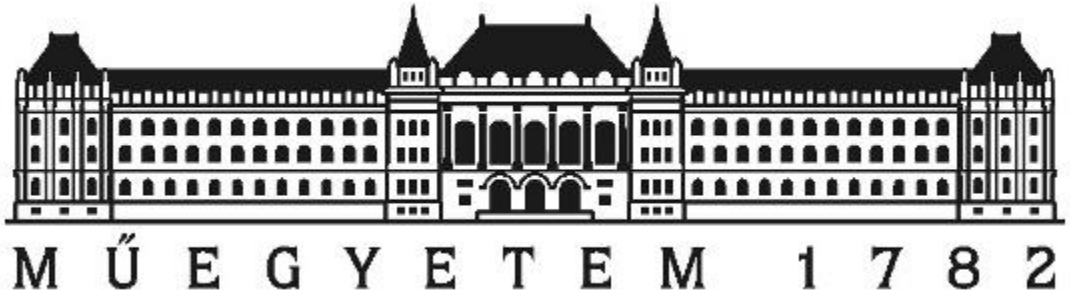

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EFFECTS OF AGGREGATE TYPE ON CONCRETE SUBJECTED TO ELEVATED TEMPERATURES

Ph.D. thesis

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DECLARATION OF AUTHENTICITY

I declare that the contents and the work described in this thesis were performed at the Budapest University of Technology and Economics, Faculty of Civil Engineering. I certify that all material presented in this dissertation is either my own work or acknowledged wherever adapted from other sources.

ACKNOWLEDGMENTS

بِسْمِ اللَّـهِ الرَّحْمَـٰنِ الرَّحِيمِ

رَبِّ أَوْزِعْنِي أَنْ أَشْكُرَ نِعْمَتَكَ الَّتِي أَنْعَمْتَ عَلَيَّ وَعَلَىٰ وَالِدَيَّ وَأَنْ أَعْمَلَ صَالِحًا تَرْضَاهُ وَأَدْخِلْنِي بِرَحْمَتِكَ فِي عِبَادِكَ الصَّالِحِينَ

In the Name of Allah, Most Gracious, Most Merciful

"My Lord! Grant me that I should be grateful for Your favour which You have bestowed on me and on my parents, and to do good deeds that You are pleased, and admit me, by Your mercy, among Your righteous servants" *(The Qur'an, Al-Naml 19)*

My deepest gratitude to my beloved family. Special thankfulness to my dear Father; you have been the symbol of sacrifice, faith, and giving, and to the moon of my life, my dear Mother, your blessings and prayers have been the secret behind my achievements.

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SUMMARY

Concrete, the backbone of modern infrastructure, exhibits varying mechanical behaviour that depends on its components, with aggregates playing a crucial role in its strength and durability. The work presented in this thesis investigates the effect of aggregate type on concrete properties when subjected to elevated temperatures. The research is motivated by the need to understand the behaviour of concrete under high temperatures, considering the increasing global demand for construction materials and the environmental impact of concrete waste. The study variables include five different coarse aggregates, the three concrete ages, five elevated temperatures up to 1000 ℃, in addition to the ambient temperature and the fibre content. Ten concrete mixes tested for fresh properties, physical properties, mechanical strength, and thermal response after subjecting to elevated temperatures. A comprehensive evaluation of concrete mixes was conducted using quartz, andesite, expanded clay, expanded glass coarse and crushed clay bricks aggregates. Representing three main aggregates categories, natural aggregates, lightweight aggregates and recycled aggregates, respectively; for each coarse aggregate type, concrete mixtures were made with the same amount of Portland cement, water-cement ratio, natural sand and superplasticizers. The findings provide valuable insights into concrete properties under elevated temperatures. Regarding fresh properties, lightweight aggregates resulted in lower fresh densities, while quartz aggregate exhibited higher densities. The presence of PP fibres had minimal impact on fresh density. Air content varied between mixtures, with slightly higher values observed in fibre-reinforced mixtures. In terms of physical properties, moisture content decreased as the concrete aged, providing insights into its behaviour during thermal exposure. Hardened density remained relatively stable, with a gradual decrease over time. Weight loss percentages increased with higher temperatures, influenced by aggregate composition and fibre inclusion. Mechanically, compressive strength improved over time regardless of aggregate type, with andesite aggregates demonstrating higher strength. Flexural and shear strength generally decreased with increasing temperature, but certain mixtures exhibited improved resilience based on their aggregate types. Thermal properties analysis showed that aggregate type significantly affected thermal conductivity, with lightweight aggregates demonstrating better thermal performance. The inclusion of polypropylene fibres enhanced crack control and initial shear strength but did not prevent strength reduction at high temperatures.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AN	Andesite aggregate
°C	Celsius degree
C&D	Construction and demolition
CB	Clay bricks
C-S-H	Calcium Silicate Hydrate
EC	Expanded clay aggregate
EG	Expanded glass aggregate
HPC	High-performance concrete
HSC	High strength concrete
ITZ	Interfacial transition zone
LWA	Lightweight aggregates
LWAC	Lightweight aggregates concrete
LWC	Lightweight concrete
OC	Ordinary concrete
OPC	Ordinary Portland cement
PP	Polypropylene fibres
QZ	Quartz aggregate
RAC	Recycled aggregate concrete
RCA	Recycled concrete aggregate
SEM	Scanning electron microscope
TGA	Thermogravimetric analysis
UHPC	Ultra-High Performance Concrete
w/c	Water to cement ratio
M1-QZ	Concrete mix number 1, made using quartz river aggregates.
M2-AN	Concrete mix number 2, made using andesite aggregates.
M3-EC	Concrete mix number 3, made using expanded clay aggregates.
M4-EG	Concrete mix number 4, made using expanded glass aggregates.
M5-CB	Concrete mix 5, made using crushed clay bricks aggregates.
M6-QZPP	Concrete mix 6, made using quartz river aggregates and polypropylene fibres.
M7-ANPP	Concrete mix 7, made using andesite aggregates and polypropylene fibres.
M8-ECPP	Concrete mix 8, made using expanded clay aggregates and polypropylene fibres.
M9-EGPP	Concrete mix 9, made using expanded glass aggregates and polypropylene fibres.
M10-CBPP	Concrete mix 10, made using crushed clay bricks aggregates and polypropylene fibres.

CHAPTER 1 : INTRODUCTION

1.1. Introduction and research significance

Over time, the human needs on the earth are changing due to the increase in population. Construction is one of the things that humanity has always needed [1]. Today, at the beginning of the 21st century, it is undeniable that concrete was the primary construction material of the twentieth century and is likely to remain during the current century. Concrete is a worldwide building material that consumes large amounts of raw materials. Concrete structure raw materials can be found almost anywhere and can be moulded easily. Nevertheless, the concrete industry produces a lot of waste, and the old concrete often goes to landfills [2,3].

During the structural design of buildings, fire resistance is an essential factor that must be considered [4]. Construction materials can maintain their intended load-bearing capabilities when subjected to fire. Material selection plays a significant role in fire resistance and can minimise structural failure and save lives [5]. The construction industry provides a wide range of materials whose structural behaviour is affected by temperature to varying degrees. Concrete has recently become one of the most popular building materials for various structures. While information and research concerning concrete characteristics at ambient temperature are common, the behaviour at elevated temperatures must be extensively researched [6].

The behaviour of concrete under elevated temperatures is directly influenced by factors such as the temperature of exposure, mixture composition, moisture content, heat exposure duration, cooling methods, and the properties of its individual components [5,7,8]. Aggregates compose around 70% of the concrete structure [9], which greatly influences the thermal response of concrete and its mechanical and physical properties. Therefore, aggregates have a crucial effect on the phenomena exhibited by concrete under elevated temperatures.. Various observations clearly show aggregate effects on concrete behaviour at elevated temperatures [10,11].

For instance, Khoury et al. [12] observed that the stresses caused by the difference in the thermal expansion coefficients between the coarse aggregate and the hardened cement paste contribute to the appearance of micro-cracks in the cement paste, subsequently reducing the concrete's strength.

This research studies the behaviour of concrete under ambient and elevated temperatures to determine the effect of different coarse aggregate types on concrete properties. A series of experimental tests were conducted using ten selected concrete composites, which differ in the type

of coarse aggregate used and the fibre content, coarse aggregates used to represent different concrete categories, ordinary concrete (OC), lightweight concrete (LWC) and recycled aggregate concrete (RAC).

1.2. Aim and objectives

The study aims to investigate the effect of aggregate type on concrete properties after subjecting to elevated temperatures at different ages, considering the incorporation of fibres.

To achieve this objective, a series of laboratory experiments will be conducted on concrete specimens. The experiments will involve the use of different types of aggregates, including natural, lightweight (artificial) and recycled aggregates, to assess their impact on the hardened properties of concrete. Polypropylene fibres will also be incorporated into the concrete mixes to evaluate their influence on the overall behaviour. The experimental program will study various parameters, such as different ages of concrete specimens, levels of elevated temperatures, and varying fibre contents. The investigation will focus on analysing properties that are directly interconnected to the concrete macro/microstructure. These properties include mechanical properties such as compressive strength, flexural tensile strength, shear strength and any observable changes in the microstructure, physical properties such as density, moisture content and the weight loss, thermal properties including the thermal conductivity.

By specifying the controlled and variable parameters, the main objectives of this PhD thesis can be outlined as follows:

1- Investigate the effect of aggregate types on the fresh properties of concrete.
2- Evaluate the effect of aggregate types on the mechanical properties of concrete.
3- Evaluate the effect of using polypropylene microfibre on the physical and mechanical properties of concrete made with different aggregate types.
4- Study the effect of concrete age on the properties of concrete made with different aggregate types.
5- Evaluate the effect of elevated temperatures on the properties of concrete made with different aggregate types.
6- Investigate the influence of using polypropylene microfibre on the physical and mechanical properties of concrete made with different aggregate types after subjected to elevated temperatures.

7- Study the effect of concrete age on the properties of concrete made with different aggregate types after subjected to elevated temperatures.
8- Investigate the effect of using different aggregates derived from the same base materials on concrete's mechanical and thermal properties.
9- Utilize the Hungarian andesite as a coarse aggregate for structural concrete and evaluate its performance in comparison to other aggregate types.

These objectives will contribute to a comprehensive understanding of how aggregate type, fibre content, and concrete age interact and affect the properties of concrete under elevated temperature conditions. The findings will provide valuable insights for the development of more resilient and durable concrete structures under elevated temperature conditions.

1.3. Research outline

This thesis is divided into six chapters.

- Chapter 1 Following this introductory chapter.
- Chapter 2 provides a review of the literature relevant to the research presented within this thesis. The review covers main findings in the literatures and the previous studies about the behaviour of natural, lightweight and recycled aggregate concretes at both ambient and high temperatures. Effects of age on concrete properties and the influence of using fibres on the concrete behaviour under elevated temperature.
- Chapter 3 will explain the experimental program, methodology, and material properties, including description and testing for each type of the used materials, testing methods and evaluations and mixing design approaches.
- Chapter 4 will present and discuss the testing results. Results comprehensive analysis and description for the effects of concrete fresh, physical, thermal and mechanical properties in the case of using different types of coarse aggregates.
- Chapter 5 will cover the main conclusions which emerge throughout this study. The limitations and conditions of this research and offers suggestions for further studies in the field.
- Finally, Chapter 6 will briefly highlight the new scientific results and novel findings obtained from the research. It emphasises all significant contributions or advancements made in understanding the effects of aggregate type on concrete properties under elevated temperatures.

CHAPTER 2 : LITERATURE REVIEW

This chapter covers an overview of the use of different aggregate types on concrete, the concrete properties at different ages and the effects of fibres on concrete behaviour and state of the art for concrete fire resistance and their properties after subjected to elevated temperatures.

2.1. Introduction

The concept of creating concrete by combining stones, sand, and cement or binding has been recognised since ancient times, dating back to the Stone Age [13]. The Romans made notable contributions to the development of concrete technology, pioneering advances such as pozzolanas, experimentation with reinforced concrete using bronze bars, and the introduction of lightweight, air-entrained concrete. While initially included as bulking materials, the writings of *Vitruvius in De Architectura* revealed that the Romans understood the significance of rock types and particle size distribution in selecting aggregates for high-quality concrete and mortars [8,14].

Generally, concrete is considered a fire-resistant material due to the nature of the constituent materials, essentially inert, low thermal conductivity, and high heat capacity [4–6]. The degradation of concrete resulting from the action of high temperatures is slow and complex. When concrete is exposed to heat temperatures over 100 °C, the heterogeneity of concrete is enhanced due to the physical, chemical, and mineralogical transformations that occur in the cement paste and the aggregate, with consequent degradation of mechanical properties [15–19]. These transformations include evaporation of the moisture in the concrete, decomposition of the C-S-H gel, conversion of calcium hydroxide to calcium oxide, and crystalline phase changes in the aggregates. Heat also causes changes in the pore structure of the hydrated cement paste and cracking associated with differential thermal expansions between aggregates and paste [20,21].

The behaviour of concrete under elevated temperatures is directly influenced by several factors, including the exposed temperature, mixture composition, moisture content, heat exposure time, cooling mode, and properties of individual components [5,7,8]. As the aggregates compose the largest part of concrete components by around 70%, that leads to a significant impact on the thermal response and mechanical properties of concrete by the aggregate type [9,22–24]. Observations have shown that aggregate type plays a crucial role in concrete behaviour at elevated temperatures, as shown in Figure 2-1 and Figure 2-2, as the difference in thermal expansion

coefficients between coarse aggregates and hardened cement paste can lead to micro-cracks and reduced strength [11,12,25]. Additionally, factors such as stress differentials, moisture content, heat exposure time, cooling mode, and specific test conditions affect concrete behaviour at high temperatures [8,16,26].

In summary, understanding the effects of aggregate type on concrete subjected to elevated temperatures is crucial for comprehending the behaviour of concrete under such conditions. It is evident that aggregates significantly influence concrete's thermal response and mechanical properties. Furthermore, concrete degradation mechanisms at high temperatures are complex and involve various transformations and changes in its microstructure. The mechanical properties are fundamental parameters for understanding and predicting the behaviour of concrete structures at elevated temperatures. Studies concerning the behaviour of concrete made with natural aggregates, lightweight and recycled aggregates concrete, in addition to factors such as age and fibre content, will be mentioned briefly in the following section, concerning various concrete properties, especially the mechanical such as compressive strength, tensile strength, and shear strength.

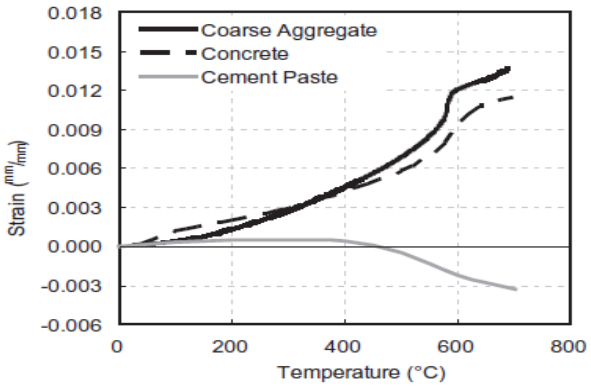


Figure 2-1. Thermal expansion of concrete constituent material [27]

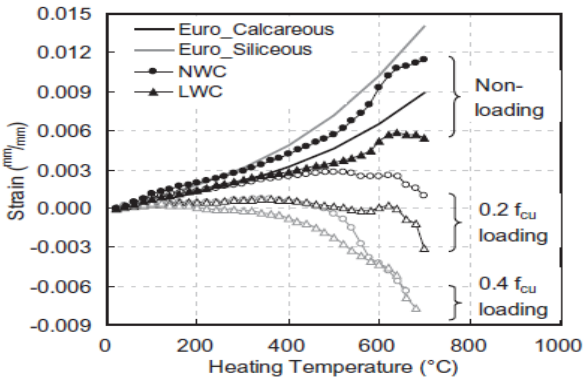


Figure 2-2. Thermal expansion and total strain by coarse aggregate type [27]

2.2. The behaviour of natural aggregate concrete at elevated temperature

Concrete made with natural aggregates exhibits various physicochemical changes that affect its thermo-mechanical properties when exposed to high temperatures. The current knowledge of the behaviour of these concretes are widely known. Under heating, several physicochemical changes occur, resulting in the material's mechanical properties deterioration depending on the temperature range. Over the past few decades, extensive studies have been conducted on the high-temperature mechanical properties of concrete made with natural aggregates (NA).

