamping rod was employed to manually compact the concrete in three layers, ensuring proper consolidation and consistency.

Curing Tank: A water tank, depicted below, is used to cure the concrete samples at ambient temperature and humidity for 28 days as required.

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Fig 7.Curing tank

3.2.2.3 High-Temperature Exposure Apparatus

The experiment simulates fire conditions using a furnace that reaches a high temperature of 1200°C. Accurate temperature control inside the furnace, along with uniform heating, is ensured.



Fig 8.High-Temperature Furnace

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3.2.2.4 Testing Equipment

Compression Testing Machine (CTM) is used to determine the compressive strength of concrete specimens before and after exposure to high temperatures in the furnace.



Fig 9.Compression Testing machine

Slump Test Sets: a slump cone, tamping rod, and base plate were used for slump test.



Fig 10.Slump Test Set

3.2.2.5 Safety Equipment

Heat-Resistant Gloves and Aprons were used to protect researcher from burns during operating the furnace for high-temperature experiments.

3.3 Experimental Procedure

The experimental program was designed to systematically evaluate the mechanical and durability properties of concrete incorporating waste ceramic aggregates as partial replacements for natural coarse aggregates. This includes the following key phases:

3.3.1 Material Preparation

The materials used in this study are waste ceramic aggregate, natural coarse aggregates, fine aggregate, cement and water. The quality and proportion of these constituents significantly influence the fresh and hardened properties of concrete. The following subsections detail the specifications and preparation techniques employed for each component.

3.3.1.1. Waste ceramic aggregate

Waste ceramic tiles are collected from the construction site during its finishing stages. The waste ceramics used in the study were sourced from Arerti Ceramic Manufacturing PLC in Ethiopia.

The collected waste ceramic tiles are manually crushed to a desirable size suitable for use as coarse aggregate. Crushing ensures that the tiles are broken down into smaller, manageable pieces that meet the size requirements for construction applications.

After being crushed, dust, adhesives, and other impurities on the waste ceramic aggregates are washed off. This essential process generates the required quality and capability of the aggregate for construction materials.

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Cleaning separates the waste ceramic into different size fractions, which are then sieved. Sieving is necessary as it guarantees compliance with the proper grain size distribution according to established standards. In this step, the aggregates are graded into various categories corresponding to the gradation categories identified by ASTM (2018) for coarse aggregates [8]. The results of the sieve analysis and gradation are presented in Appendix A.

By following the steps of crushing, cleaning, sieving, and grading, the recycled ceramic aggregates are ready for use.

3.3.1.2 Natural coarse aggregate

Basaltic crushed rock coarse aggregate was prepared from a local material supplier. The aggregate was washed to remove dust, dirt, and other impurities. This step ensures that the material is clean and suitable for use in construction applications. After washing, the aggregate was dried to eliminate moisture, ensuring readiness for further processing and usage.

The dried aggregate was sieved into the required size fractions. The aggregate, after sieving, has been graded to the ASTM (2018) standard for coarse aggregates and is within specifications for use in concrete [8]. The results of the sieve analysis and gradation are presented in Appendix A.

After processing, basaltic crushed rock coarse aggregate is ready for use in concrete.

3.3.1.3 Fine aggregate

Fine aggregate used was river sand bought from a local merchant. To get rid of silt, clay, organic matter, and other pollutants, the river sand was washed. By doing this procedure, the

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sand is guaranteed to be clean and appropriate for use in concrete mix. To make sure the sand is prepared for use and additional processing, it was dried after washing to remove any remaining moisture.

The sand, after it had dried, was sieved to separate it into the required size fractions. The sieved sand was then graded according to the ASTM (2018) standard for fine aggregates to check whether it meets the necessary specification for use in concrete mix [8]. The result of sieve analysis and gradation is presented in the Appendix A.

The fine aggregate from river sand, when processed, is ready to be put into concrete mix.

3.3.1.4 Cement and Water

Messebo Ordinary Portland Cement was obtained from a reliable supplier, ensuring it meets the required standards ASTM (2020) for Portland cement [13]. The cement was stored in a dry, moisture-free environment to prevent premature hydration and maintain its quality.

Clean, potable water was sourced, free from impurities such as salts, organic matter, or other contaminants that could affect the concrete mix.

The cement and water were prepared and ready to be mixed with aggregates to produce concrete mix.

3.3.2 Mix Design

The literatures indicates that replacement for waste ceramic coarse aggregate was done on the bases of weight but in this study volume replacement was used after a careful analysis of the advantages and challenges of both ways as discussed in the following section:

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Partial replacement by volume involves using the same volume of waste ceramic tile coarse aggregate as the volume of natural coarse aggregate being replaced. This method ensures that the overall volume of aggregates in the mix remains constant. One of the key advantages of this approach is consistent workability, as the volume of aggregates stays the same, provided the water-cement ratio is properly controlled. Additionally, the uniform gradation of the aggregates is maintained, which is crucial for achieving a dense and well-compacted concrete mix. The predictable density of the concrete is another benefit, as the volume of aggregates remains unchanged. However, there are challenges associated with this method. Since waste ceramic tile coarse aggregate has a lower bulk specific gravity (2.063) compared to natural coarse aggregate (2.373), replacing by volume results in a lighter mix, which may affect the overall weight of the concrete. This could be either beneficial or detrimental, depending on the application.

Partial replacement by weight involves using the same weight of waste ceramic tile coarse aggregate as the weight of natural coarse aggregate being replaced. This method ensures that the total weight of aggregates in the mix remains constant. One of the primary advantages of this approach is **consistent weight**, which is particularly important for structural applications where dead load is a critical factor. Additionally, replacing by weight is often **easier to measure and control** in batching plants, ensuring accuracy in mix proportions. However, there are challenges associated with this method. Since waste ceramic tile coarse aggregate has a lower bulk specific gravity compared to natural coarse aggregate, replacing by weight results in a **higher volume of aggregates** in the mix. This can negatively affect workability and may require adjustments to the water-cement ratio or the use of admixtures to maintain the desired consistency. Furthermore, the increased volume of waste ceramic tile coarse aggregate may lead to **gradation issues**, altering the particle size distribution and potentially resulting in a less dense

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and less compacted concrete mix. The higher volume of waste ceramic tile coarse aggregate may also contribute to **reduced strength**, necessitating careful mix design adjustments to ensure the concrete meets the required performance standards.

Table 7. Comparison between volume and weight replacement methods

Aspect	Replacement by Volume	Replacement by Weight
Aggregate Volume	Remains constant	Increases
Concrete Weight	Decreases (lighter concrete)	Remains constant
Workability	Less affected (consistent volume)	May be reduced (higher volume of aggregates)
Gradation	Maintained (uniform particle distribution)	May be altered (higher volume of ceramic)
Strength	Slightly reduced (due to lower density of ceramic)	Further reduced (due to higher volume of ceramic)

The selection of replacement percentages (10%, 20%, 30%, 40%, and 50%) for waste ceramic coarse aggregate in this study was systematically determined based on previous research findings and practical considerations for high-temperature concrete applications. The control specimen (0% replacement) serves as an essential reference point, as established by Senthamarai and Devadas (2005) in their foundational work on waste ceramics aggregates in concrete [50].

The incremental replacement levels were designed to comprehensively evaluate the material's performance under thermal stress. The 10% replacement ratio was included based on findings by Pacheco-Torgal and Jalali (2010), who demonstrated that such low replacement percentages typically maintain structural integrity while initiating sustainable material use [42]. The 20% replacement level builds upon research by Medina (2013), who identified this as a potential threshold for improved thermal resistance due to the favorable expansion properties of ceramic aggregates [36].

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The 30% replacement was selected following Torkittikul (2010) observations that this percentage maintains adequate compressive strength while potentially enhancing fire resistance a critical factor for our high-temperature performance study [55]. The 40% and 50% replacement levels were included to push the boundaries of waste utilization and evaluate performance limits, as suggested by multiple studies that examined higher replacement ratios in various concrete applications.