Initially, slow capillary water loss occurs as the temperature rises from 20 °C to 80 °C, accompanied by water expansion [17,28]. From 80 °C to 100 °C, ettringite (a mineral in the cement paste) dehydrates and decomposes, leading to the physical bonding of water in aggregates and the cement matrix evaporating. This process increases capillary porosity and microcracking [28–30]. Between 100 °C and 200 °C, concrete continues to lose water, and the calcium silicate hydrate (C-S-H) in the cement paste starts to dehydrate and decompose, forming αC_2S [29]. Additionally, between 120 °C and 300 °C, the cement gel layers move closer, resulting in increased *Van der Waals* forces [19,31,32]. This can increase strength up to 300 °C, and hydration of unhydrated cement grains may also occur, contributing to a constant or increased strength. Up to 350 °C, water loss is almost complete and intensifies, and C-S-H continues to decompose, further increasing porosity and microcracks. Beyond 300 °C, concrete experiences significant loss of strength and stiffness [19,29].

From 400 °C to 600 °C, portlandite (CH) decomposes, contributing to microcracking in the cement paste [28,29]. Siliceous aggregates containing quartz transformation at 573 °C [17,29]. From 600 °C to 800 °C, a second phase of C-S-H decomposition occurs, resulting in a substantial loss of compressive strength [17] Figure 2-3 shows the cracking of concrete after subjected to 600 °C on the microstructure level. Dehydrated phases begin to melt at severe temperatures from 800 °C and up to 1200 °C, causing intense microcracking. Depending on their mineralogical composition, aggregates also start to melt at temperatures above 1000 °C [17,29].

Apart from phase changes and reactions, heating creates a thermal mismatch between the cement paste and aggregates. When heated, cement paste first expands but rapidly after 100 °C. The cement paste shrinks while most aggregates expand, leading to thermal-induced stresses [12,18]. These stresses can generate microcracks in the interfacial transition zone (ITZ) and the cement paste, contributing to the degradation of mechanical properties. The selection of aggregates influences the thermal stability of concrete at high temperatures since they occupy a significant volume of the concrete (60% to 80%). The behaviour of aggregates under heating depends on their mineralogical and chemical compositions as well as their petrographic origin.

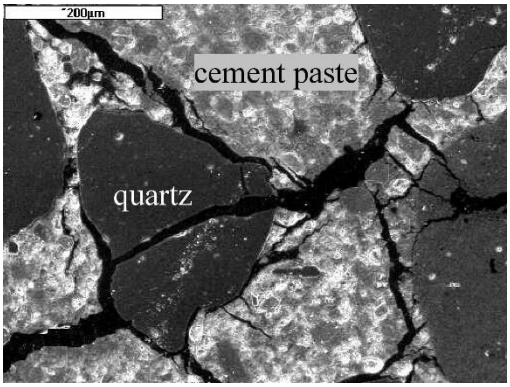


Figure 2-3. Microstructure photo for concrete after exposure to 600 °C [17]

In terms of mechanical properties, the fire response of the concrete made with natural aggregate depends on the aggregate type, thermal, mechanical, and deformation properties. Several fundamental parameters are considered, including compressive strength, modulus of elasticity, tensile strength, and stress-strain response. Kodur [33] compiled and compared experimental results with standard recommendations. Figure 2-4 and Figure 2-5 illustrate the relative evolution (ratio between high-temperature and room-temperature properties) of compressive strength and tensile strength with temperature. Moreover, Figure 2-6 to *Figure 2-9* presented the relative values after being subjected to elevated temperatures of different regimes from 100 °C to 1000 °C. These figures incorporate data from Eurocode (EN 1991-1-2) [34], ASCE (American Society of Civil Engineers) [35] as well as findings from published literature sources [19,36–39].[19]

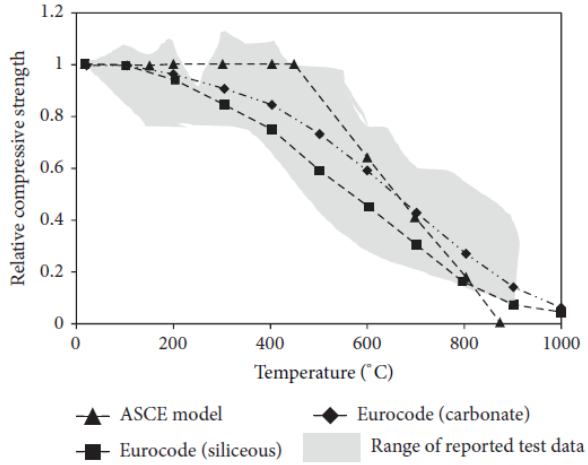


Figure 2-4. Variation of relative compressive strength of normal strength concrete as a function of temperature [33]

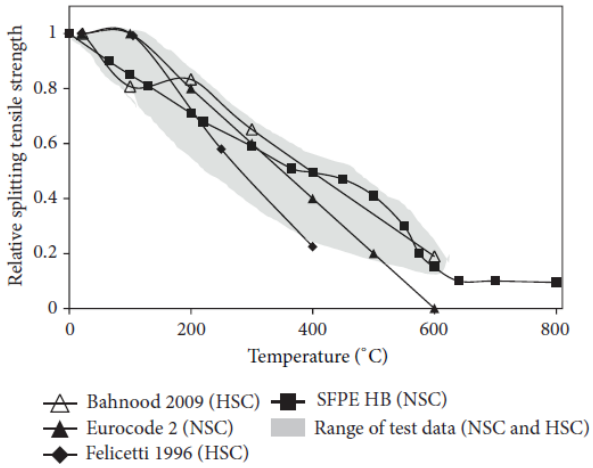


Figure 2-5. Variation in relative splitting tensile strength of concrete as a function of temperature [33]

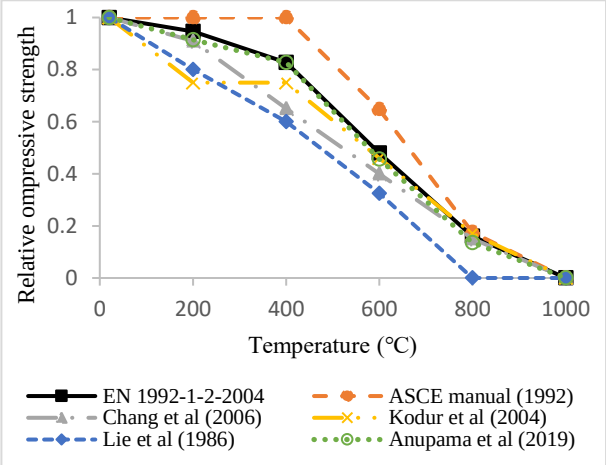


Figure 2-6. Relative compressive strength models from literatures [33–35,37–39]

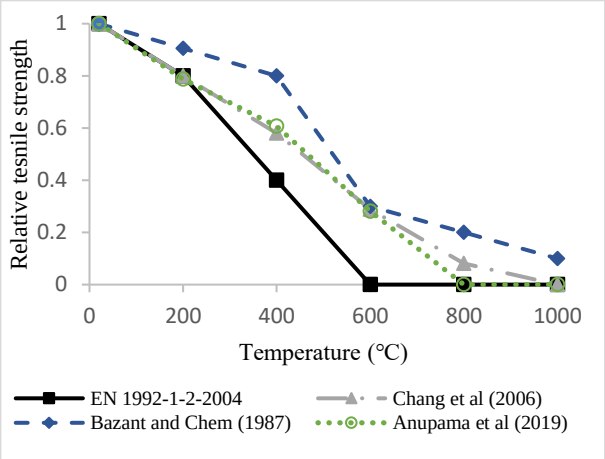


Figure 2-7. Relative tensile strength models from literatures [34,36–38]

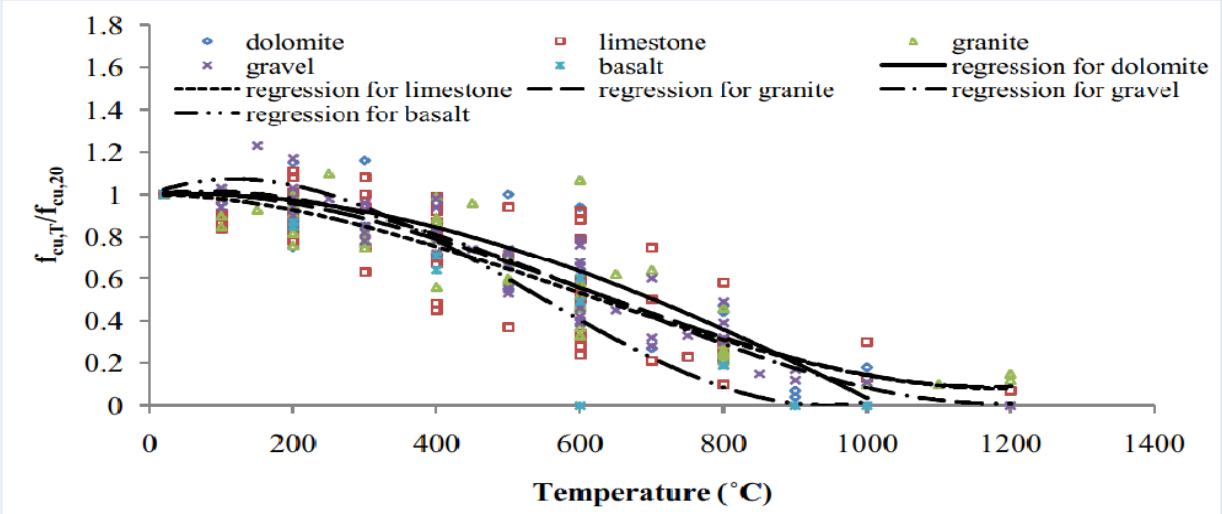


Figure 2-8. Influence of type of aggregate on residual compressive strength of concrete subjected to elevated temperatures [19]

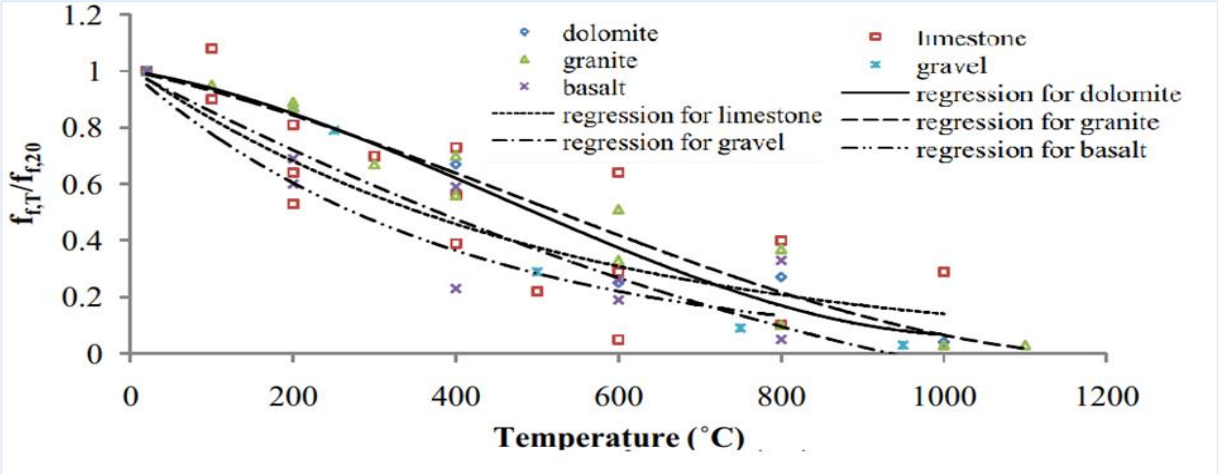
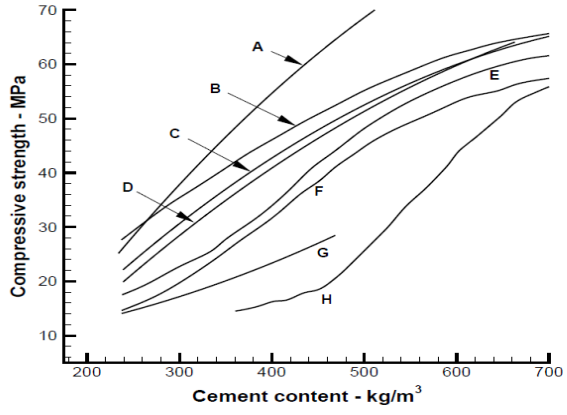


Figure 2-9. Influence of type of aggregate on residual flexural strength of concrete subjected to elevated temperatures [19]

2.3. The behaviour of lightweight aggregate concrete at elevated temperatures

Lightweight aggregate concrete is classified according to its density; according to the EN 206-1, and ACI 213R-03 standards, lightweight aggregate concrete (LWAC) is concrete with a density (801 to 2000) kg/m^3, and (1120 and 1920) kg/m^3, respectively [40], [41]. Therefore, density is the main factor in defining the lightweight concrete (LWC). Lightweight aggregate concrete (LWAC) was presented for the first time by the Romans 2000 years ago, *The Port of Cosa* was built in 273 B.C using lightweight concrete made from natural volcanic materials, on 27 B.C *The Pantheon* was built also using LWC, and the amazing *Coliseum* built-in 75 to 80 A.D. using crushed volcanic lava for foundations and crushed brick aggregate for walls [41].

Lightweight aggregate concrete's main characteristics and attractiveness are lower density and better thermal insulation. These advantages include reduced dead load, fasting building rates in construction, and lower transporting and handling costs. Roman buildings like Pantheon and Coliseum, built with lightweight concrete material, are still standing eminently in Rome until now for about 18 centuries, showing that lighter materials can be used in concrete construction and bringing economic advantages [42]. Lightweight aggregate concrete consists of normal and artificial lightweight aggregate such as crushed clay bricks, oil palm shells, expanded glass, and lightweight expanded clay aggregate [44][45]. Compared to normal-weight concrete, lightweight concrete generally exhibits lower mechanical strength, requiring higher cement content [8,43,44] as depicted in Figure 2-10.



A) Normal-weight concrete.
B) Sintered fly ash and normal-weight fine aggregate
C) Blast furnace slag and normal-weight fine aggregate
D) Sintered fly ash
E) Sintered shale
F) Expanded slate
G) Expanded clay and sand
H) Expanded slag

Figure 2-10. The relationship between compressive strength and cement content at 28 days age for normal weight and various *lightweight aggregate concretes with a slump of 50 mm* [43–45]

The influence of particle size on the mechanical strength of lightweight aggregate concrete is complicated compared to normal-weight concrete. In relation to particle size, the volume fraction

of lightweight aggregates plays a more prominent role [46,47]. Chen et al. [48] finds that the compressive strength of expanded shale lightweight concrete increases as the maximum size of aggregate particles decreases. This increase can reach up to 40% when using a particle size of 12.5 mm instead of 19 mm, with a density ranging from 500 to 800 kg/m^3. However, this increase is limited by the total porosity of the lightweight aggregate within the concrete mix. When the porosity reaches around 25%, there is no significant effect on compressive strength.

The high porosity of lightweight aggregates is also considered a significant factor, resulting in lower thermal conductivity. Thermal conductivity in lightweight aggregate concrete (LWAC) is typically 40-53% lower than in normal-weight concrete [49]. Additionally, the higher porosity of lightweight aggregates leads to more porous concretes, which affects permeability. The permeability of LWAC increases to varying degrees depending on the porous network of the aggregate and the presence or absence of a thick outer shell. The porous structure within lightweight aggregates can vary significantly depending on the type, ranging from predominantly closed pores in expanded shale to mostly open pores in certain types of expanded clays and pumice. These differences in porous structure influence the permeability of lightweight aggregate concrete and the paths through which fluids can migrate.

Despite their good thermal stability, artificial lightweight aggregates have higher porosity and water absorption than ordinary aggregates. The water absorption capacity of lightweight aggregate affects the density of lightweight concrete due to the increase in specific gravity when the aggregate absorbs water [50]. Calculating the water absorbed by the aggregate particles is crucial for designing lightweight concrete mixtures [44]. This affects the thermo-physical and water transfer properties of lightweight concrete. The presence of lightweight aggregates affects concrete's thermal gradient, liquid pressure, and water vapour pressures under high-temperature conditions.

Previous research has shown that lightweight aggregate concrete (LWAC) generally maintains slightly better mechanical properties compared to normal-weight concrete (NWC) after exposure to ISO fire conditions. However, in the case of lightweight aggregate, the behaviour of each aggregate type varies, exhibiting different deformations in response to temperature changes [51] Figure 2-11 illustrates the strong influence of aggregate type on the behaviour of concrete exposed to high temperatures. LWAC typically experiences a loss of around 50% and 91% of its initial compressive and tensile strength, respectively [52]. Studies on pumice-based lightweight

aggregates have demonstrated that LWAC retains a higher relative compressive strength at elevated temperatures compared to NWC [53]. Cracks in pumice-based LWAC tend to follow a weak and porous zone inside the aggregate rather than the ITZ [54]. The cooling regime after exposure to high temperatures also influences the residual mechanical strength of LWAC [55]. The difference in tensile strength behaviour between LWAC and NWC can be attributed to reduced kinematic incompatibility between coarse aggregates and cement paste due to water expulsion from lightweight aggregates and the smaller stiffness of these aggregates [56]. LWAC also exhibits lower thermal strain than NWC, indicating good resistance to high temperatures [27]. Cooling the specimens to room temperature before conducting compressive strength tests is necessary since the heated specimens exhibit higher residual compressive strength than those tested at room temperature [57]. At approximately 200 °C elevated temperature, an initial decrease in compressive strength is observed for regular concrete containing quartz gravel and limestone, followed by a temporary increase. The temporary loss of concrete strength can be attributed to the different coefficients of thermal conductivity of the cement matrix and aggregate [58]. As the temperature increases, micro-cracks appear on the boundary surface between the aggregate particles and cement matrix due to the thermal expansion of both materials. With further temperature rise, these cracks close due to the expanding aggregate. Up to 400 °C, the strength values decrease, and the cracking of the cement matrix can explain this reduction. Beyond 400 °C, the effect of aggregate type on concrete strength differs significantly and should be discussed separately. In normal concrete with quartz aggregate (strength classes ranging from C20/25 to C50/60), the extent of strength reduction is approximately 40% up to 550 °C. However, the reduction is around 20% in the expanded clay lightweight aggregate. The strength reduction in concrete exposed to temperatures between 450 °C and 550 °C is caused by the decomposition of portlandite and the differential heat expansion of the aggregate and cement matrix [51,52].

Yao et al. [59] compared to regular concrete with lightweight aggregate concrete after being subjected to high temperatures, and they showed that all-lightweight shale ceramics aggregate concrete has a great advantage due to its high-temperature performance. All-lightweight shale ceramics aggregate concrete specimen remains intact, without any damage and peeling, after 1000 °C exposure. Under this temperature, the mass and compressive strength loss are 11.56% and 71.7%, respectively, while under the same temperature, these values for the normal concrete are 27.01% and 88.5%, respectively. Furthermore, the strength loss rate of the semi lightweight shale

ceramics aggregate concrete is similar to the normal concrete because of the multiple effects of high-temperature softening of calcareous gravel, high-temperature decomposition, and decomposition of the cement paste. In contrast, the ceramsite lightweight aggregate is an excellent high-temperature resistant material, resulting in a limited loss of mass and strength after exposure.

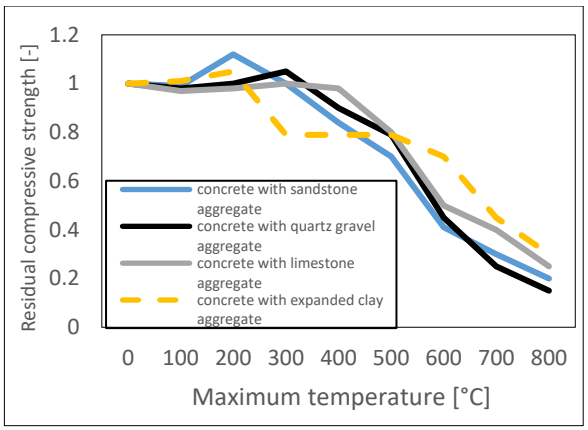


Figure 2-11. Changing of residual compressive strength of concrete at high temperature as a function of the type of the aggregate [51]

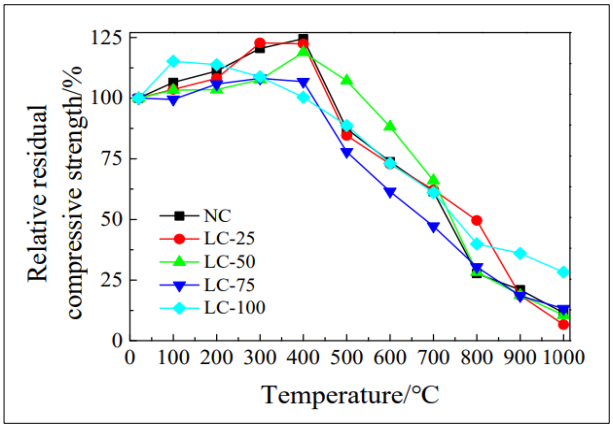


Figure 2-12. Relative residual compressive strength of concrete after exposure to high temperature [59]

2.4. The behaviour of recycled aggregate concrete at elevated temperatures

The construction industry faces a significant challenge of resource depletion and generating construction and demolition wastes (C&DW). As the most widely used construction material, concrete contributes to the industry's environmental impact. To address sustainability, recycling and reusing C&DW, particularly using recycled concrete aggregates (RCA) in new construction, have gained attention. RCA offers the potential to reduce waste, preserve natural resources, and mitigate the environmental impact associated with aggregate production and transportation [60,61].

Recent research has focused on investigating the mechanical and durability performance of concrete incorporating RCA, considering the unique characteristics of RCA, such as the presence of attached mortar and the interfacial transition zones (ITZ) between different materials. While RCA exhibits heterogeneity, porosity, and lower strength compared to natural aggregates (NA) [62], it has not significantly hindered achieving desired structural performance in recycled aggregate concrete (RAC), even at high replacement rates [63].

However, challenges remain in the widespread use of recycled aggregates, particularly concerning their behaviour under high temperatures; several researchers have conducted experimental

programs to observe the effect of elevated temperatures on RAC performance. Sarhat and Sherwood [64] partially replaced natural aggregates with recycled aggregates to prepare concrete specimens and exposed them to temperatures ranging from 20 °C to 750 °C. They concluded that the residual mechanical properties of concrete with varying percentages of recycled aggregates were comparable to those of conventional concrete, with some variations.

Salau et al. [65] substituted up to 30% of natural aggregates in concrete with recycled aggregates and exposed the specimens to temperatures of 200 °C, 400 °C, and 600 °C. They observed a gradual improvement in the compressive strength of the concrete from 200 °C to 450 °C, after which a steady drop occurred. It was determined that the RAC exhibited almost similar behaviour to normal concrete.

Vieira et al. [66] investigated the residual mechanical performance, including compressive strength, splitting tensile strength, and elastic modulus, of concrete mixtures made with varying percentages of recycled aggregates and exposed to ambient temperature, 400 °C, 600 °C, and 800 °C. The results indicated no significant differences in the residual mechanical behaviour of concrete made with recycled aggregates compared to the control mixture prepared with natural aggregates.

Xiao and Zhang [67] replaced varying percentages of natural aggregates in concrete from 0% to 100% with recycled aggregates. They determined the residual properties of specimens after exposing them to temperatures ranging from 20 °C to 800 °C. They observed that at certain exposure temperatures, the residual compressive strength of concrete mixtures prepared with recycled aggregates was higher than that of the control mixture prepared with natural aggregates.

Salahuddin et al. [68] investigated the influence of elevated temperature on concrete containing varying percentages of recycled coarse aggregates. The study utilized 30%, 60%, and 100% recycled aggregates obtained from demolished building debris. Additionally, binder enhancements and reinforcement were incorporated into the mixtures. The specimens were subjected to different temperatures and evaluated for mass loss, ultrasonic pulse velocity, compressive strength, and splitting tensile strength. The findings revealed that even with 100% recycled aggregates, the residual compressive strength of the concrete remained satisfactory at elevated temperatures. This study underscores the potential of using recycled aggregates in concrete, showcasing their ability to meet structural requirements under high-temperature conditions.

Cülfik and Özturan [69] investigated the effect of high temperature on the residual compressive and splitting tensile strengths of concrete mixtures prepared by replacing 10% OPC with silica fume. They experienced that after 100 °C, normal strength concrete specimens exhibited decreased residual mechanical properties, whereas mixtures containing silica fume performed better at high temperatures than the control mixtures with 100% OPC.

Xu et al. [70] conducted experiments to evaluate the compressive strength, splitting tensile strength, macro destruction mode, and microstructure of recycled clay brick aggregate concrete (RBC) with varying recycled clay brick aggregate (RBA replacement rates). The results indicate that the compressive strength and splitting tensile strength of RBC are lower compared to natural aggregate concrete (NAC), but the influence of RBA on the splitting tensile strength is not significant. The water-cement ratio (w/c) has a smaller impact on RBC's splitting tensile strength than that of NAC. The compressive strength of RBC initially decreases and then increases with increasing RBA replacement rates. The effect of RBA replacement rates on compressive strength decreases as the w/c increases. The microstructure analysis reveals that the AFt (aluminum-iron-tetrahedrite) in NAC is thicker than that in RBC, and the C-S-H (calcium-silicate-hydrate) in RBC forms agglomerated networks with larger and more uniform pores and less filler. These findings provide insights into the behaviour and characteristics of recycled clay brick aggregate concrete.

Akhtaruzzaman et al. [71] investigated the utilization of well-burnt brick as a coarse aggregate in concrete. The findings demonstrated that crushed brick could be effectively employed as the coarse aggregate, leading to the development of high-strength concrete. The primary focus of their investigation was to evaluate the mechanical properties of concrete containing brick aggregates rather than examining the properties of the brick aggregates independently. The findings in other studies [18,72] provided evidence that various test conditions, including heating rate and test modality (residual/hot), significantly impact the determination of mechanical properties. Furthermore, the research revealed that as the temperature rises, the mechanical properties of the brick aggregate concrete deteriorate, similar to conventional concrete with normal aggregates. Using recycled aggregates in concrete is an attractive option from an environmental perspective [73,74], as it reduces the need for virgin materials and can also reduce the carbon footprint of concrete production. However, the use of recycled aggregates may also have an impact on the behaviour of concrete under high-temperature conditions. Similarly, lightweight aggregates can also affect the behaviour of concrete under high-temperature conditions [51,75,76], as they can

reduce the thermal conductivity of the concrete and potentially slow down the rate of strength loss [77,78].

A comprehensive review of about thirty previous literature reveals varying findings and conclusions regarding the performance of concrete made with recycled concrete aggregates (RCA) compared to natural aggregates (NA) after exposure to high temperatures. Different authors have presented contradictory results, leading to distinct interpretations. One group of studies [63,79–81] indicates that concrete incorporating RCA exhibited lower relative compressive strength than NA concrete. The reduction in compressive strength is often attributed to factors such as the high porosity of RCA, weak interfacial transition zones (ITZ) between old and new cement paste, reduced strength of RCA at elevated temperatures, and potential microcracking within the RCA. These findings suggest that the presence of RCA can negatively impact the compressive strength of concrete. Another group of authors [82–86] reported similar performance between concrete with RCA and conventional concrete. However, these studies did not establish a clear relationship between the degradation of compressive strength and the replacement rate of NA with RCA.

Contrarily, a third group of investigations [64,87–94] observed an increase in concrete's relative residual mechanical properties incorporating RCA. These properties include compressive strength, flexural strength, and tensile strength. However, the underlying mechanisms for this improvement were not extensively elucidated in these studies.

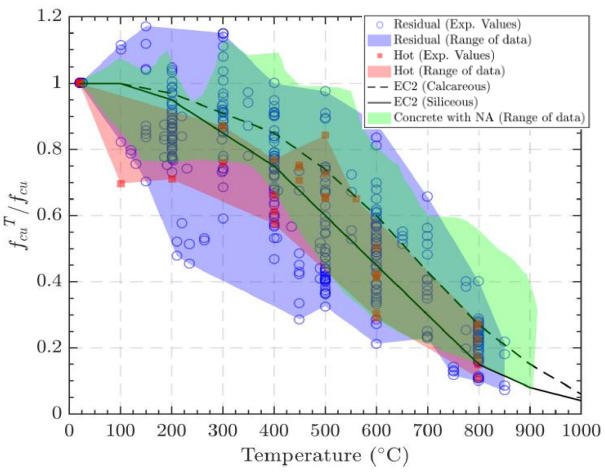


Figure 2-13. Relative compressive strength of concrete made with RCA at elevated temperatures [63]

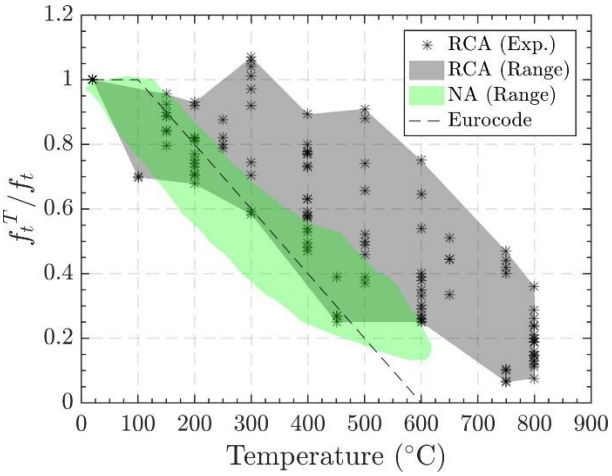


Figure 2-14. Relative splitting tensile strength of concrete made with RCA at elevated temperatures. [63]

Considering the conflicting outcomes in the literature as shown in Figure 2-13 and Figure 2-14, it is apparent that the performance of concrete containing RCA after exposure to high temperatures

is influenced by multiple factors, such as the porosity of RCA, the quality and strength of RCA, the characteristics of the ITZ, and the amount of mortar in the mixtures. Further research is warranted to comprehensively understand these factors and their influence on the mechanical properties of concrete incorporating RCA.

2.5. The behaviour of fibre-reinforced concrete at elevated temperatures

Fibre-reinforced concrete (FRC) is a composite material that combines the properties of concrete and reinforcing fibres to improve its mechanical performance. The type of aggregate used in FRC can significantly impact the mechanical properties, including compressive strength, density, and reactivity [95]. Polypropylene fibres are widely employed as a reinforcing material in concrete due to their ability to improve various aspects of the material. The inclusion of polypropylene fibres impacts concrete's multiple properties in its fresh and hardened states. These properties include compressive strength, tensile strength, flexural strength, workability, bond strength, fracture properties, creep strain, impact resistance, crack prevention, and chloride penetration [96].

Furthermore, the addition of polypropylene fibres in concrete offers several benefits. Polypropylene fibres resist drying and plastic shrinkage, reducing water bleeding in concrete and significantly decreasing permeability [97]. In addition, polypropylene fibres can reduce crack propagation and increase impact strength, enhance resistance against high temperatures, freezing and thawing cycles, and improve fatigue strength [98].