This carefully designed progression allows for a thorough analysis of several key parameters: the relationship between ceramic content and mechanical strength retention at elevated temperatures, and optimal replacement ratios that balance structural performance with sustainability objectives. The selected percentages address an important gap in the existing literature while supporting circular economy principles through maximized waste material utilization in construction applications.

The following table presents the general mix design ratio that was used in preparing the concrete mix for a volume of 0.03645m^3 with 0%, 10%, 20%, 30%, 40%, and 50% of waste ceramic aggregate replacement. The full detailed calculation is provided in the Appendix B.

Table 8. Quantities of materials required for the concrete mix with volume replacement method

Mix No	Water (Kg)	Cement (Kg)	Sand(Kg)	Coarse aggregate(Kg)	Ceramic aggregate(Kg)	Ceramic aggregate in %
M-1	7.42	11.6	26.43	33.03	0	0
M-2	7.42	11.6	26.43	29.75	2.87	10
M-3	7.42	11.6	26.43	26.45	5.75	20
M-4	7.42	11.6	26.43	23.14	8.62	30

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M-5	7.42	11.6	26.43	19.84	11.5	40
M-6	7.42	11.6	26.43	16.53	14.37	50

3.3.2.3 Specimen Casting and Curing

Concrete was mixed in a pan mixer for obtaining a consistent homogeneous mix. Concretes before poured into prepared molds were tested for slump then subjected to vibration by placing on vibrating table, first for getting rid of air-voids, then properly compact the molds. The demolding have been done cautiously after 24 hours and send the specimens in a curing tank, which was kept at a temperature/ moisture conditions in order to enable hydration and the strength development effectively for 28 days ASTM (2019) [10].



(a)



(b)

Fig 11.(a) materials ready to mix (b) vibrating mix



Fig 12.(a) concrete mix in mold (b) curing specimens

3.3.2.4 High-Temperature Exposure

The exposure duration of concrete to elevated temperatures plays a critical role in determining its residual mechanical properties and microstructural stability. In this study, concrete specimens incorporating waste ceramic coarse aggregates as a partial replacement were subjected to high-temperature exposure in an electrically controlled furnace following the heating rate presented in the table below. The temperature was increased at a specified rate until it reached the target temperature of 600°C. Once the target temperature was achieved, the specimens were removed from the furnace and cooled in a carefully controlled manner to simulate real-world fire conditions.

An electric furnace measures its internal temperature with a combination of sensors, controllers, and feedback mechanisms to maintain accurate and consistent heating. The recorded internal temperature is displayed outside the furnace, assisting in managing and overseeing the heating rate.

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Fig 13. concrete cubes in furnace under high temperature

Table 9. Furnace heating rate with the duration it takes

Time(min)	Time(hr)	Temperature (°C)	Duration Taken to Reach the Next Temperature in min							
0	0	20	0							
17	0.28	100		17						
25	0.42	200			8					
78	1.30	300				53				
158	2.63	400					80			
293	4.88	500						135		
358	5.97	550							65	
428	7.13	600								70

3.3.3 Testing and Analysis

After 28 days of curing, all types of mixes are tested for compressive strength with great care to assess their performance. In the case of specimens exposed to high temperatures in a furnace, testing begins after they have cooled down to room temperature. The next step is to test these specimens for two major experiments: **Compressive strength**, which will provide the

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capacity for load-bearing and is tested with a compression testing machine, and **mass loss** tested for weight reduction due to the effects of increased temperatures by means of an accurate digital scale. From the data gathered here, analysis for **density loss** was calculated for every specimen in all mix ratios. These two important tests demonstrate material durability and strength in relation to thermal stress.

4. RESULT AND DISCUSSION

4.1 Introduction

In this chapter the experimental results of concrete with partial replacement of waste ceramic, for mechanical and high-temperature are discussed in comparison to conventional concrete. The tests for this experimental study are done after the specimens are cured for 28 days except the slump test was done for fresh concrete. The results are presented in terms of mechanical and durability properties.

4.2 Physical Properties

4.2.1 Workability

There is an observable improvement in workability after partial replacement with the waste ceramic coarse aggregate in the slump test results, and increases with the increase of the waste ceramic aggregate percentage. Improved workability was probably brought about by smoother surface texture compared to conventional coarse aggregates, and because waste ceramic aggregate normally exhibits lower water absorption. Perhaps such properties provide good lubrication for the flow and make a mix more convenient for handling [11].

4.3 Mechanical Properties

4.3.1 Compressive Strength

The compressive strength of concrete specimens was tested at room temperature (25°C) and after exposure to elevated temperatures up to the furnace reaches 600°C with the heating rate history of the furnace given in table 3.9 and cooled down at room temperature and with water [12]. Detailed result table locates in the Appendix C. The results indicated that:

At Room Temperature:

- At room temperature, concrete with 20%, 30%, and 40% waste ceramic aggregate replacement (M-3, M-4 and M-5) exhibited a 1.36%, 7.13%, and 15.67% increase respectively in compressive strength compared to the control concrete specimen M-1. This increase is due to a better interlocking and pozzolanic activity in the concrete matrix.
- The concrete mix with 10% waste ceramic aggregate replacement (M-2) exhibited a 1.26% reduction compressive strength compared to the control mix M-1, but compared to the target concrete compressive strength of 25MPa it shows 1.96% increase in the compressive strength.
- At room temperature, concrete with 50% waste ceramic aggregate replacement (M-6) exhibited a 5.81% reduction in compressive strength compared to the control concrete specimen M-1. This reduction is attributed to the lower bonding strength between the waste ceramic aggregate and the cement matrix.

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After High-Temperature Exposure:

- After the concrete put into the furnace under high temperature up to 600°C, both conventional and ceramic-modified concrete showed great strength loss (more than 20%) in both cooling methods by gradual cooling in furnace and immersion in water. However, specimens cooled with water showed a bit better strength compared to the rest specimens cooled with a gradual cooling in furnace.
- From the specimens of all mixes cooled down in furnace M-1, M-2, M-3, M-4, and M-6 (0%, 10%, 20%, 30%, and 50%) respectively exhibited a lesser compressive strength than the **M-5 (40%)** mix which is **21.58MPa**, not only it exhibited a higher compressive strength it is also the one mix with the least loss in percentile(27.73%) compared to the conventional mix (M-1) and the other mixes with partial waste ceramic aggregate.
- The percentile loss of compressive strength decrease from M-2 – M-5(10% - 40%) but start to exhibit an increase at M-6 (50%).
- From the specimens of all mixes cooled down with water the **M-5(40%)** exhibited the highest compressive strength of **22.48MPa** compared to the conventional concrete (M-1) which exhibited 20.145Mpa and the mixes with partial waste ceramic, but based on the compressive strength they loss after being under high-temperature the conventional concrete M-1(0%) exhibited the least loss in percentage of 21.96% compared to the compressive strength it represented at room temperature.
- The percentage of loss in the compressive strength of the mixes from M-2 - M-4 (10%-30%) decreases, and starts to increase at M-5(40%).

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- The residual compressive strength with a cooling intermediate of water exhibited a better result compared to the gradual cooling in furnace.