The principal role of the fibres is to bridge across the cracks that developed in the matrix when the composite's strain has reached the matrix's ultimate strain capacity. Fibres transfer the load to the matrix and cause multiple cracking; this continues until the fibres fail or de-bond and increases the fracture toughness (work for fracture). Fibres obstruct the microcrack propagation and delay the onset of tension cracks. As a result, tensile strength increases. Figure 2-15 to Figure 2-17 shows the schematic behaviour of fibres bridging around the crack in fibre-reinforced concrete and the effect of fibre size on co-crack bridging.

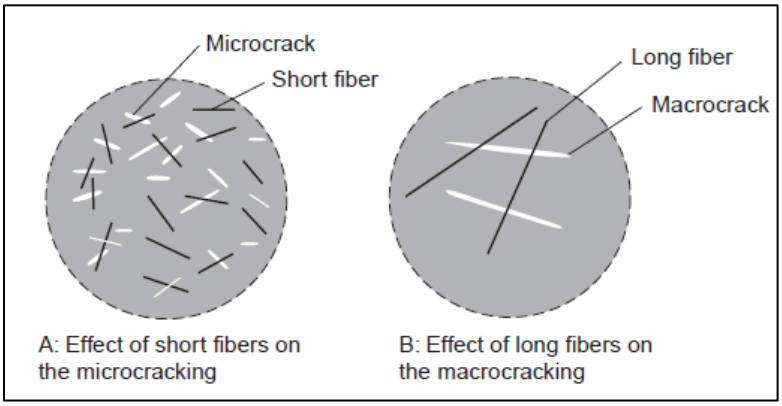


Figure 2-15. The role of using short or long fibres in concrete microcracking [99]

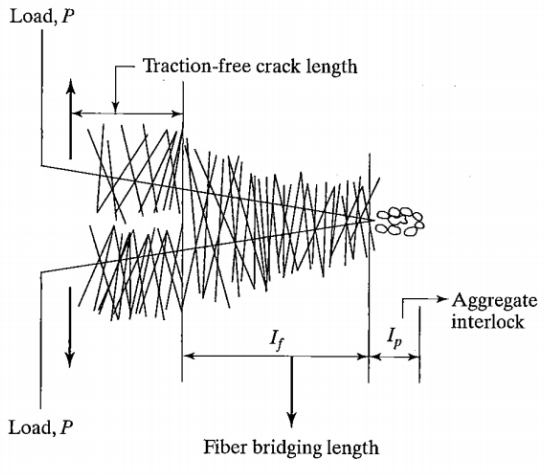


Figure 2-16. Schematic behaviour of fibres bridging across a crack [100]

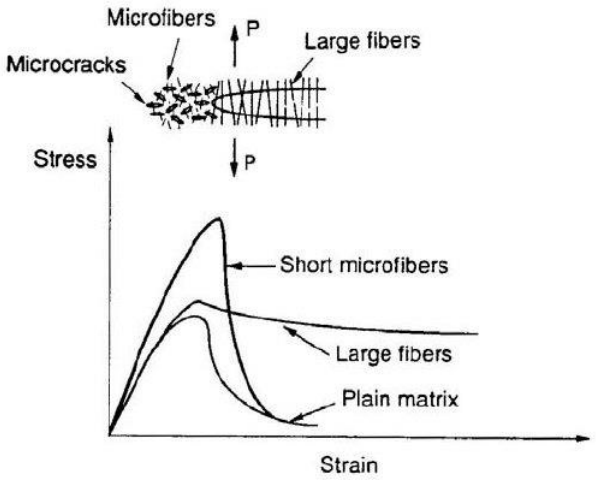


Figure 2-17. Effect of fibre size on crack bridging [101]

In recent years, significant research efforts have been dedicated to investigating the mechanical behaviour of Fibre-Reinforced Concrete (FRC) at elevated temperatures. The exposure of concrete materials to high temperatures can lead to the deterioration of their mechanical properties, necessitating a thorough understanding of FRC's performance under fire conditions [19,100,102]. The fire performance studies on FRC have primarily focused on the effects of different types of fibres, such as polymer and steel fibres. Polymer fibres, including polypropylene (PP), linear low-density polyethene (LLDPE), polyamide (PA), and polyvinyl alcohol (PVA), have proven to be effective in preventing spalling and improving permeability at elevated temperatures, facilitating the release of vapour pressure [103].

Existing literature demonstrated that the choice fibre and the aggregate in FRC significantly impact performance at elevated temperatures [102]. Liang et al. [104] analysed the effect of two types of aggregates, quartz and steel slag as fine aggregates, and two types of fibres, Polypropylene fibres and steel fibres in addition to the hybrid case on the Ultra-High Performance Concrete under the fire condition. The study revealed that all UHPC specimens exhibited an increase in compressive strength up to 400 °C, regardless of the fibre or fine aggregate used. Beyond 400 °C, the steel slag-based hybrid UHPC specimens exhibited slower strength degradation. This was attributed to the reduced amount of calcium hydroxide (CH) in the steel slag-based UHPC and the improved interfacial transition zone (ITZ) resulting from the rough surface of steel slag aggregates. At 1000 °C, the strength reduction was approximately 70% for PP-UHPC (quartz-based), 75% for hybrid UHPC (quartz-based), and only 30% for hybrid UHPC (steel slag-based). Similarly, the

residual elastic modulus experienced a decrease of around 25% in steel slag-based UHPC at 800 °C, while the decrease was approximately 81% in quartz-based UHPC.

The behaviour of FRC under elevated temperatures is complex and influenced by various factors. Several studies have highlighted the importance of fibre content and aspect ratio. Komonen and Penttala [105] compared the elevated temperature compressive performance of cement paste with and without PP fibres. They observed that the residual compressive strength of the unreinforced paste increased up to 440 °C, while for PP fibre-reinforced paste, the strength only increased up to 150 °C due to the increased porosity caused by melted fibres. Additionally, Seyam et al. [98] conducted an experimental study to evaluate the influence of polypropylene and the fibre percentage on the fire resistance of ultra-high performance concrete (UHPC); results demonstrated that 0.75% of the cement content as polypropylene fibres is the optimal dosage for improving fire resistance, and adding polypropylene fibres by 0.75% of cement content to the concrete mixture improved the fire resistance of the concrete by 27% and 72% when the samples were exposed to 250 °C and 500 °C for 2.5 hours, respectively, compared to concrete mixes without fibres.

On the other hand, Zheng et al. [106] observed an opposite trend for PP fibre-reinforced concrete specimens. The compressive strength of the specimens without fibres continuously decreased with increasing temperature. However, specimens with 0.2-0.3% fibre content exhibited a slight increase in strength from 200 to 600 °C due to the melting of PP fibres, which created more space inside the matrix and acted as a thermal shock absorber.

Despite extensive research, there is still no consensus on the optimal fibre dosage of PP fibres for achieving the best performance in FRC. Ju et al. [107] found that a fibre volume of 0.3% did not effectively improve strength up to 300 °C, while a volume of 0.9% was determined to be optimal for enhancing the residual strength of PPRPC. On the other hand, Hiremath and Yaragal [108] observed that even a low % fibre volume of 0.1% maintained strength comparable to room temperature values. Furthermore, a fibre volume of 0.9% did not significantly improve residual strength until 400 °C and had a negative effect afterwards. These disparities in findings may stem from variations in fibre lengths or aspect ratios employed in different studies.

In summary, the elevated temperature performance of FRC is influenced by multiple factors, including fibre type, aggregate selection, and fibre dosage. Figure 2-18 further supports these findings by demonstrating the lack of a clear trend in the relationship between the fibre content, type and percentage and the performance of concrete under elevated temperatures. This lack of

consistency can be attributed to the differences in fibre aspect ratios utilized across various literature.

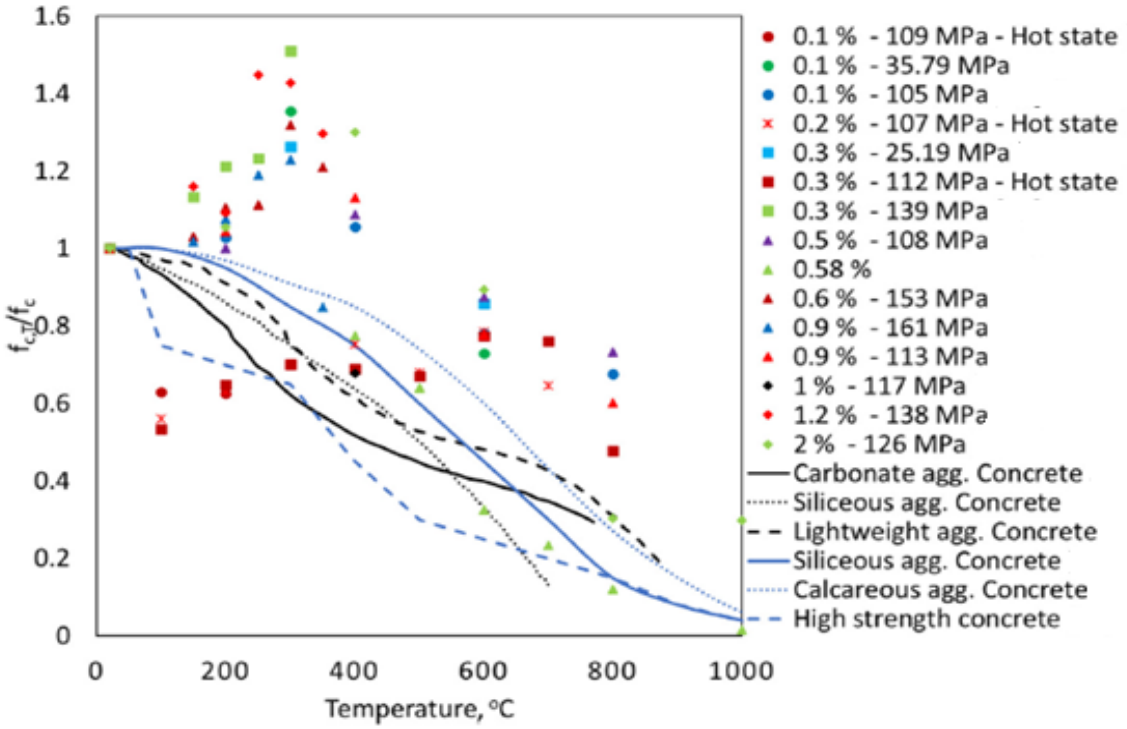


Figure 2-18. The compressive strength of concrete contains polypropylene fibres as a function of temperature [102]

2.6. Effects of concrete age on concrete properties

The age of concrete significantly impacts its properties, including strength and durability. Understanding the relationship between concrete age and these properties is crucial, especially when considering the effects of severe conditions on concrete performance [109].

The 28 days value traditionally characterizes the nominal strength of concrete. However, concrete strength is influenced by age, which typically increases the strength over time as shown in Figure 2-19. knowing the strength-time relationship is of great importance when a structure is subjected to a certain type of loading at a later age [8]. Concrete gains strength as it undergoes a process called hydration, where the cementitious materials react with water to form a solid matrix. During the early stages of hydration, the concrete may have relatively low strength, but it continues to develop strength as hydration progresses. The rate of strength gain varies depending on factors such as cement type, water-cement ratio, aggregate type, curing conditions, and environmental factors as shown in Figure 2-20 [110,111].

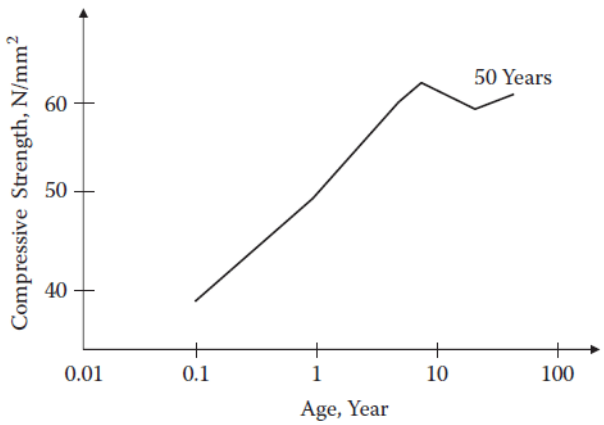


Figure 2-19. Concrete compressive strength variation with time [112]

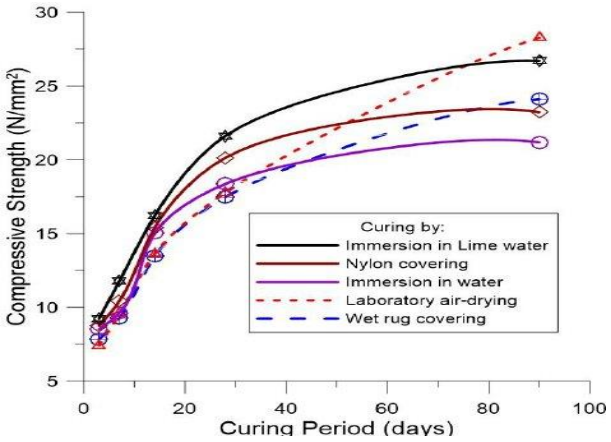


Figure 2-20. Variation of compressive strength with curing period [113]

In the research conducted by Sadiq et al. [111], the investigation focused on examining the impact of long-term concrete age and strength level on the development of compressive strength in standard concrete cores. Concrete panels and cubes with compressive strengths ranging from 25-55 MPa were meticulously prepared and subjected to laboratory testing. The tests were carried out at various concrete ages, specifically 28, 60, 90, 120, 180, and 270 days. A comparative analysis of the test results obtained from the core specimens and the standard specimens shown in Figure 2-21 revealed that the compressive strength increased with the concrete's age.

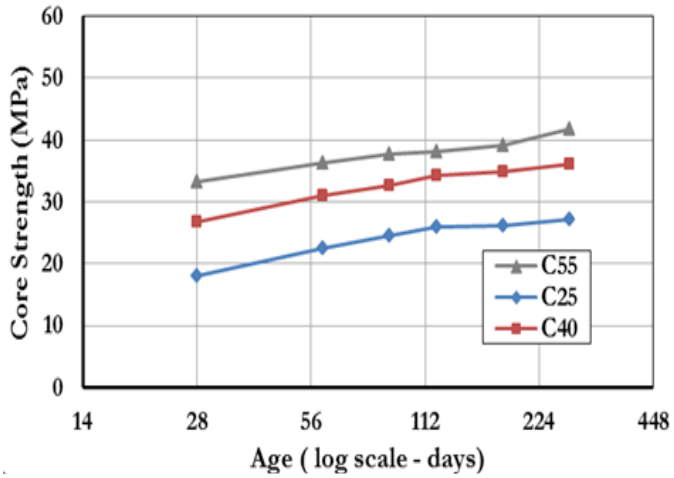


Figure 2-21. The development of the concrete core strength with age [111]

Severe conditions, such as exposure to high temperatures or aggressive chemical environments, can affect the strength development of concrete. These conditions can accelerate hydration, leading to rapid strength gain in the early stages. However, if the concrete is not properly cured or if the hydration process is compromised, the concrete's long-term durability and mechanical performance may be compromised. Inadequate curing or insufficient compaction during placement can result in reduced strength and durability over time [114,115].

Previous research has highlighted the importance of considering the age of concrete when evaluating its strength development [115]. However, limited studies have specifically examined the effects of high temperatures on the compressive strength of concrete at different ages [116]. This knowledge gap impedes accurate assessments of the residual strength of concrete structures that may be exposed to elevated temperatures throughout their service life. Many studies have tested concrete cured for ages 28, 90, 180, and 365 days [117] to understand how age and curing conditions affect the concrete's strength and elasticity over time. According to ASTM C192 [118], the age of test specimens for compressive strength should not be less than 28 days. However, it is recommended to test the specimens at the age of 28, 90 and 180 days to ensure the concrete's strength development [119].