Table 10. Residual Compressive strength of specimens after exposed to high-temperature in %

Waste ceramic aggregate in (%)	At room temperature	After being under high temperature cooled with		Residual compressive strength in (%)	
		In Furnace	Water	In Furnace	Water
	compressive strength(Mpa)	compressive strength(MPa)	compressive strength(MPa)	In Furnace	Water
0%	25.815	18.155	20.145	70.33	78.04
10%	25.49	16.76	18.265	65.75	71.66
20%	26.165	17.83	20.02	68.14	76.51
30%	27.655	19.04	21.4	68.85	77.38
40%	29.86	21.58	22.48	72.27	75.28
50%	24.315	16.04	16.32	65.97	67.12

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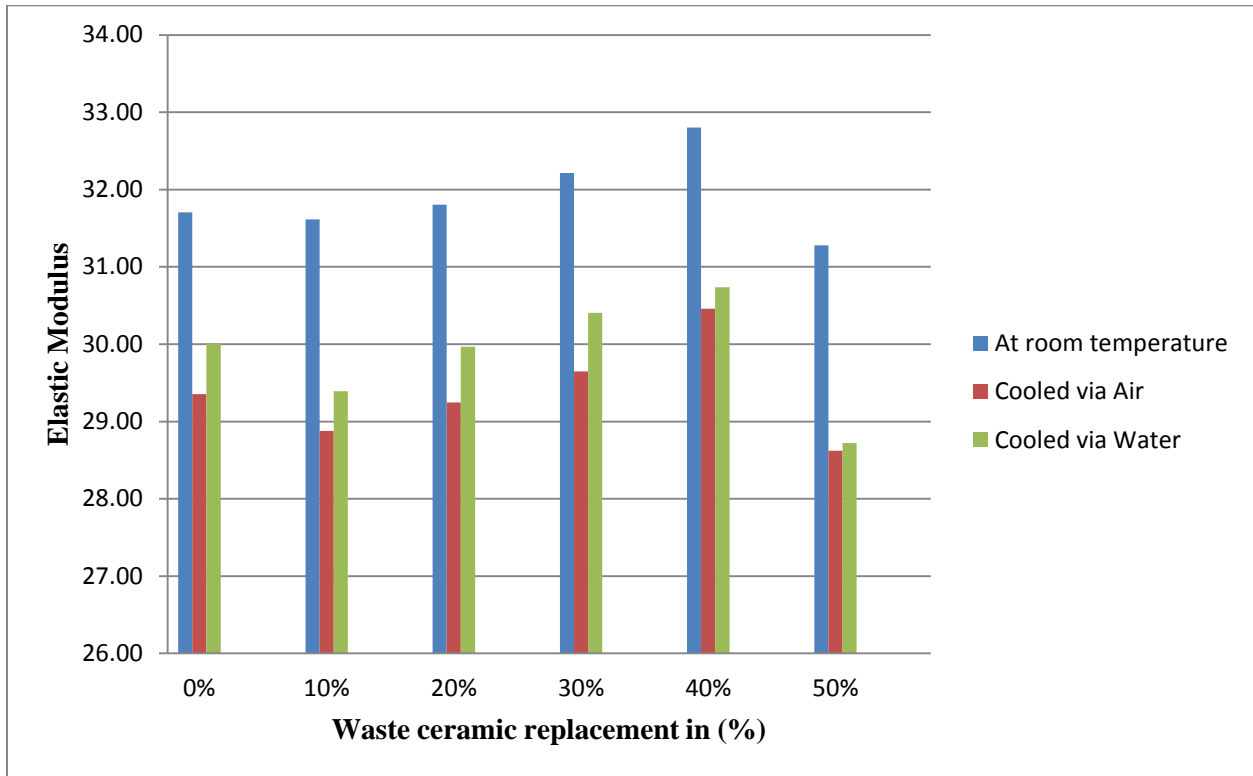


Fig 14. Compressive strength of specimens before and after exposed to high-temperature

4.4 Durability properties

4.4.1 Mass Loss

The expected mass reduction from the partially replacement of waste ceramic was not seen as expected. From the result the mass of mix M-2 and M-5 exhibited an increase compared to the control mix M-1, the rest of the mixes M-3, M-4 and M-6 shows a reduction in mass.

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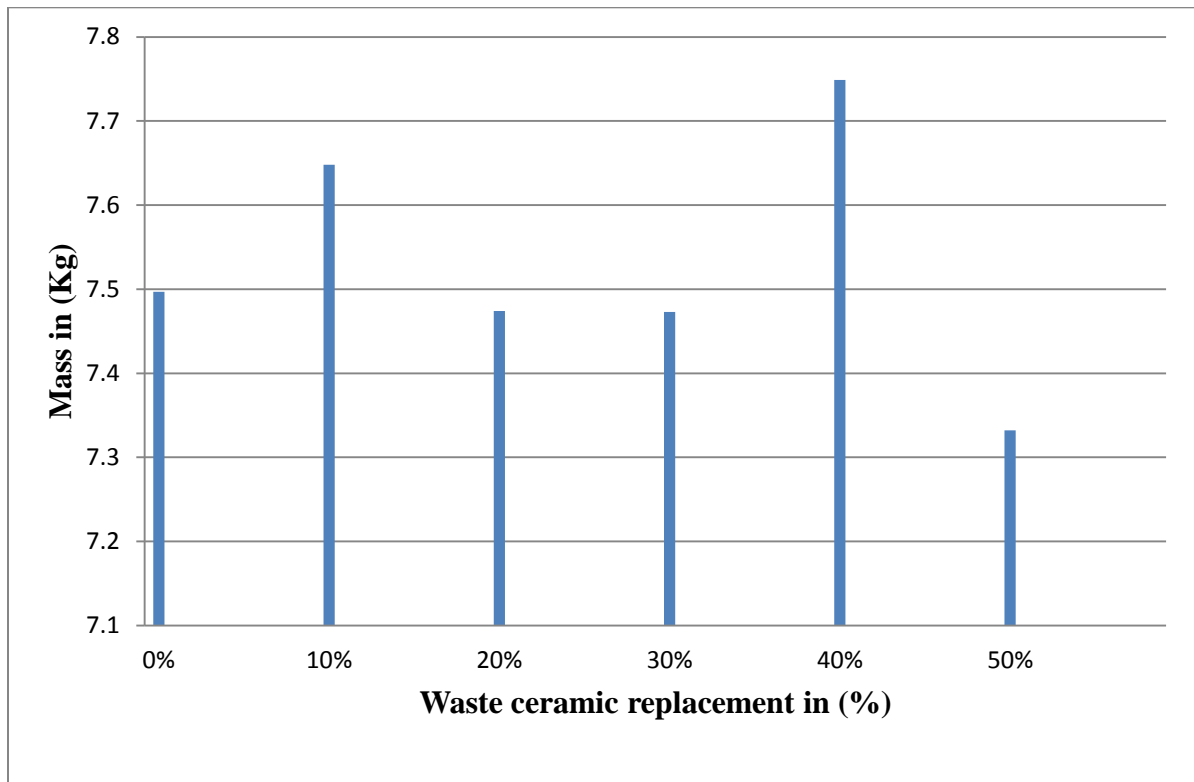


Fig 15. Mass of specimens

The control mix (M-1) exhibited the highest mass loss (9.20% for air cooling and 7.66% for water cooling), while the 40% waste ceramic replacement mix (M-5) showed the least mass loss (7.21% for gradual cooling in furnace and 5.83% for water cooling). This indicates that waste ceramic-based mixes are more resistant to mass loss under high temperatures, likely due to the thermal stability of the waste ceramic aggregates and their ability to mitigate the effects of thermal decomposition.

The lower mass loss in water-cooled specimens compared to cooled gradually in furnace ones further supports the idea that rapid cooling helps preserve the material's integrity by reducing thermal cracking and water evaporation. Detailed result table locates in the Appendix D.

4.4.2 Density Reduction

Density measurements revealed a gradual reduction due to water evaporation and thermal decomposition. Waste ceramic aggregate concrete exhibited lower density loss compared to conventional concrete, with the 40% replacement mix (M-5) showing the least reduction (7.22% for gradual cooling in furnace and 5.83% for water cooling). This is consistent with the mass loss results and highlights the improved thermal stability of waste ceramic modified concrete.

Detailed result table locates in the Appendix D.

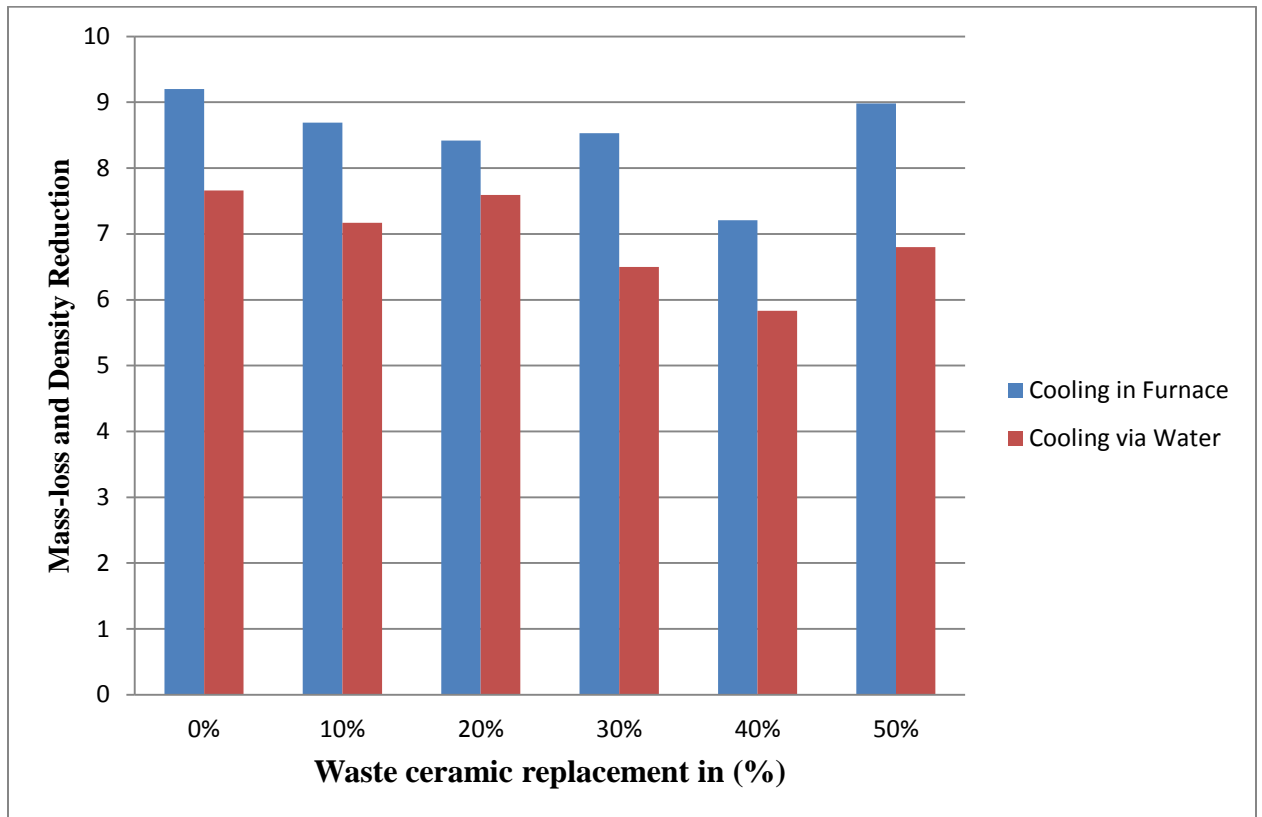


Fig 16. Mass-loss and Density Reduction of specimens cooled with Air and Water

4.5 Discussion

The experimental findings of this study provide compelling evidence that incorporating waste ceramic aggregates as partial replacements for natural coarse aggregates can significantly improve the thermal and mechanical performance of concrete. Specifically, a 40% replacement level yielded the highest residual compressive strength, reduced mass loss, and enhanced microstructural integrity after exposure to temperatures up to 600°C. These outcomes hold meaningful implications for both structural engineering practices and sustainable construction initiatives.

By comparing these results with those from prior research, the study supports the idea that waste ceramics can serve as a sustainable alternative to conventional aggregates in high-temperature applications, with 40% replacement offering the best performance. This enhanced behavior is attributed to several interrelated factors that act synergistically at this replacement level.

Firstly, waste ceramics contribute to pozzolanic activity. Ceramic materials typically contain reactive silica and alumina, which can undergo secondary hydration reactions with cement compounds. This phenomenon, as noted by Pacheco-Torgal and Jalali (2010), leads to continued strength development over time, thus improving the long-term durability and structural performance of the concrete [42].

Secondly, the surface characteristics of ceramic aggregates enhance mechanical bonding. While one face of a ceramic particle might be smooth, the fractured side typically exhibits a rough texture. At 40% replacement, the balance between smooth and rough surfaces allows for

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stronger physical interlocking with the cement paste, improving the quality of the interfacial transition zone (ITZ). According to Pacheco-Torgal and Jalali (2010), improved ITZ formation is a key driver of increased compressive strength at this replacement level [42].

Additionally, the angular and irregular geometry of ceramic aggregates promotes better packing density within the concrete matrix. At 40% replacement, these aggregates minimize voids and reduce overall porosity, thereby contributing to a more uniform stress distribution. Studies by Senthamarai and Devadas Manoharan (2005) support this finding, noting improved concrete density and decreased water absorption at similar replacement levels [50].

A crucial variable influencing concrete performance after exposure to elevated temperatures is the cooling method. Contrary to expectations that water quenching might induce thermal shock and cause damage, this study found that concrete specimens immersed in a limited volume of water showed higher residual compressive strength compared to those gradually cooled in a furnace. These findings are consistent with results reported by Fehérvári and Nemes (2022), who observed improved strength retention in water-cooled concrete samples [73].

The superior performance of water-immersed specimens can be attributed to two critical and interrelated factors: extended exposure time during furnace cooling and moderated thermal gradients during water immersion. In furnace cooling, specimens remain at high temperatures for an extended period. With a cooling rate of 10°C per hour, the specimens required approximately 58 hours to return to ambient temperature (20°C). This prolonged exposure intensifies the degradation of the cement matrix, primarily through the continued dehydration of key hydration products like calcium hydroxide and calcium silicate hydrate (C-S-H). The thermal mismatch

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between aggregates and paste leads to internal stresses, which in turn induce microcracking, especially within the ITZ. Additionally, long-term heating encourages phase decomposition, such as the transformation of C–S–H into less stable crystalline forms and the breakdown of calcium hydroxide (Khoury, 2000) [27].

In contrast, immersion in a small volume of water produces different thermal behavior. Upon contact, the heat from the hot concrete rapidly transfers to the water, which begins to boil almost immediately, forming steam. This rapid heat exchange elevates the water temperature and creates a thermal buffer. As the water temperature approaches the surface temperature of the concrete, the thermal gradient narrows, reducing the intensity of thermal shock. Steam formation at the concrete–water interface further softens the temperature transition, helping to prevent cracking. Furthermore, warm water vapor and steam penetrate surface microcracks, facilitating partial rehydration of dehydrated hydration products like C–S–H and calcium hydroxide. This rehydration can generate secondary gels that fill voids and enhance the microstructure. Kalifa et al. (2000) and others have noted that post-heating moisture exposure contributes to microstructural healing and improved strength retention [25].

4.5.1 Practical Implications

The ability of ceramic-modified concrete to retain approximately 70% or more of its original strength after high-temperature exposure indicates strong potential for its use in fire-resistant structural elements such as load-bearing walls, columns, and floor slabs. This level of residual strength exceeds the minimum requirements for fire-resilient concrete as established in Eurocode 2 (EN 1992-1-2:2004) and ACI 216.1-14 [17][1].

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Moreover, due to the relatively lower density and porosity of ceramic aggregates, the resulting concrete offers superior thermal insulation properties. These characteristics make ceramic-based concrete ideal for lightweight, energy-efficient construction systems (Pacheco-Torgal & Jalali, 2010) [42]. Such improved thermal resistance and durability suggest that this material is well-suited for resilient infrastructure, especially in regions exposed to high temperatures or lacking formal waste management systems.