Finally, many literatures have shown that concrete's strength develops as the concrete's age increases [120–123] that is attributed to the ongoing chemical reactions during the curing process, which continue to evolve over time, leading to changes in the concrete's microstructure [124,125]. Limited studies have considered the effect of high temperatures on the compressive strength of concrete at different ages, Mohseni et al. [126] investigated the thermal degradation of concrete at the ages of 7, 28, and 90 days and found that the compressive strength of the concrete increased as the age of the concrete increased. Similarly, Felippe and Tang [119,127] investigated the effect of curing temperature on compressive strength and observed that the highest strength was achieved when concrete was cured at the optimal temperature.

CHAPTER 3 : EXPERIMENTAL PROGRAM

This chapter presents the method used to achieve the aim of this Ph.D. work. The used materials, experimental and analytical work steps, and procedures for achieving every single experiment are explained. This chapter discusses the research procedure and provides a flowchart for the overall research program.

3.1. Background

Recent advancements in construction materials have emphasised on the importance of understanding and improving the behaviour of concrete materials under elevated temperatures. As concrete structures are frequently exposed to fire or high-temperature environments during their service life, it is crucial to investigate the response of concrete under such conditions and its impact on mechanical, physical and thermal properties.

In this chapter, the strategic approach to studying the effects of utilising various types of aggregates were presented, including natural, lightweight, and recycled aggregates, by conducting a series of laboratory tests on concrete specimens to analyse and evaluate the concrete properties. In addition to the aggregate types, we also investigate the incorporation of the micro-fibres and their influence on the behaviour of concrete under elevated temperatures. The experimental program involves subjecting the concrete specimens to elevated temperatures to simulate real-fire conditions. Through controlled experiments, we assess the mechanical and physical properties such as compressive strength, shear strength, flexural tensile, density, moisture content and mass loss after elevate temperature. These properties provide insights into the concrete's mechanical and physical response and ability to withstand elevated temperatures. Furthermore, the study considers the concrete's age as a variable parameter. By examining the properties of concrete at different ages, a comprehensive understanding gained, of how the age of the material affects its behaviour when exposed to elevated temperatures.

By combining the investigation of various aggregate types, the incorporation of fibres, and the consideration of concrete age, the study aims to provide a holistic understanding of the effects of these factors on the mechanical, physical and thermal concrete properties.

3.2. Materials

3.2.1. Binder

The research employed an unified binder, ordinary Portland cement (OPC) CEM I 42.5 N, in accordance with EN 197-1:2011 [128], which was supplied by the reputable company "Duna

Dráva Cement." OPC CEM I 42.5 N is a commonly used cement type for producing various concrete applications. OPC cement is renowned in the construction industry for its versatility and widespread availability. The physical properties of the cement used in this study are presented in Table 3-1; Additionally, the chemical composition analysis of the cement was conducted following to the standards of EN 196-2:2013 [129], with the composition listed in Table 3-2.

Table 3-1. Physical properties of the used cement

Property	Value
Initial setting time	157 minutes
Final setting time	214 minutes
Soundness	0.4 mm
Specific surface area	3690 cm^2/g
Fineness	10% retained on a 90 μm sieve
Density	3.11 g/cm^3
Water demand	31 %

Table 3-2. Chemical compositions of the used CEM I 42.5N

Component	Content (%)
Silicon Dioxide (SiO_2)	20.02
Aluminium Oxide (Al_2O_3)	3.98
Iron (III) Oxide (Fe_2O_3)	3.46
Calcium Oxide (CaO)	65.4
Magnesium Oxide (MgO)	1.48
Sulfur Trioxide (SO_3)	2.61
Sodium Oxide (Na_2O)	0.2
Potassium Oxide (K_2O)	0.6
Loss on Ignition (LOI)	1.02

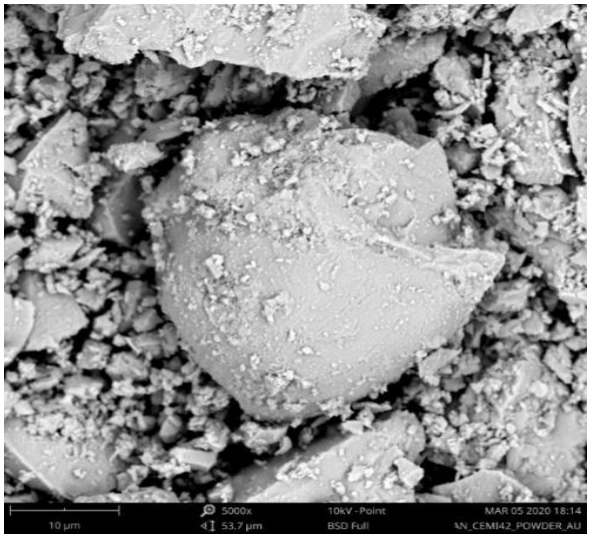


Figure 3-1. SEM image for the cement used, CEM I 42.5 N

3.2.2. Fine aggregate

The fine aggregate employed in this study was the natural river quartz sand shown in Figure 3-2, with a maximum particle size of 4 mm, comprising approximately 45% of the total aggregate volume. Natural river quartz sand is widely recognised for its favourable properties as a fine aggregate in concrete production. The sand's particle size distribution, shape, and texture were assessed according to the European standard EN 12620:2013 [130]. Sand's sieve analysis and particle sizes were evaluated based on the standards specified in EN 933-1 [131] and shown in Figure 3-3. The properties of the sand, including fineness modulus, bulk density, water absorption, and moisture content, were determined in accordance with the standards. The detailed properties of the sand are presented in Table 3-3.

Figure 3-2. Natural river quartz sand

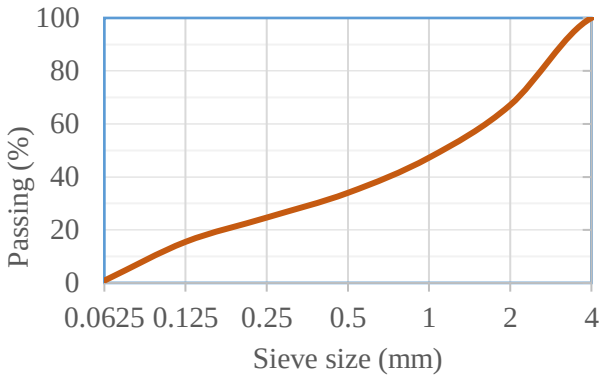


Figure 3-3. Fine aggregates grading curve

Table 3-3. Physical properties for the fine aggregates

Property	Value
Specific gravity	2.64 kg/m³
Shape	Rounded
Modulus of fineness	4.1
Bulk density	1670 kg/m³
Water absorption	1.87%

3.2.3. Coarse aggregate

In this research, five types of coarse aggregates were utilised, all with a particle size range of 4-8 mm. These aggregates represented three main categories: natural aggregates, lightweight aggregates, and recycled aggregates. The natural aggregate category included river quartz

aggregate and andesite. The lightweight aggregate consisted of expanded clay and expanded glass aggregates. The recycled aggregate category was represented by crushed clay bricks obtained from waste materials. The coarse aggregates accounted for 55% of the total aggregate content in the mixture. The characteristics of these coarse aggregates, including their microstructure and chemical composition, were thoroughly examined, complemented by Thermogravimetric Analysis (TGA). TGA is a valuable technique for studying mass loss and thermal decomposition, such as releasing carbon dioxide from carbonates. It is important to consider the testing parameters, such as sample size, heating rate, and gas environment, as they can influence TGA results. Although loss-on-ignition and TGA measurements generally exhibit similar mass loss, the temperature at which it occurs may differ due to the static nature of loss-on-ignition testing compared to dynamic TGA measurements [132].

The flow chart presented in Figure 3-4 shows the coarse aggregate preparation, types and testing.

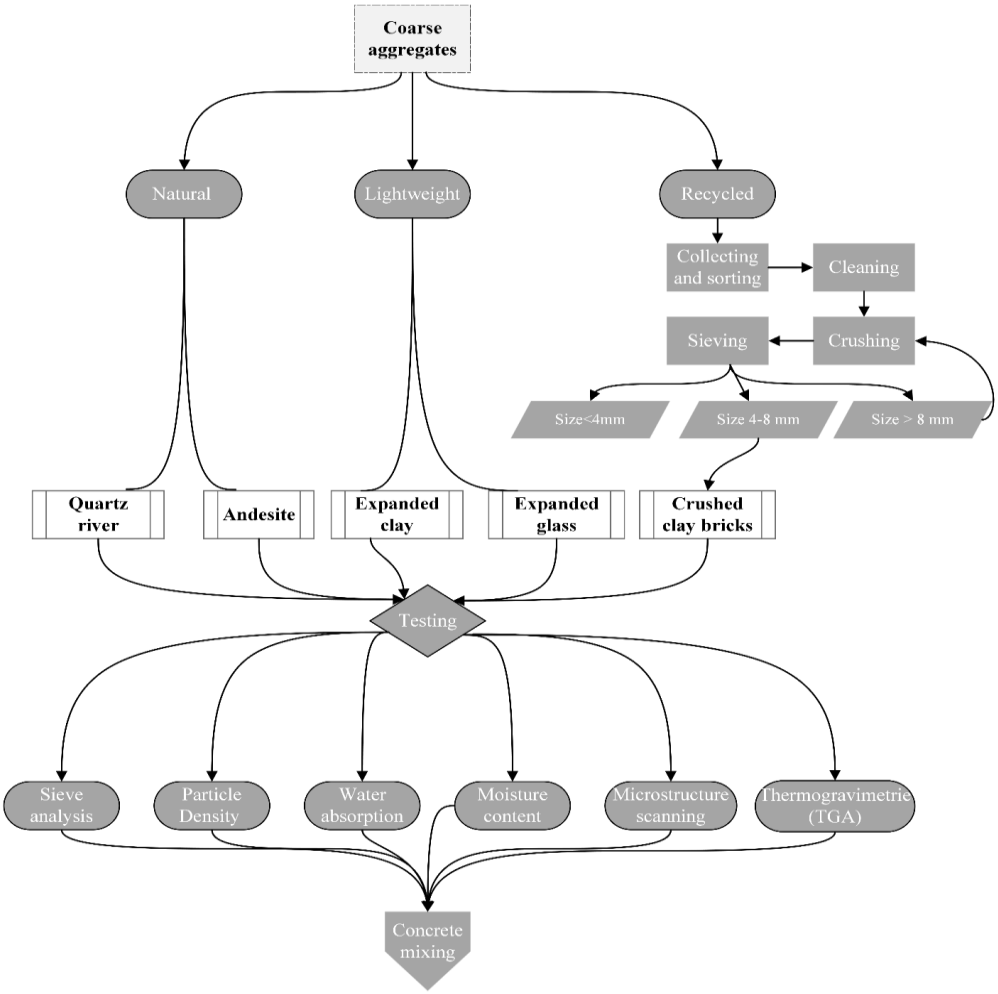


Figure 3-4. Coarse aggregate testing and preparation flowchart

3.2.3.1. Quartz aggregate (QZ)

Quartz aggregates is one of the most commonly used coarse aggregates [133]. The quartz aggregate utilised in this research, shown in Figure 3-5, is sourced from the Danube river beds. The aggregate properties were deeply evaluated, including particle size distribution and water absorption following to the European standards specified in [130,131] The internal structure and the chemical compositions of the quartz aggregates shown in Figure 3-6 were analysed using SEM, and the analysis shows that quartz aggregates contain around 36%wt, 35%wt Oxygen and 29%wt Aluminium. Moreover, the Thermogravimetric Analysis (TGA) where made to analyse the thermal stability, decomposition behaviour, and other thermal characteristics Figure 3-7, The TGA results demonstrated that the quartz aggregate exhibited no significant changes or weight loss during the test, indicating its excellent thermal stability and resistance to heat-induced alterations. In addition to the nature of quartz The alpha α –beta β phase transition of quartz occurs at 573 °C, which leads to a significant increase in volume [134–136]. The transformation process of the quartz crystal structure is illustrated in Figure 3-8. Consequently, the quartz aggregate was employed as a comparative reference to understand its behaviour better when used in concrete mixtures.

Figure 3-5. Quartz river aggregates (QZ)

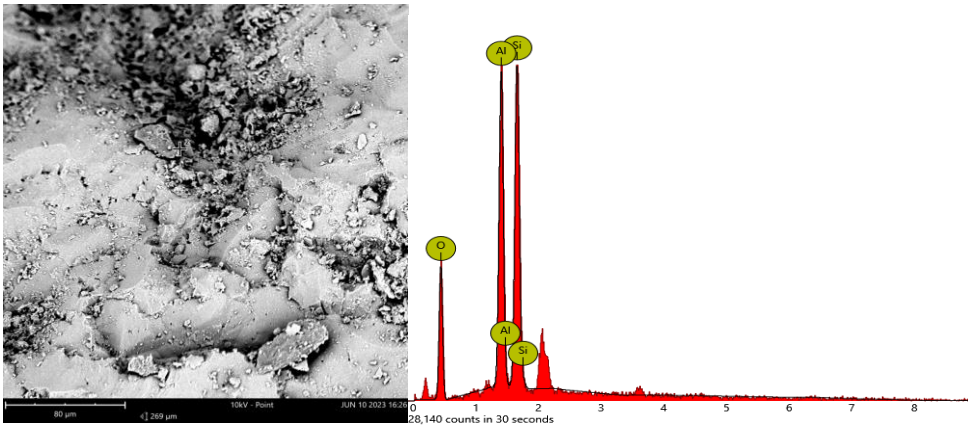


Figure 3-6. Internal structure for the quartz aggregates and the chemical components

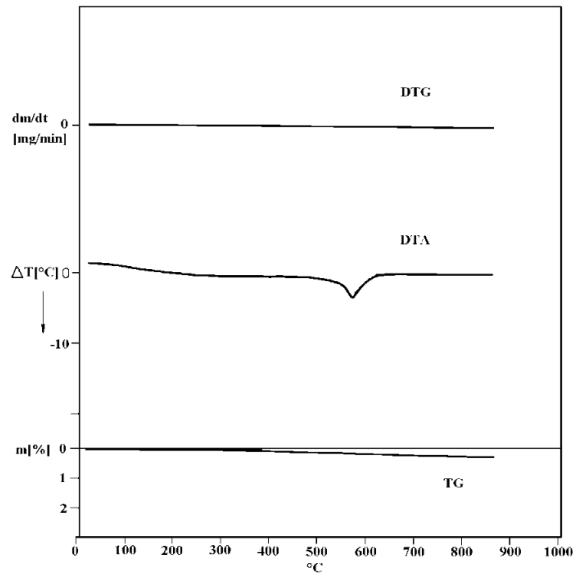


Figure 3-7. Quartz aggregates thermogravimetric analysis

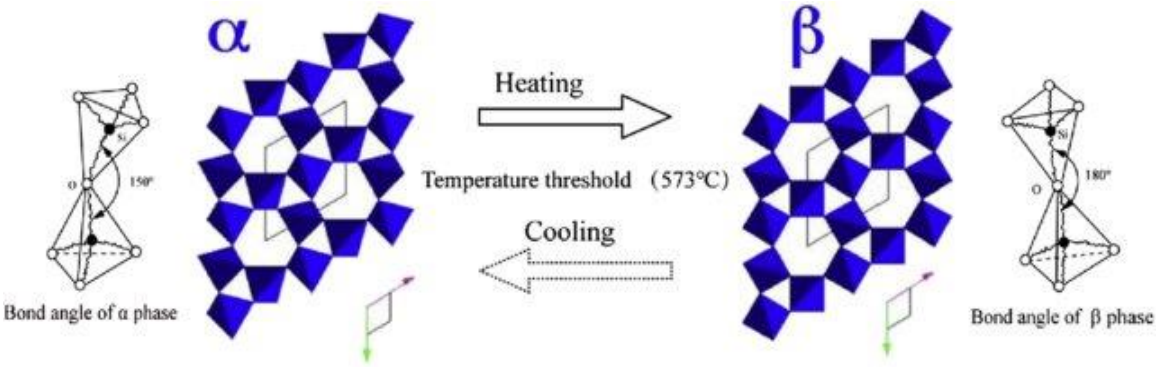


Figure 3-8. Transition process of quartz-α to quartz-β at 573 ℃ [136]

3.2.3.2. Andesite (AN)

The andesite aggregate used in this study, excavated from Kisnána (Mátra), is a grey-black, fine-grained volcanic rock with a silica content of approximately 53-63%. It exhibits a porphyritic texture and is composed of plagioclase and pyroxene microliths (clinopyroxene and orthopyroxene), feldspar, pyroxene, and biotite phenocrysts embedded in a glass matrix, along with small amounts of magnetite minerals. SEM analysis of the andesite aggregate, as shown in Figure 3-10, revealed its chemical composition with approximately 69.92% oxygen, 20.85% silicon, 5.25% aluminium, and 2.22% potassium by weight.