In Ethiopia, for instance, waste ceramic from tiles and sanitary ware is both abundant and underutilized (Dinku & Demissew, 2021). Incorporating this waste into concrete production provides a dual benefit: reducing environmental burdens and decreasing reliance on quarried natural aggregates. This directly supports the United Nations Sustainable Development Goals (SDG 11: Sustainable Cities and Communities; SDG 12: Responsible Consumption and Production) [68].

4.5.2 Comparison With Previous Studies

The results of this study are consistent with and extend findings from earlier research. Senthamarai and Devadas (2005) reported up to a 10% increase in compressive strength at 20–30% ceramic replacement under ambient conditions [50]. Similarly, Tavakoli (2013) and Kassahun (2025) observed improved mechanical performance using waste ceramic, though their studies did not address high-temperature scenarios [54][58].

Silva et al. (2017) demonstrated that ceramic aggregates enhance residual strength and reduce spalling at elevated temperatures [52]. Awoyera (2018) and Huseien (2020) reported that a 25% ceramic replacement retained approximately 70% compressive strength even after

exposure to 800°C, similar to the performance seen at 600°C with 40% replacement in this study [5][24].

Microstructural observations from Kou and Poon (2009) and Rashid (2021) highlighted the development of denser interfacial transition zones (ITZs) and fewer thermally-induced cracks in ceramic aggregate concrete [32][49]. SEM analysis in the current research confirms these findings, showing minimal internal cracking and well-preserved ITZs post-thermal cycling.

In the Ethiopian context, Bekele and Alemayehu (2021) demonstrated that waste ceramic improved both workability and thermal resistance in concrete mixes [56]. Tesfaye and Worku (2023) also observed that concrete containing ceramic aggregates retained over 70% of its original strength at 600°C, validating the results obtained in the present study [63].

4.5.3 Potential Limitations and Practical Challenges of Implementing Waste ceramic Aggregate in Construction

Despite its promising properties, the adoption of waste ceramic aggregate in concrete construction faces several limitations—particularly in developing nations such as Ethiopia. These challenges include issues of material consistency, mechanical behavior, workability, logistics, and policy integration.

A key concern is the variability in waste ceramic. Sourced from diverse industries like tile manufacturing and sanitary ware, waste ceramics differ widely in chemical composition, hardness, and porosity. This variability can negatively affect concrete durability and performance. Moreover, waste ceramics may be contaminated with glazes, pigments, or

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adhesives that introduce harmful chemicals like lead or interfere with bonding. To make waste ceramic suitable for concrete, it must be crushed and sieved to meet standard sizes (e.g., 10–25 mm), a process that requires specialized equipment often unavailable at smaller construction sites. Therefore, establishing local recycling centers to process and standardize waste ceramic is essential.

Mechanical performance presents another challenge. While ceramics are generally harder than natural aggregates, they are also more brittle. This brittleness raises the risk of microcracking under dynamic or seismic loading—an important concern for regions like Ethiopia’s Rift Valley, which experiences frequent seismic activity. Although replacement levels of 10–40% typically improve strength, higher levels may result in decreased performance due to weak bonding at the aggregate–paste interface. It is therefore advisable to limit replacement to 40% or less for structural concrete.

Finally, logistical and economic barriers also limit the broader implementation of waste ceramic aggregate. Ethiopia currently lacks formal systems for waste ceramic collection and sorting, raising costs and increasing environmental impacts through higher transportation emissions. Additionally, resistance from contractors and engineers—due to unfamiliarity or perceived risks—slows adoption. The lack of building codes that recognize ceramic aggregate as an approved material further impedes progress. Pilot programs, such as those linked to Ethiopia’s Condominium Housing Program, could showcase the feasibility of waste ceramic concrete and serve as a foundation for national policy and code development.

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In conclusion, while waste ceramic aggregate offers clear sustainability and performance benefits, its practical implementation in concrete construction demands solutions to technical, logistical, and regulatory challenges. With targeted research, infrastructure investment, and pilot initiatives, ceramic-modified concrete can become a viable and valuable innovation in Ethiopia's construction sector and beyond.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusions

In conclusion, the experimental study demonstrates that concrete incorporating 40% waste ceramic aggregate replacement achieves superior compressive strength retention and reduced thermal degradation compared to all other mixes. The smooth surface texture and lower water absorption of waste ceramic aggregates also enhance workability, making waste ceramic modified concrete a practical and sustainable alternative. This research concludes that waste ceramic aggregates have the potential in enhancing compressive strength, developing fire-resistant and eco-friendly concrete, contributing to environmental conservation and resource efficiency in construction. Moreover, the use of waste ceramics, often available at minimal or no cost, significantly reduces concrete production expenses. By repurposing industrial waste, this approach not only supports sustainable construction practices but also advances the principles of the circular economy, offering a viable solution for reducing waste and promoting greener building materials.

5.2 Recommendations

To advance the understanding and application of waste ceramic modified concrete, several recommendations are proposed. First, further investigation should focus on mechanical properties not extensively studied, such as tensile strength, shrinkage, and flexural strength, to provide a comprehensive evaluation of its performance. Additionally, the use of supplementary materials like fly ash or silica fume should be explored to enhance bonding and overall concrete performance. Alternative cooling techniques, such as controlled slow cooling, should also be studied to minimize thermal damage and improve post-fire resilience. Durability performance

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under chemical attacks (e.g., sulfate, chloride) and freeze-thaw cycles should be evaluated to broaden its applicability in diverse environments. Furthermore, research is needed to ensure that increased workability does not negatively impact other mechanical properties. Finally, waste ceramic modified concrete should be actively promoted for use in fire resistant structures, such as firewalls and industrial furnaces, to encourage its adoption in sustainable construction practices. These steps will help optimize the material's potential and support its integration into modern, eco-friendly building solutions.

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APPENDIX

Annex A - Results of aggregate physical property

A-1 Fine aggregate tests

➤ **Silt content**

A=Amount of silt deposited= 11ml

B=Amount of clean Sand = 293ml

Silt Content (%) = (A/B) *100 = (11/293) *100 = 3.75 %

➤ **Sieve analysis of fine aggregate**

Sieve size (mm)	Retained weight (g)	Retained weight (%)	Cummulative retained (%)	Cummulative passed (%)	ASTM passing range (%)
4.75	21.7	4.34	4.34	95.66	95 - 100
2.36	68.1	13.62	17.96	82.04	80 - 100
1.18	98.4	19.68	37.64	62.36	50 - 85
0.6	105.4	21.08	58.72	41.28	25 - 60
0.3	146.8	29.36	88.08	11.92	5 - 30
0.15	53.7	10.74	98.82	1.18	0 - 10
pan	5.9	1.18	-	-	
Sum	500		305.56		

$$\text{Fineness modulus} = \frac{\Sigma \text{cumulative coarser}(\%)}{100} = \frac{305.56}{100} = 3.055$$

➤ **Specific gravity and Absorption of fine aggregate**

Where;

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A = mass of oven-dry specimen in air, g = 490

B = mass of pycnometer filled with water, g = 705.9

S = mass of the saturated surface-dry specimen, g = 500

C = mass of pycnometer with specimen and water to the calibration mark, g = 992.7

D = mass of original specimen, g = 495

$$\text{Absorption capacity} = \frac{S-A}{A} \times 100 = \frac{500-490}{490} \times 100 = 2.04\%$$

$$\text{Bulk Specific Gravity} = \frac{A}{B+S-C} = \frac{490}{705.9+500-992.7} = 2.3$$

$$\text{Bulk Specific Gravity(SSD)} = \frac{S}{B+S-C} = \frac{500}{705.9+500-992.7} = 2.35$$

$$\text{Apparent Specific Gravity} = \frac{A}{B+A-C} = \frac{490}{705.9+490-992.7} = 2.41$$

$$\text{Moisture Content} = \frac{D-A}{A} = \frac{495-490}{490} \times 100 = 1.02\%$$

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A-2 Coarse aggregate tests

➤ Sieve analysis of coarse aggregate

Sieve size (mm)	Retained weight (g)	Retained weight (%)	Cummulative retained (%)	Cummulative passed (%)	ASTM passing range (%)
25	177.6	3.552	3.552	96.448	95 - 100
19	1524.6	30.492	34.044	65.956	-
12.5	2001	40.02	74.064	25.936	25 - 60
9.75	1110	22.2	96.264	3.736	-
4.75	177.8	3.556	99.82	0.18	0 - 10
Pan	9	0.18	0	0	-
Sum	5000		307.744		

$$\text{Fineness modulus} = \frac{\Sigma \text{cumulative coarser}(\%)}{100} = \frac{307.744}{100} = 3.077$$

➤ Specific gravity and Absorption of coarse aggregate

Where;

D = Mass of original sample, g = 2000

A = Mass of oven dry sample in air, g = 1960

B = Mass of saturated – surface dry sample in air, g = 2007.5

C = Mass of saturated sample in water, g = 1181.5

$$\text{Absorption capacity} = \frac{B-A}{A} \times 100 = \frac{2007.5-1960}{1960} \times 100 = 2.42\%$$

$$\text{Bulk Specific Gravity} = \frac{A}{B-C} = \frac{1960}{2007.5-1181.5} = 2.373$$

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$$\text{Bulk Specific Gravity (SSD)} = \frac{B}{B-C} = \frac{2007.5}{2007.5-1181.5} = 2.43$$

$$\text{Apparent Specific Gravity} = \frac{A}{A-C} = \frac{1960}{1960-1181.5} = 2.518$$

$$\text{Moisture Content} = \frac{D-A}{A} = \frac{2000-1960}{1960} \times 100 = 2.04\%$$

➤ Unit weight of coarse aggregate

Where;

U = mass of the container, g = 4660

W = mass of sample + container, g = 14515

r = diameter of container, m = 0.1

h = height of container, m = 0.225

$$\text{Volume of container (V)} = \frac{\pi}{2} \times r^2 \times h = \pi \times 0.1^2 \times 0.225 = 0.0070686 \text{ m}^3$$

$$\text{Unit weight} = \frac{W-U}{V} = \frac{14515-4660}{0.0070686} = 1394.2 \text{ Kg/m}^3$$

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A-3 Waste Ceramic Coarse aggregate tests

➤ Sieve analysis of waste ceramic coarse aggregate

Sieve size (mm)	Retained weight (g)	Retained weight (%)	Cummulative retained (%)	Cummulative passed (%)	ASTM passing range (%)
25	86.5	1.73	1.73	98.27	95 - 100
19	1986	39.72	41.45	58.55	-
12.5	1459.5	29.19	70.64	29.36	25 - 60
9.75	1409.1	28.182	98.822	1.178	-
4.75	51.4	1.028	99.85	0.15	0 - 10
Pan	7.5	0.15	-	-	-
Sum	5000		312.492		

$$\text{Fineness modulus} = \frac{\Sigma \text{cumulative coarser}(\%)}{100} = \frac{312.492}{100} = 3.125$$

➤ Specific gravity and Absorption of waste ceramic coarse aggregate

Where;

D = Mass of original sample, g = 2000

A = Mass of oven dry sample in air, g = 1990

B = Mass of saturated – surface dry sample in air, g = 2064.5

C = Mass of saturated sample in water, g = 1100.1

$$\text{Absorption capacity} = \frac{B-A}{A} \times 100 = \frac{2064.5-1990}{1990} \times 100 = 3.744\%$$

$$\text{Bulk Specific Gravity} = \frac{A}{B-C} = \frac{1990}{2064.5-1100.1} = 2.063$$

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$$\text{Bulk Specific Gravity (SSD)} = \frac{B}{B-C} = \frac{2064.5}{2064.5-1100.1} = 2.141$$

$$\text{Apparent Specific Gravity} = \frac{A}{A-C} = \frac{1990}{1990-1100.1} = 2.236$$

$$\text{Moisture Content} = \frac{D-A}{A} = \frac{2000-1990}{1990} \times 100 = 0.503\%$$

➤ Unit weight of waste ceramic coarse aggregate

Where;

U = mass of the container, g = 4660

W = mass of sample + container, g = 12910

r = diameter of container, m = 0.1

h = height of container, m = 0.225

$$\text{Volume of container (V)} = \frac{\pi}{2} \times r^2 \times h = \pi \times 0.1^2 \times 0.225 = 0.0070686 \text{ m}^3$$

$$\text{Unit weight} = \frac{W-U}{V} = \frac{12910-4660}{0.0070686} = 1167.14 \text{ Kg/m}^3$$

Annex B – Concrete mix design

B-1: Mix design for C-25 concrete

Step 1:- Material physical properties

Test Description	Cement	Sand	Coarse Aggregate	Ceramic coarse Aggregate
Specific Gravity	3.15	2.3g/m ³	2.373g/cm ³	2.063g/cm ³
Unit Weight			1394.2Kg/m ³	1167.14Kg/m ³
Moisture Content		1.02%	2.04%	0.50%
Water Absorption		2.04%	2.42%	3.74%
Fineness Modulus(FM)		3.05%	3.07	3.125

Step 2: - Choice of Slump

According to ACI 211 Table: 6.3.1 (Recommended slumps for various types of construction), the recommended slump to address more frequent constructions of concrete we considered Beams, Columns, and reinforced walls whose slump ranges between 25mm to 100mm.

In accordance with ACI 211 Table 6.3.1 (Recommended slumps for various types of construction), we took into consideration reinforced walls, beams, and columns whose slump falls between 25 and 100 mm in order to address more common concrete constructions.

Step 3: - Choice of maximum aggregate size

Coarse aggregates =25mm

Step 4: - Estimation of Mixing water and Air content

From Table 6.3.3 of ACI standards (Approximate mixing water and air content requirements for different slumps and nominal maximum aggregates), considering non-air-entrained concrete and for non-air-entrained and slump of 75 mm-100 mm, the water in 1m³ of concrete is 192.815kg.

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Step 5: - Selection of Water to Cement ratio (W/C)

According to Table 6.3.4 (a) (Relationship between water – cement or water – cementitious materials ratio and compressive strength of concrete), for the slump of 75mm to 100mm, water to cement ratio is 0.61

Step 6: - Calculation of Cement content

$$\text{Cement content (kg/m}^3\text{) is } = \frac{\text{water in 1m}^3}{(w/c)} = \frac{192.815}{0.61} = 316.39\text{kg/m}^3 \approx 317\text{Kg/m}^3$$

Step 7: - Estimation of Coarse Aggregate (CA) content

According to Table 6.3.6 (Volume of coarse aggregate per unit volume of concrete), for Fineness modulus of fine aggregate (F.M) = 3 and Maximum aggregate size = 25mm.

The volume of oven dry – rodded coarse aggregate per cubic meter of concrete is 0.65. The mass of coarse aggregate can be estimated as:

$$\text{C.A} = 0.65 * \text{unit weight of coarse aggregate} = 0.65 * 1394.2 \text{ Kg/m}^3 = 906.23 \text{ Kg/m}^3$$

Step 8: - Estimation of fine Aggregates (FA) content

From the data gathered up to step 7 the volume of water, cement, and coarse aggregate can be calculated as follow;

$$\text{Volume of water} = 192.815 \text{ Kg} \approx 0.1928\text{m}^3$$

$$\text{Volume of cement} = \frac{\text{weight of cement in 1m}^3 \text{ concrete}}{\text{specific gravity of cement} \times 1000} = \frac{317\text{Kg}}{3.15\text{Kg/m}^3 \times 1000} = 0.1\text{m}^3$$

$$\text{Volume of coarse aggregate} = \frac{\text{weight of coarse agg. in 1m}^3 \text{ concrete}}{\text{specific gravity of coarse agg.} \times 1000} = \frac{906.23\text{Kg}}{2.373\text{Kg/m}^3 \times 1000} = 0.382\text{m}^3$$

Volume of air trapped = 0.01m³; as per the standard

$$\text{Volume of sand (fine aggregate)} = 1\text{m}^3 - 0.01\text{m}^3 - 0.1928\text{m}^3 - 0.1\text{m}^3 - 0.382\text{m}^3 = 0.3152\text{m}^3$$

Weight of fine aggregate = volume of fine aggregate * specific gravity of sand * 1000

$$= 0.3152\text{m}^3 * 2.3 \text{ g/m}^3 * 1000 = 725 \text{ Kg/m}^3$$

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Step 9: - Adjustment for aggregate moisture

If absorption capacity is greater than the moisture content of aggregate, we need to add water up to its moisture capacity.

$$\text{C.A water} = 2.42\% - 2.04\% = 0.38\%$$

$$\text{F.A water} = 2.04\% - 1.02\% = 1.02\%$$

$$\text{Total water required} = 192.815 + [0.38\% * 906.23 + 1.02\% * 725] = 203.654 \text{Kg/m}^3$$

The estimated ingredients for a meter cube of concrete are, therefore, summarized as follows.