Thermogravimetric Analysis (TGA) of the andesite aggregate, as depicted in Figure 3.9, indicated the presence of a peak value (N) between 20 and 120 °C, attributed to the dissolution of water from

the aggregate's pores. This shows that the andesite aggregate has water loss within the measured temperature range but does not change its chemical composition significantly due to heat.

Figure 3-9. Andesite aggregate (AN)

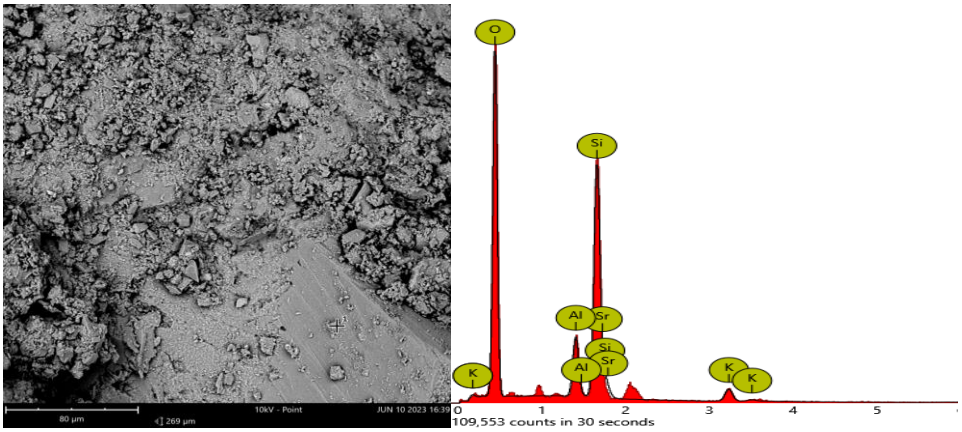


Figure 3-10. Microscaning photo and chemical analysis for the andesite aggregates

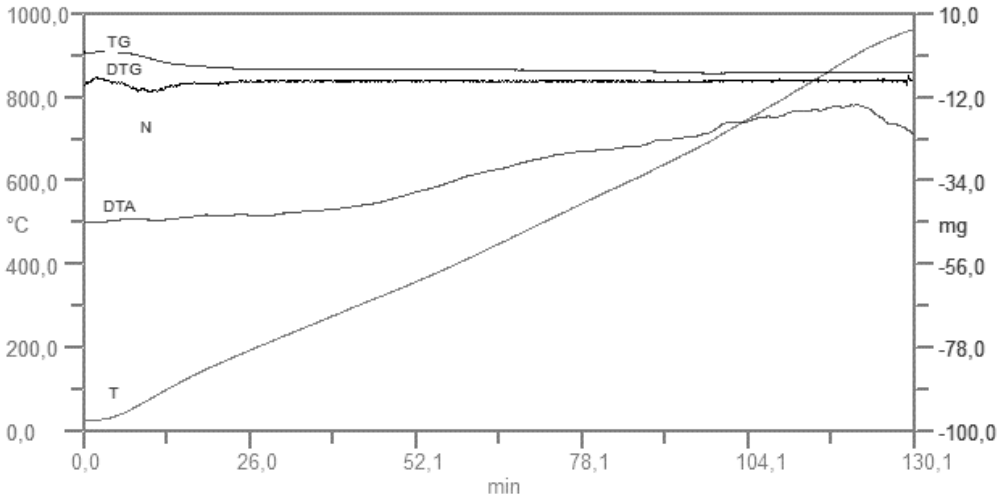


Figure 3-11. The Thermogravimetric Analysis (TGA) of the andesite aggregate

3.2.3.3. Expanded clay (EC)

The expanded clay aggregate used in this research is Liapor 8F, shown in Figure 3-12. It falls under the category of lightweight aggregates. Liapor 8F is manufactured by expanding clay materials through a heating process. The firing temperature of expanded clay aggregate under manufacturing is 1200 °C [51,134] this firing process improves the EC properties after subjected to elevated temperatures [134]Moreover, this results in lightweight, porous aggregates with excellent insulating properties. The expanded clay aggregate is known for its low density, high strength, and thermal efficiency. These properties make it suitable for various applications in the construction industry, including lightweight concrete and insulation systems [52,137]. To evaluate the characteristics and compositions of the expanded clay, a microscanning analysis was made in Figure 3-14, which shows the internal porous of the structures and the chemical components, mainly Oxygen: 61 %, Silicon: 22% and Aluminium: 12%. The Thermogravimetric analysis (TGA) of expanded clay exhibited three peak points: 16.99 m% weight loss between 28-113 °C, 7.06 m% weight loss between 115-194 °C, and 2.48 m% weight loss between 632-728 °C, corresponding to the release of absorbed water and decomposition of carbonates (e.g., $MgCO_3$ and $CaCO_3$) Figure 3-13.

Figure 3-12. Expanded clay (Liapor 8F)

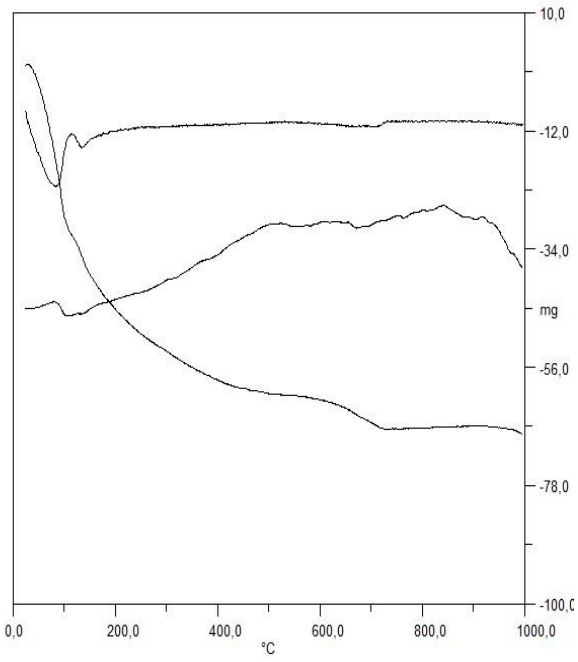


Figure 3-13. TGA analysis for the expanded clay aggregate

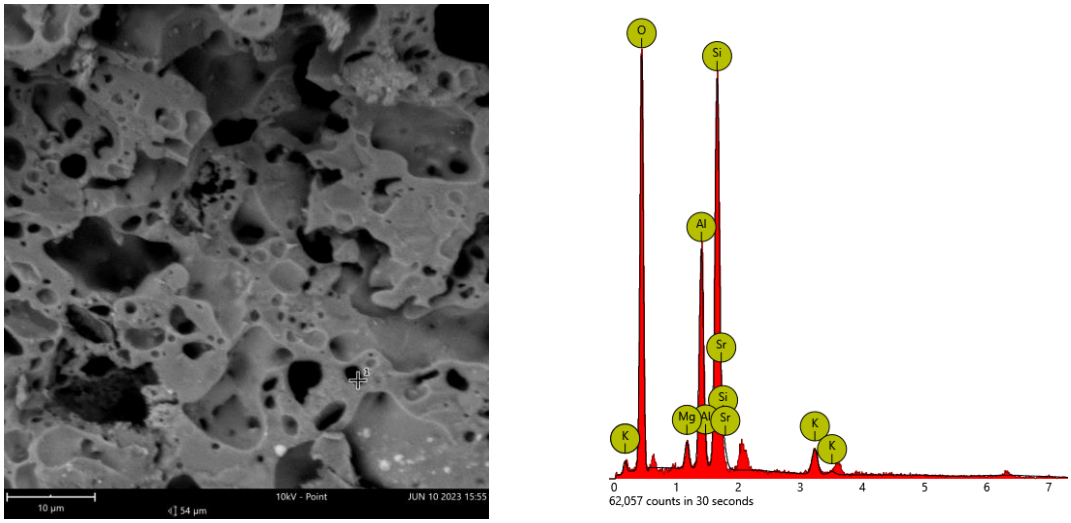


Figure 3-14. SEM photo for the expanded clay (Liapor 8F)

3.2.3.4. Expanded glass (EG)

The expanded glass aggregate used in this research is a type of lightweight aggregate. It is manufactured by Stikloporas, a recognised producer of expanded glass products. The used aggregates are shown in Figure 3-15. The process involves heating and foaming recycled glass materials at a temperature between 700 °C and 900 °C, resulting in lightweight cellular aggregates with varying particle sizes [138]. Expanded glass aggregates have several advantages, including low density, high insulation value, and good durability[139]. They are commonly used in lightweight concrete, drainage systems, and landscaping applications. In this research, the expanded glass aggregate manufactured by Stikloporas serves as a specific type of lightweight aggregate, allowing for the evaluation of its unique characteristics and performance in concrete mixtures, enabling a comparison to other coarse aggregates. The internal structure and the chemical components assisted using SEM Figure 3-16, the analysis revealed their internal atomic concentrations: 59.93% oxygen, 14.88% silicon, 14.19% carbon, 6.44% sodium, and 1.93% calcium.

Figure 3-15. Expanded glass (EG)

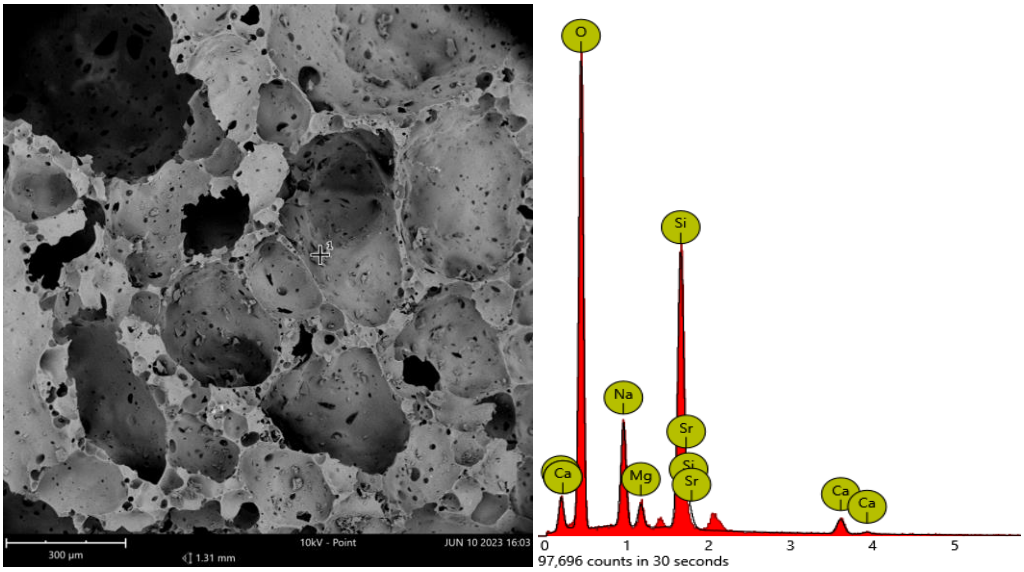


Figure 3-16. SEM image for the expanded glass used

3.2.3.5. Crushed clay bricks (CB)

The crushed clay brick aggregates utilised in this study were obtained from the demolition wastes of the cladding bricks that had been in service for more than 50 years. These bricks were carefully selected and cleaned Figure 3-17; the cleaning process involved careful removal of debris and contaminants, such as mortar residues and any other undesired substances. Subsequently, the bricks underwent mechanical crushing using a specialised machine, resulting in a 4-8 mm particle size range shown in Figure 3-19. The crushed clay bricks underwent a comprehensive sieve analysis and meticulous sorting to comply with the specified particle size distribution requirements. Before casting the concrete, and due to water absorption of the recycled aggregate, aggregates pre-wetted for thirty minutes. Using wet aggregates instead of fully-saturated aggregates (common with RCA) was adopted to have a method that could be easily reproduced in a concrete industrial plant. Before casting, the aggregates moisture content was measured to adjust the water content added to the mix.

The crushed clay bricks were studied intensively to define the internal structures and the chemical components using SEM Figure 3-18, which showed the atomic concentrations: 50.62% oxygen, 31.23% silicon, 8.18% aluminium, and 6.56% calcium. Moreover, the Thermogravimetric analysis (TGA) of crushed clay bricks showed that indicates a total weight loss of 2.82 m% throughout the entire temperature range.

Figure 3-17. The collected clay bricks, and the crushed materials

Figure 3-18. Crushed clay bricks used (CB)

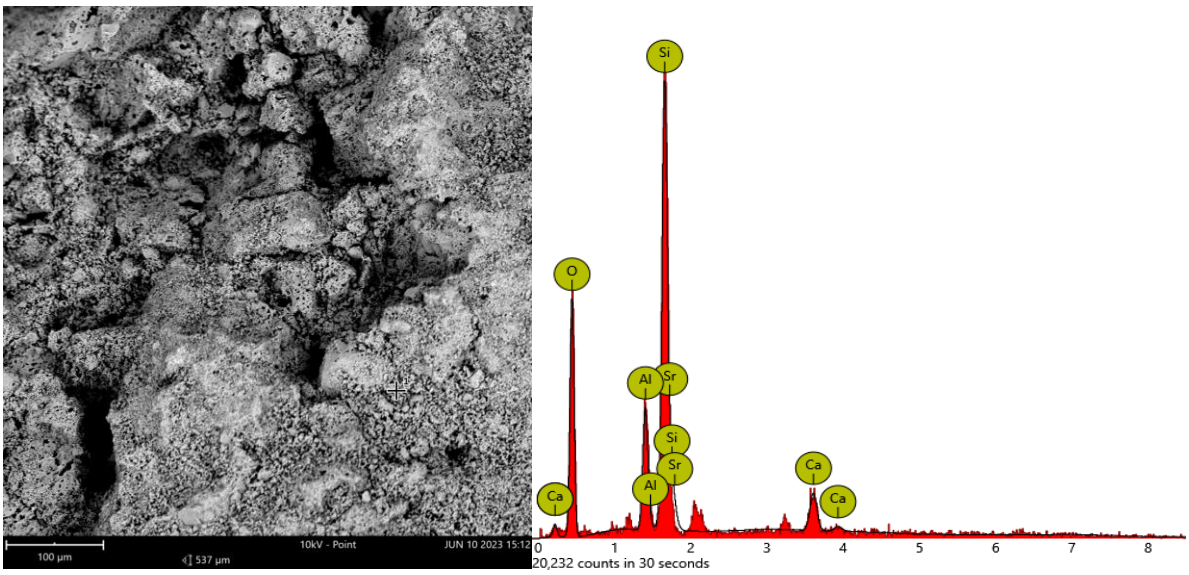


Figure 3-19. SEM photo for the crushed clay bricks used

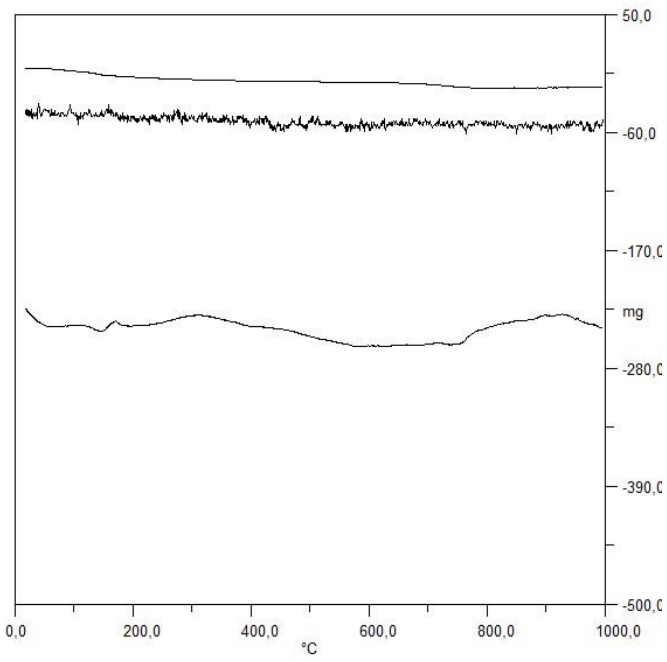


Figure 3-20. TGA for the crushed clay bricks

3.2.3.6. Coarse aggregate properties

Coarse aggregates for all types were selected with particle size 4-8 mm, and sieve analysis tests for all used aggregates were made in accordance to the EN 933-1 [131], grading curves shown in Figure 3-21, aggregates particle density and water absorption were measured based on EN 1097-6 [140], moisture content was also assessed based on standards EN 1097-5 [141] results of the aggregates physical properties tests presented in Table 3-4

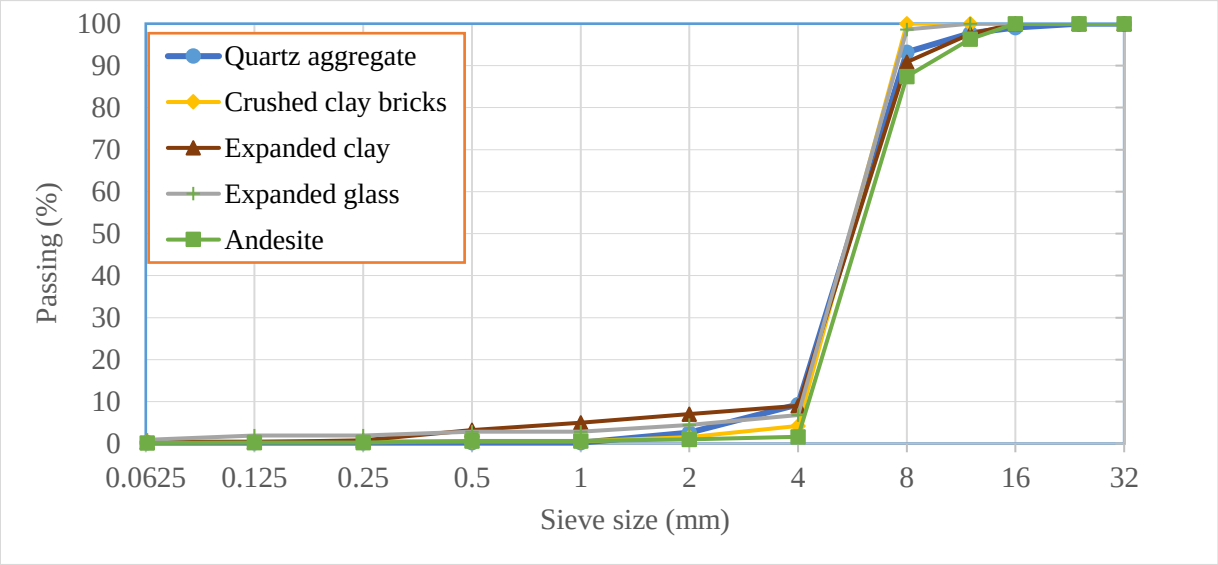


Figure 3-21. Grading curve for the coarse aggregates used in the research

Table 3-4. Coarse aggregate physical properties

Type	Symbol	Density kg/m^3	Water absorption wt%	Classification
Quartz river	QZ	2590	1.01	Natural aggregate
Andesite	AN	2600	1.27	Natural aggregate
Expanded clay	EC	1490	12.5	Lightweight aggregates
Expanded glass	EG	380	16.1	Lightweight aggregate
Crushed clay bricks	CB	1990	17.44	Recycled aggregate

3.2.4. Fibres

Polypropylene fibres in concrete have been found to improve the material's toughness, impact resistance, and overall durability. In this study, micro polypropylene fibres (MasterFibre 018), shown in Figure 3-22, were used to reinforce the concrete. The fibre used was compatible with EN 14889-2:2006-11 [142]. The fibres are made of a polyolefin polymer and have a round sectional shape with a 910 kg/m^3 density. The diameter of the fibres is 6.6 dtex, and it have a straight longitudinal shape. PP fibre length is 17.7 mm, and the polymer's melting point is between 150-170 °C.

Figure 3-22. Polypropylene fibre (MasterFibre 018)

3.2.5. Water and superplasticiser

The hydration reaction of cement could start only in the presence of water. The mixing water used for the reference was tap water that complies with the requirements of EN 1008 [143]. The rheological properties of the concrete were ensured by adding the superplasticiser to the fresh concrete. This admixture type reduces a concrete mixture's water dosage for the desired slump class. MasterGlenium 300, a second-generation polycarboxylic ether polymer, was used as a superplasticiser.

3.3. Mix design

3.3.1. Approach

Concrete mixtures were designed using a volumetric approach, with fine aggregate comprising 45% of the total aggregate mix volume and coarse aggregate constituting 55%. The primary focus was to investigate the influence of coarse aggregate, and thus the other mix components were held constant throughout the study. Consequently, for all the mixes, the cement mass was fixed at 450 kg/m^3, and the water-to-cement ratio (w/c) was maintained at 38% or 171 kg/m^3 in terms of weight. In order to further explore the effects of incorporating fibres into the concrete, an additional mix design was developed. These fibre-reinforced mixes were created to examine the impact of fibre content, which was consistently set at 0.75% of the cement content or 3.375 kg/m^3 in terms of weight.

By utilising this comprehensive approach, this study encompassed ten concrete mixes, as outlined in Table 3-5. These mixes included both non-fibre and fibre-reinforced combinations. The distinct mix designs allowed for a thorough investigation of the influence of coarse aggregate and the subsequent effects of fibre incorporation on the properties of the concrete.

Table 3-5. Concrete mix proportions

Material	Mix number	*Component materials for 1 m^3 (kg/m^3)*									
		M1-QZ	**M2-AN**	**M3-EC**	**M4-EG**	**M5-CB**	**M6-QZPP**	**M7-ANPP**	**M8-ECPP**	**M9-EGPP**	**M10-CBPP**
Cement		450	450	450	450	450	450	450	450	450	450
Water		171	171	171	171	171	171	171	171	171	171
Aggregate 0/4		803	803	803	803	803	797	797	797	797	797
Aggregate 4/8	*Natural quartz*	964	-	-	-	-	956	-	-	-	-
	Andesite	-	968	-	-	-	-	959	-	-	-
	Expanded clay	-	-	555	-	-	-	-	550		
	Expanded glass	-	-	-	142	-	-	-	-	140	
	Crushed clay bricks	-	-	-	-	738	-	-	-	-	734
Fibres		-	-	-	-	-	3.375	3.375	3.375	3.375	3.375
Superplasticiser		2.93	2.93	2.93	2.93	2.93	5.4	5.4	5.4	5.4	5.4

3.3.2. Mixing, casting, and curing of concrete samples

All tests were made in the Department of Construction Materials and Technologies laboratory at the Budapest University of Technology and Economics (BME). The casting process for the concrete specimens commenced with meticulous preparation of the moulds in strict accordance

with EN 12390-1 [144]. A thorough cleaning procedure ensured the removal of any residual concrete debris, followed by applying a thin layer of oil on all joints and internal surfaces to establish an impermeable barrier and prevent concrete adhesion to the mould. The dry components were precisely pre-mixed for approximately two minutes using a 0.1 m^3 vertical portable mixer, adhering to the guidelines specified in EN 12390-2 [145] to ensure consistency in the composition of each concrete mix. Gradually adding the required amount of mixing water during the blending process achieved the desired consistency.

The freshly mixed concrete was cast into the moulds in a stratified manner, involving three distinct layers. Each layer underwent thorough compaction utilising a vibrating table to eliminate any significant air bubbles on the concrete surface. Excess concrete protruding beyond the upper edge of the mould was meticulously removed using a steel trowel, ensuring the attainment of a relatively smooth and consistent finish, as shown in Figure 3-23.

After the casting procedure, the prepared samples were stored in a controlled laboratory environment, shielded by a nylon sheet to maintain a humid atmosphere around the specimens. After an initial curing period of 24 hours, the samples were carefully de-moulded, appropriately marked for identification, and then submerged in a temperature-controlled water tank at 20 ± 2 °C. After preliminary curing, water evaporation was prevented by keeping them in water basins for seven days. Specimens were left ageing and drying in natural air conditions at the laboratory, as shown in Figure 3-24, for 28 days, 120 days and 240 days with a temperature of 20 ± 5 °C and relative humidity of 50 ± 5 %.

Figure 3-23. Specimens in moulds

Figure 3-24. Specimens on the lab, after the initial curing, were stored for up to 240 days.

3.4. Evaluations and testing methods

3.4.1. Fresh properties

The fresh properties of each concrete mix were meticulously evaluated in accordance with EN 12350-1 standard [146] and EN 1051-6 [147]. The workability of the concrete was assessed using the flow table test, following the guidelines outlined in the European standards EN 12350-5 [148]. This test provided quantitative data on the concrete's flowability and workability. The fresh concrete density was measured as outlined in EN 12350-6 [149]. Furthermore, the air content of the fresh concrete was calculated using the gravimetric method as specified in ASTM C138 [150]. This method involved measuring the mass of the concrete sample before and after subjecting it to a specific drying process, allowing for the precise calculation of the concrete air content.

3.4.2. Physical properties

The physical properties of the concrete were comprehensively assessed, encompassing visual observation, density, moisture content, and mass loss. The hardened concrete density and moisture content at various ages were measured in accordance with EN 12390-7 [151].

Additionally, mass loss after the heating load was evaluated. After subjecting the samples to the heating load, they were allowed to cool in the ambient air, and the following day they underwent testing. Each specimen was meticulously weighed and dimensioned before and after the heat loading test, enabling the calculation of mass loss. This analysis provided valuable insights into the impact of the heating load on the concrete specimens.

3.4.2.1. Moisture content

The determination of moisture content in concrete is crucial for optimizing its properties and ensuring long-term performance. Three representative specimens are selected, taking into account each mix design and age of the specimen. The initial specimen weight (W1) is recorded, followed by the application of the oven-drying method at 105 °C until a constant weight (W2) is achieved. This method adheres to the specifications outlined in EN 1097-5 [141]. The moisture content is then calculated using the formula: Moisture Content (%) = (W1 - W2) / W1 × 100.

3.4.2.2. Hardened Density

The investigation of hardened density at distinct ages (28, 120, and 240 days) is crucial for assessing the long-term structural integrity of concrete in accordance with European standards EN 12390-7 [151]. Concrete specimens, prepared following the guidelines specified in EN 12390-2,

undergo density testing based on the Archimedes' principle at specified ages. The testing process involves measuring the mass of each specimen (m), along with the specimen volume (V), allowing for the determination of hardened density = (m / V). This multi-age approach facilitates a comprehensive understanding of the concrete's evolution over time.

3.4.2.3. Weight loss due to heating

The evaluation of weight loss due to heating is pivotal in understanding the thermal characteristics of concrete. In this study, a controlled heating process is employed to investigate weight loss in concrete specimens subjected to elevated temperatures of 200, 400, 600, 800, and 1000 ℃. The specimens, representing various mixes and ages, are carefully weighed before and after exposure to these temperatures for a consistent duration of 2 hours at each desired temperature. The weight loss percentage is then calculated for each mix, age, and temperature by comparing the weight before heating with the weight after heating. This method provides valuable insights into the concrete's response to heat, offering crucial data for assessing its fire resistance and thermal stability.

3.4.3. Mechanical properties

The mechanical properties that were examined included compressive strength, flexural tensile strength, and shear strength. Compressive strength testing was carried out in accordance with EN 12390-3 [152] flexural tensile strength was tested following to EN 12390-5 [153] *w*hile the shear strength was indirectly evaluated using the push-off model with a uniaxial loading as in EN 12390-3 [152].

These tests aimed to investigate the concrete's characteristic and residual mechanical properties after elevated temperatures. The specific number and shapes of the tested specimens for each mixture and testing age are outlined in Table 3-6.

The specimens designated for mechanical strength tests underwent rigorous assessment utilising suitable testing procedures.

3.4.3.1. Compressive strength

The compressive strength of the concrete was determined in accordance to EN 12390-3:2009 [152] the test was performed utilising a uniaxial compressive strength machine shown in Figure 3-25, with a capacity of 3000 kN, ensuring reliable and accurate results. The loading process was conducted at a constant loading rate within the 0.6 ± 0.2 MPa/s range. The compressive strength

test employed two sizes of cubic specimens: 150 mm x 150 mm x 150 mm and 100 mm x 100 mm x 100 mm. These specimens were subjected to the compressive strength test at ages 28, 120, and 240 days, enabling the evaluation of the concrete's compressive strength development over time.

Figure 3-25. Compressive test machine

3.4.3.2. Flexural tensile strength

The flexural tensile strength of the concrete was determined through a three-point flexural strength test. This test was conducted using prismatic specimens with dimensions of 70 mm x 70 mm x 250 mm. A dedicated 3-point loading bending flexure machine is shown in Figure 3-26. The samples were subjected to a constant loading rate of 80 N/s, following the European standard [153].

Figure 3-26. Three-point loading flexural tensile test machine

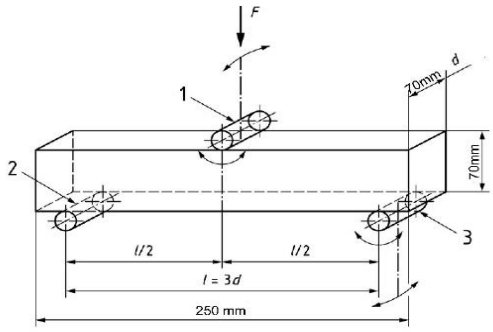


Figure 3-27. Three-point bending flexural test

3.4.3.3. Shear strength

The shear strength of the concrete was assessed using the push-off test model. A compressive testing machine with a capacity of 3000 kN was employed to conduct the push-off tests. These tests were performed under ambient conditions, as previously mentioned. The specimens were subjected to vertical loading at a constant loading rate of 6.25 kN/s. Since the push-off specimen

is not a standard shape, previous researchers have utilised various dimensions. In this study, the uncracked push-off model was designed as cylindrical specimens with a diameter of 100 mm and a height of 200 mm. After two weeks of casting, two notches with a width of 4 mm were cut perpendicular to the axis of the specimen using a saw cut-off machine. These notches formed the shear plane, with a length of 64 mm. The adopted dimensions are shown in Figure 3-28.