No	Ingredients	Weight(Kg/m ³)
1	Water	203.65
2	Cement	317
3	Fine aggregate	725
4	Coarse aggregate	906.23

B-2: Mix design of M-1 (0%) concrete

The mix volume needed for the study was **0.03645m³**, based on the volume the following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645 \text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42 \text{Kg}$$

$$\text{Weight of Cement} = 0.03645 \text{m}^3 * 317 \text{ Kg/m}^3 = 11.6 \text{Kg}$$

$$\text{Weight of Fine aggregate} = 0.03645 \text{m}^3 * 725 \text{ Kg/m}^3 = 26.43 \text{Kg}$$

$$\text{Weight of Coarse aggregate} = 0.03645 \text{m}^3 * 906.23 \text{Kg/m}^3 = 33.03 \text{Kg}$$

M-1	Ingredients	Weight(Kg)
	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	33.03

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B-3: Mix design of M-2 (10%) concrete

The mix volume needed for the study was 0.03645m^3 , based on the volume replacement method 10% of the coarse aggregate is replaced with waste ceramic aggregate. By interpolating the volume of coarse aggregate from the needed volume of concrete mix, it is found that 0.01393m^3 volume of coarse aggregate are used. The following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645\text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42\text{Kg}$$

$$\text{Weight of Cement} = 0.03645\text{m}^3 * 317 \text{ Kg/m}^3 = 11.6\text{Kg}$$

$$\text{Weight of Fine aggregate} = 0.03645\text{m}^3 * 725 \text{ Kg/m}^3 = 26.43\text{Kg}$$

$$\text{Weight of Coarse aggregate} = (0.01393\text{m}^3 * 90\%) * 2.373\text{g/cm}^3 = 29.75\text{Kg}$$

$$\text{Weight of Ceramic aggregate} = (0.01393\text{m}^3 * 10\%) * 2.063\text{g/cm}^3 = 2.874\text{Kg}$$

	Ingredients	Weight(Kg)
M-2	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	29.75
	Ceramic aggregate	2.874

B-4: Mix design of M-3 (20%) concrete

The mix volume needed for the study was 0.03645m^3 , based on the volume replacement method 20% of the coarse aggregate is replaced with waste ceramic aggregate. By interpolating the volume of coarse aggregate from the needed volume of concrete mix, it is found that

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0.01393m³ volume of coarse aggregate are used. The following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645\text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42\text{Kg}$$

$$\text{Weight of Cement} = 0.03645\text{m}^3 * 317 \text{ Kg/m}^3 = 11.6\text{Kg}$$

$$\text{Weight of Fine aggregate} = 0.03645\text{m}^3 * 725 \text{ Kg/m}^3 = 26.43\text{Kg}$$

$$\text{Weight of Coarse aggregate} = (0.01393\text{m}^3 * 80\%)* 2.373\text{g/cm}^3 = 26.445\text{Kg}$$

$$\text{Weight of Ceramic aggregate} = (0.01393\text{m}^3 * 20\%)* 2.063\text{g/cm}^3 = 5.748\text{Kg}$$

	Ingredients	Weight(Kg)
M-3	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	26.445
	Ceramic aggregate	5.748

B-5: Mix design of M-4 (30%) concrete

The mix volume needed for the study was **0.03645m³**, based on the volume replacement method 30% of the coarse aggregate is replaced with waste ceramic aggregate. By interpolating the volume of coarse aggregate from the needed volume of concrete mix, it is found that **0.01393m³** volume of coarse aggregate are used. The following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645\text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42\text{Kg}$$

$$\text{Weight of Cement} = 0.03645\text{m}^3 * 317 \text{ Kg/m}^3 = 11.6\text{Kg}$$

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$$\text{Weight of Fine aggregate} = 0.03645\text{m}^3 * 725 \text{ Kg/m}^3 = 26.43\text{Kg}$$

$$\text{Weight of Coarse aggregate} = (0.01393\text{m}^3 * 70\%)* 2.373\text{g/cm}^3 = 23.139\text{Kg}$$

$$\text{Weight of Ceramic aggregate} = (0.01393\text{m}^3 * 30\%)* 2.063\text{g/cm}^3 = 8.621\text{Kg}$$

	Ingredients	Weight(Kg)
M-4	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	23.139
	Ceramic aggregate	8.621

B-6: Mix design of M-5 (40%) concrete

The mix volume needed for the study was **0.03645m³**, based on the volume replacement method 40% of the coarse aggregate is replaced with waste ceramic aggregate. By interpolating the volume of coarse aggregate from the needed volume of concrete mix, it is found that **0.01393m³** volume of coarse aggregate are used. The following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645\text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42\text{Kg}$$

$$\text{Weight of Cement} = 0.03645\text{m}^3 * 317 \text{ Kg/m}^3 = 11.6\text{Kg}$$

$$\text{Weight of Fine aggregate} = 0.03645\text{m}^3 * 725 \text{ Kg/m}^3 = 26.43\text{Kg}$$

$$\text{Weight of Coarse aggregate} = (0.01393\text{m}^3 * 60\%)* 2.373\text{g/cm}^3 = 19.84\text{Kg}$$

$$\text{Weight of Ceramic aggregate} = (0.01393\text{m}^3 * 40\%)* 2.063\text{g/cm}^3 = 11.5\text{Kg}$$

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M-5	Ingredients	Weight(Kg)
	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	19.84
	Ceramic aggregate	11.5

B-7: Mix design of M-6 (50%) concrete

The mix volume needed for the study was **0.03645m³**, based on the volume replacement method 50% of the coarse aggregate is replaced with waste ceramic aggregate. By interpolating the volume of coarse aggregate from the needed volume of concrete mix, it is found that **0.01393m³** volume of coarse aggregate are used. The following amount of material ingredients used in Kg.

$$\text{Weight of Water} = 0.03645\text{m}^3 * 203.654 \text{ Kg/m}^3 = 7.42\text{Kg}$$

$$\text{Weight of Cement} = 0.03645\text{m}^3 * 317 \text{ Kg/m}^3 = 11.6\text{Kg}$$

$$\text{Weight of Fine aggregate} = 0.03645\text{m}^3 * 725 \text{ Kg/m}^3 = 26.43\text{Kg}$$

$$\text{Weight of Coarse aggregate} = (0.01393\text{m}^3 * 50\%)* 2.373\text{g/cm}^3 = 16.53\text{Kg}$$

$$\text{Weight of Ceramic aggregate} = (0.01393\text{m}^3 * 50\%)* 2.063\text{g/cm}^3 = 14.37\text{Kg}$$

M-6	Ingredients	Weight(Kg)
	Water	7.42
	Cement	11.6
	Fine aggregate	26.43
	Coarse aggregate	16.53
	Ceramic aggregate	14.37

Annex C - Results of Mechanical Properties

C-1 compressive strength at room temperature for each sample

Waste ceramic aggregate in (%)	sample N°	Weight (Kg)	Load (KN)	Compressive strength (Mpa)	Average compressive strength(Mpa)
0%	1	7.586	572.5	25.45	25.815
	2	7.619	589.2	26.18	
10%	1	7.635	571.8	25.41	25.49
	2	7.873	575.3	25.57	
20%	1	7.551	592.3	26.33	26.165
	2	7.58	584.9	26	
30%	1	7.624	634.9	28.22	27.655
	2	7.539	609.5	27.09	
40%	1	7.825	693.3	30.81	29.86
	2	7.898	650.6	28.91	
50%	1	7.413	567.1	25.2	24.315
	2	7.359	527.2	23.43	

Table C-1. compressive strength at room temperature

C-2 Compressive strength of all specimens cooled with Air after exposed to high temperature

Waste ceramic aggregate in (%)	sample N°	Weight (Kg)	Load (KN)	Compressive strength (Mpa)	Average compressive strength(Mpa)
0%	1	6.78	401.8	17.86	18.155
	2	6.754	415	18.45	
10%	1	6.937	404	17.96	16.76
	2	7.022	350.1	15.56	
20%	1	6.686	430.4	19.13	17.83
	2	6.766	371.9	16.53	
30%	1	6.773	493.4	21.93	19.04
	2	6.906	363.15	16.15	
40%	1	7.129	460.9	20.48	21.58
	2	7.169	510.2	22.68	
50%	1	6.685	363.9	16.17	16.04
	2	6.593	357.9	15.91	

Table C-2. Compressive strength of specimens cooled with air

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement

C-3 Compressive strength of all specimens cooled with Water after exposed to high temperature

Waste ceramic aggregate in (%)	sample N°	Weight (Kg)	Load (KN)	Compressive strength (Mpa)	Average compressive strength(Mpa)
0%	1	6.884	420.5	18.69	20.145
	2	6.849	486.1	21.6	
10%	1	7.068	410.4	18.24	18.265
	2	6.943	411.7	18.29	
20%	1	7.028	455	20.22	20.02
	2	6.853	445.9	19.82	
30%	1	6.876	501.6	22.29	21.4
	2	6.887	461.6	20.51	
40%	1	7.346	503.5	22.37	22.48
	2	7.119	508.2	22.59	
50%	1	6.835	370.1	16.45	16.32
	2	6.803	364.2	16.19	

Table C-3. Compressive strength of specimens cooled with water

C-4 Residual Compressive strength in percentage of specimens cooled with Water and Air after exposed to high temperature

Waste ceramic aggregate in (%)	At room temperature	After being under high temperature cooled with		Residual compressive strength in percentage	
		Air	Water	Air	Water
	compressive strength(Mpa)	compressive strength(Mpa)	compressive strength(Mpa)	Air	Water
0%	25.815	18.155	20.145	70.33	78.04
10%	25.49	16.76	18.265	65.75	71.66
20%	26.165	17.83	20.02	68.14	76.51
30%	27.655	19.04	21.4	68.85	77.38
40%	29.86	21.58	22.48	72.27	75.28
50%	24.315	16.04	16.32	65.97	67.12

Table C-4. Residual Compressive strength of specimens in percentage

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse
Aggregate as Partial Replacement

Annex D - Results of Durability Properties

D-1 Mass – loss

Waste ceramic aggregate in (%)	Cooling method	sample N ^o	Before weight (Kg)	After Weight (Kg)	weight loss(%)	Average weight loss(%)
0%	Air	1	7.466	6.78	9.19	9.20
		2	7.44	6.754	9.22	
	Water	1	7.472	6.884	7.87	7.66
		2	7.4	6.849	7.45	
10%	Air	1	7.574	6.937	8.41	8.69
		2	7.714	7.022	8.97	
	Water	1	7.666	7.068	7.80	7.17
		2	7.428	6.943	6.53	
20%	Air	1	7.276	6.686	8.11	8.42
		2	7.414	6.766	8.74	
	Water	1	7.618	7.028	7.74	7.59
		2	7.404	6.853	7.44	
30%	Air	1	7.408	6.773	8.57	8.53
		2	7.546	6.906	8.48	
	Water	1	7.352	6.876	6.47	6.50
		2	7.368	6.887	6.53	
40%	Air	1	7.664	7.129	6.98	7.21
		2	7.746	7.169	7.45	
	Water	1	7.714	7.346	4.77	5.83
		2	7.646	7.119	6.89	
50%	Air	1	7.344	6.685	8.97	8.98
		2	7.244	6.593	8.99	
	Water	1	7.332	6.835	6.78	6.80
		2	7.301	6.803	6.82	

Table D-1. Mass loss of specimens cooled with Air and Water

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement

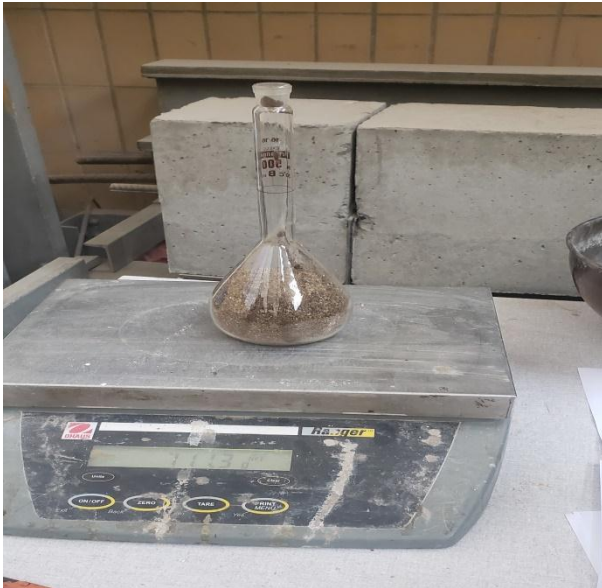
D-2 Density Reduction

Waste ceramic aggregate in (%)	Cooling method	sample N ^o	Before weight (g)	Before density (g/cm ³)	After Weight (g)	After density (g/cm ³)	Average Density loss (%)
0%	Air	1	7466	2.21	6780	2.01	9.20
		2	7440	2.20	6754	2.00	
	Water	1	7472	2.21	6884	2.04	7.66
		2	7400	2.19	6849	2.03	
10%	Air	1	7574	2.24	6937	2.06	8.69
		2	7714	2.29	7022	2.08	
	Water	1	7666	2.27	7068	2.09	7.18
		2	7428	2.20	6943	2.06	
20%	Air	1	7276	2.16	6686	1.98	8.43
		2	7414	2.20	6766	2.00	
	Water	1	7618	2.26	7028	2.08	7.60
		2	7404	2.19	6853	2.03	
30%	Air	1	7408	2.19	6773	2.01	8.53
		2	7546	2.24	6906	2.05	
	Water	1	7352	2.18	6876	2.04	6.50
		2	7368	2.18	6887	2.04	
40%	Air	1	7664	2.27	7129	2.11	7.22
		2	7746	2.30	7169	2.12	
	Water	1	7714	2.29	7346	2.18	5.83
		2	7646	2.27	7119	2.11	
50%	Air	1	7344	2.18	6685	1.98	8.98
		2	7244	2.15	6593	1.95	
	Water	1	7332	2.17	6835	2.03	6.80
		2	7301	2.16	6803	2.02	

Table D-2. Density loss of specimens cooled with Air and Water

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Annex E – Pictures taken during the picture



Pictures take while working on sand physical properties



Pictures taken while casting concrete

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement



Pictures taken while mixing concrete



Picture of the inside of conventional concrete (0%)

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement



Pictures of the concrete mix 30% and 40% replacement of ceramic aggregate(inside)

High-Temperature Performance of Concrete Utilizing Waste Ceramic Coarse Aggregate as Partial Replacement



Pictures of the compressive test, and cubes after the test the first cube being at room temperature and the later being after exposed to high temperature