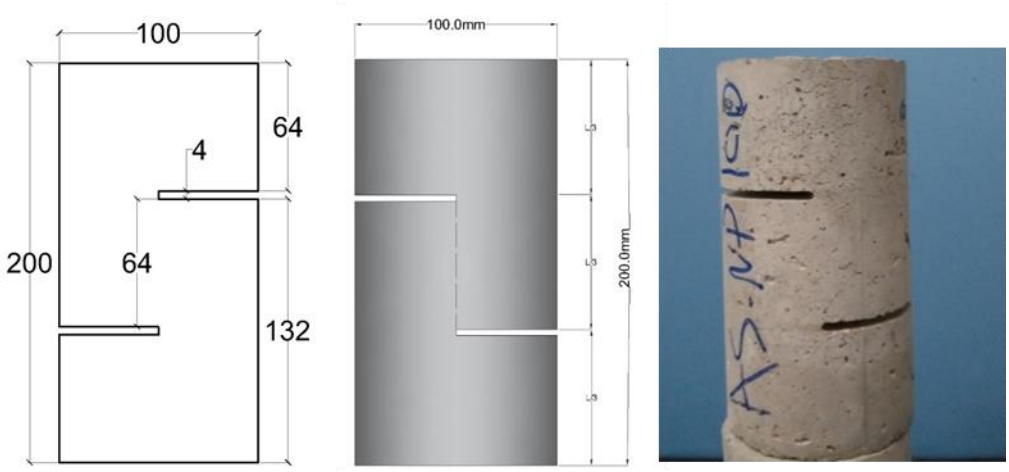


Figure 3-28. Schematic illustration of the dimensions adopted Push-off specimen

3.4.4. Thermal properties

The thermal conductivity was measured using the commercial Isomet 2104 device (Applied Precision, Ltd.). The measurement is based on the analysis of the temperature response of the material analysed to heat flow impulses. The heat flow is induced by electrical heating using a resistor heater having direct thermal contact with the sample's surface. Measurement depended on the moisture content from the dry state to water saturation.

3.4.5. Heating and cooling

Specimens were heated using an electric furnace, shown in Figure 3-30. The samples were heated to a target temperature, i.e., 200, 400, 600, 800 and 1000 °C. However, the heating rate in the electric furnace used in this study did not fully comply with the ISO834 [154], standard fire curve. To ensure standardisation, the ISO 834 standard fire curve was employed for heating the specimens to elevated temperatures. The comparison of the temperature-time relationship between the ISO 834 standard and the furnace heating rate, as shown in Figure 3-29, indicates that the furnace was able to simulate the heating rate of the ISO 834 standard. After reaching the target temperature, the specimens were maintained at that temperature for 2 hours to ensure a homogenous temperature

throughout the cross-section of the specimens. Subsequently, the samples were allowed to cool freely for 24 hours. This heating and cooling process aims to simulate the fire action and evaluate the behaviour evolution with temperature when the composition and volume of cement paste and mortar remain constant in all samples.

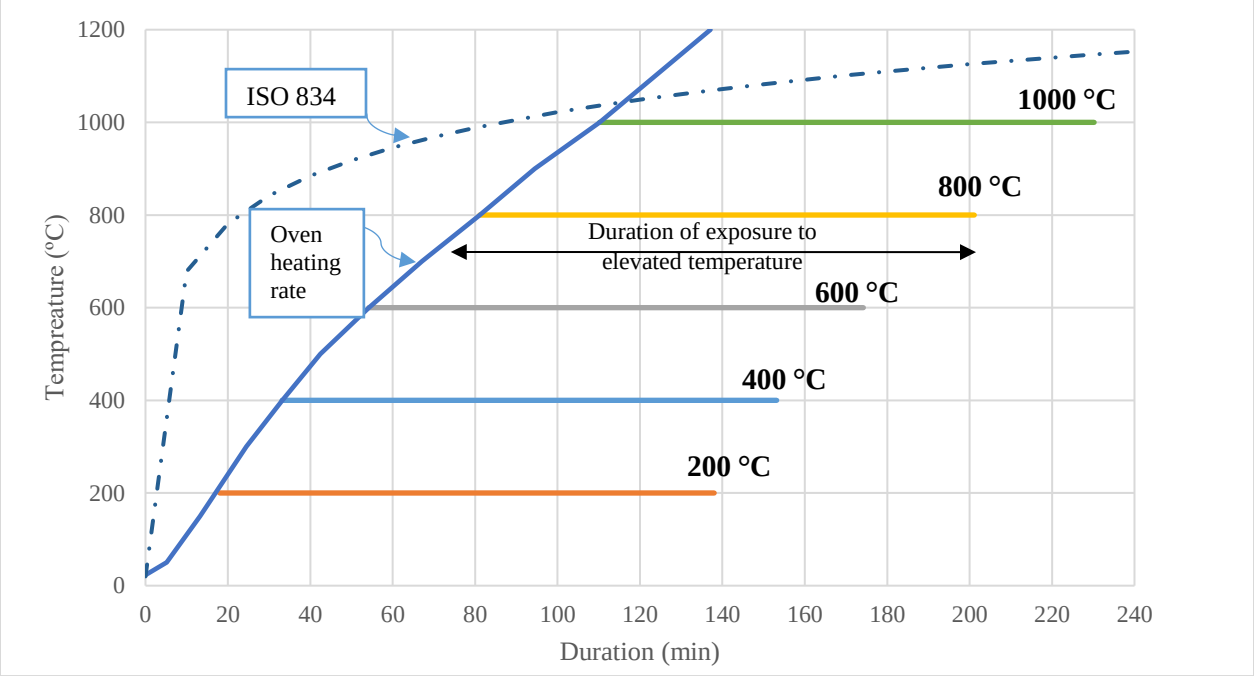


Figure 3-29. Rise in temperature in the furnace with heating duration at each heat level and ISO 834 fire curve

Figure 3-30. Electric furnaces used in the high temperature tests

Table 3-6. Number and shape of test specimens

Test	Specimen shape and size	Number for each mix				Total for all mixes
		Age (days)				
		0	28	120	240	
Compressive strength	*Cube (100x100x100 mm)*	-	6	18	18	420
Mass loss		-	3	18	18	390
Moisture content		-	3	18	18	390
Hardened density		-	3	18	18	390
Micro-scanning		-	-	-	3	30
Flexural tensile strength	*Prism (70x70x250 mm)*	-	3	18	18	390
Shear strength	*Cylinder (Ø100x200 mm)*	-	3	18	18	390
Fresh density	*Cube (150x150x150 mm)*	3	-	-	-	30
Compressive strength		-	3	3	3	90
Thermal conductivity		-	3	18	-	180

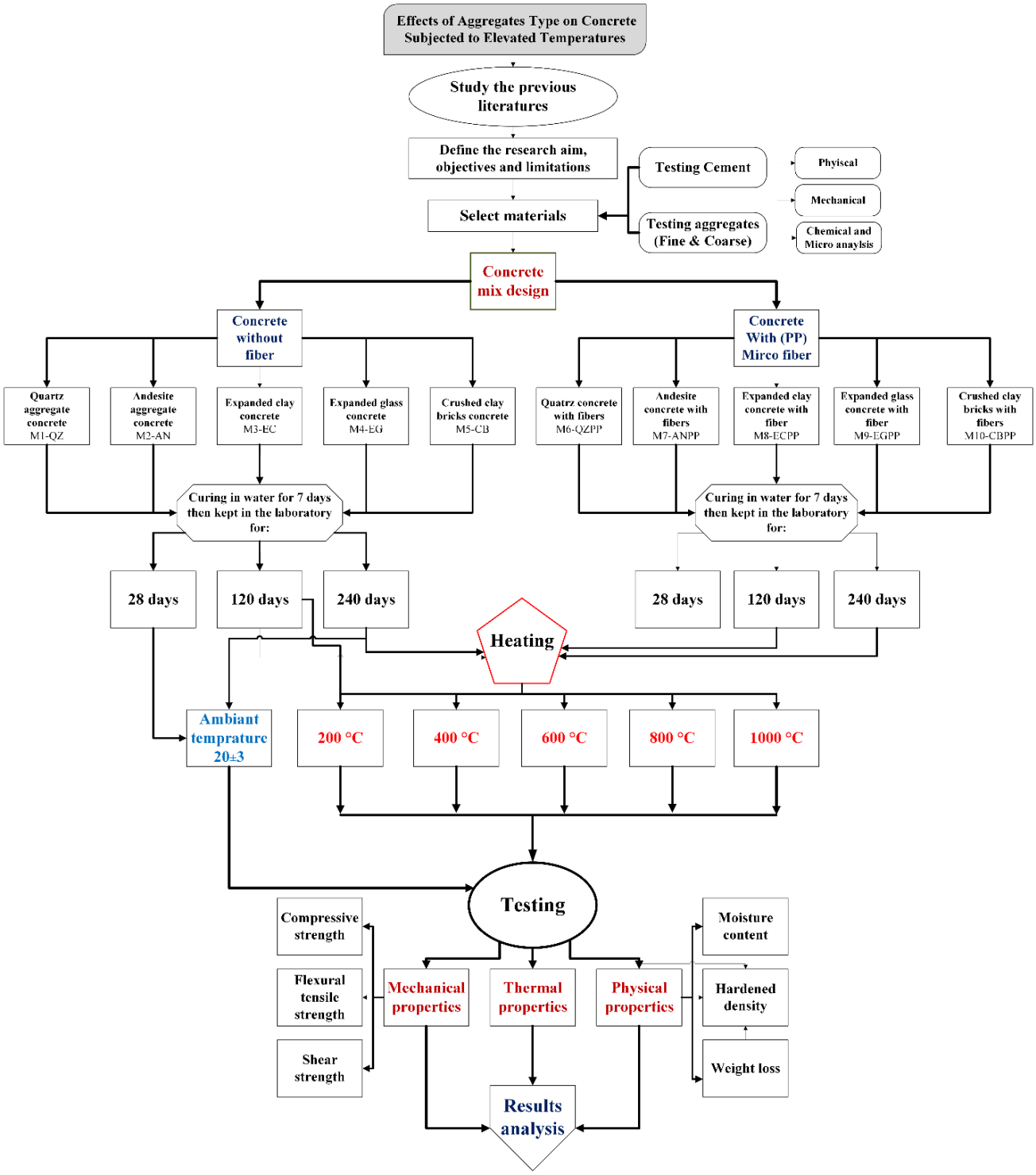


Figure 3-31. The full experimental program flowchart

CHAPTER 4 : RESULTS AND DISCUSSION

This chapter presents the results of the experimental program for the effects of concrete physical, thermal and mechanical properties in the case of using different types of coarse aggregates. The results are presented in four groups, each of which includes the presentation, analysis and discussion for part of the tested properties. The groups are fresh properties, mechanical properties, residual mechanical properties after temperature exposure and the impact of using fibres on the concrete properties.

4.1. Fresh properties

The fresh properties of concrete play a crucial role in its workability and handling characteristics during the mixing, transportation, and placement stages. This section focuses on evaluating the influence of aggregate type on the fresh properties of concrete. The following subsections present a comprehensive analysis of the specific fresh properties investigated.

4.1.1. Fresh density

The fresh density of concrete mixtures plays a significant role in determining their overall characteristics and performance. In this study, the fresh density of ten different concrete mixtures was measured according to the European standards EN123560-6 [149] The mixtures were categorized into two groups: (i) M1 to M5 without fibres and (ii) M6 to M10 with polypropylene micro fibres (PP). The resulting fresh density values for each mixture are presented in Table 4.1.

Table 4.1. Fresh properties test results

Mix	Fresh density kg/m^3	Air content %	Spread diameter mm
M1-QZ	2371	1.38	505
M2-AN	2350	2.39	525
M3-EC	1971	1.07	490
M4-EG	1542	2.23	498
M5-CB	2121	2.57	513
M6-QZPP	2346	1.87	415
M7-ANPP	2333	2.58	430
M8-ECPP	1955	1.50	416
M9-EGPP	1553	1.17	410
M10-CBPP	2077	4.20	400

Among the mixtures without fibres, notable variations in fresh density were observed. Mixture M4, which utilized expanded glass aggregate (EG), exhibited the lowest fresh density due to the lightweight nature of expanded glass. Conversely, mixture M1, incorporating quartz aggregate (QZ), had a relatively higher fresh density compared to the lightweight aggregates. This variation in fresh density can be attributed to the specific characteristics and density of the aggregates used in each mixture.

For the mixtures with PP fibres (M6 to M10), slight differences in fresh density were observed compared to their counterparts without fibres. Mixture M9-EGPP, which incorporated expanded glass with PP fibres, demonstrated a relatively low fresh density, similar to M4. Similarly, mixture M8-ECPP, utilizing expanded clay aggregate, exhibited a low fresh density, reflecting the lightweight nature of expanded clay. On the other hand, the addition of PP fibres to the mixtures with andesite aggregate (AN) (M7-ANPP) and quartz aggregate (QZ) (M6-QZPP) resulted in comparable fresh densities to their counterparts without fibres, as reported in previous studies [155,156].

In conclusion, the fresh density measurements of the concrete mixtures revealed significant variations influenced by the specific aggregate types used. The presence of lightweight aggregates, such as expanded glass and expanded clay, resulted in lower fresh densities, while quartz aggregate showed relatively higher fresh density. The addition of polypropylene (PP) fibres slightly impacted the fresh density, with mixtures containing PP fibres generally exhibiting comparable or slightly higher densities compared to the mixtures without fibres. These findings highlight the importance of selecting appropriate aggregates and considering the influence of fibres on fresh density when designing concrete mixtures.

4.1.2. Air content

The air content of concrete is a critical parameter that significantly impacts its performance and durability. It provides valuable insights into the volume of entrained air within the concrete, which plays a crucial role in its workability, resistance to freeze-thaw cycles, and overall durability. The air content was determined using the gravimetric method [150], and the results for the different concrete mixtures are presented in Table 4.1.

For the mixtures without fibres (M1 to M5), the air content values ranged from 1.07% to 2.57%. These variations can be attributed to the specific aggregate types used in each mixture. The

presence of entrained air can improve the workability and freeze-thaw resistance of concrete, leading to enhanced durability.

On the other hand, the mixtures with polypropylene (PP) fibres (M6 to M10) exhibited air content values ranging from 1.17% to 4.20%. Comparing these values with the mixtures without fibres, it is evident that the inclusion of PP fibres can potentially affect the entrained air content. The interaction between the fibres and the mortar matrix may contribute to the slight increase in air content observed in some mixtures.

The observed variations in air content emphasise on the need for careful consideration of aggregate types and fibre additions in the concrete mix design. Proper control of the air content is crucial to achieving the desired performance characteristics and ensuring the long-term durability of the concrete structures [78,157].

4.1.3. Flow table test

The flow table test is a widely used method to evaluate the workability of concrete. It measures the concrete mixture's flow spread diameter when subjected to a standardized jolting action. Through a different method of workability evaluation, methods test provides valuable insights into the ability of the concrete to flow and self-compact properties.

Flow table tests were conducted on concrete samples containing different aggregate types in accordance with European standards [148]. The flow table results are shown in Table 4.1.

The flow table results indicate the workability of each mixture, with a higher spread diameter generally suggesting better flow and self-compacting properties. Among the mixtures without fibres, M2 (Andesite) exhibited the highest flow table value, indicating good workability. M1 (Quartz) and M5 (Crushed Clay Bricks) also demonstrated favourable flow characteristics [158].

For the mixtures with PP fibres, M7-ANPP (Andesite with PP fibres) had the highest flow table value, followed closely by M6-QZPP (Quartz with PP fibres). This suggests that the inclusion of PP fibres slightly affected the workability, but the mixtures still maintained acceptable flow properties [156,157].

In conclusion, the evaluation of fresh properties in this study highlighted the influence of aggregate types and the addition of PP fibres on the characteristics of concrete mixtures. The fresh density measurements revealed notable variations, as shown in Figure 4-1, with lightweight aggregates resulting in lower densities and quartz aggregate exhibiting higher densities [159]. The inclusion of PP fibres had a slight impact on fresh density, with mixtures containing PP fibres showing

comparable or slightly higher densities, and that agreed with most of the previous related literatures [78,97,98,157,160–162].

The air content analysis demonstrated the effect of aggregate types and PP fibres on entrained air [78,157], with variations observed in the mixtures. The presence of entrained air can enhance workability and durability. Adding PP fibres resulted in some mixtures showing a slight increase in air content, suggesting an interaction between the fibres and the mortar matrix.

The flow table test provided insights into the workability of the concrete mixtures, with higher spread diameters indicating better flow and self-compacting properties [163,164]. Among the mixtures without fibres, andesite demonstrated good workability, while Quartz and Crushed Clay Bricks also exhibited favourable flow characteristics. The mixtures with PP fibres maintained acceptable workability, with Andesite and Quartz mixtures showing the highest flow table values.

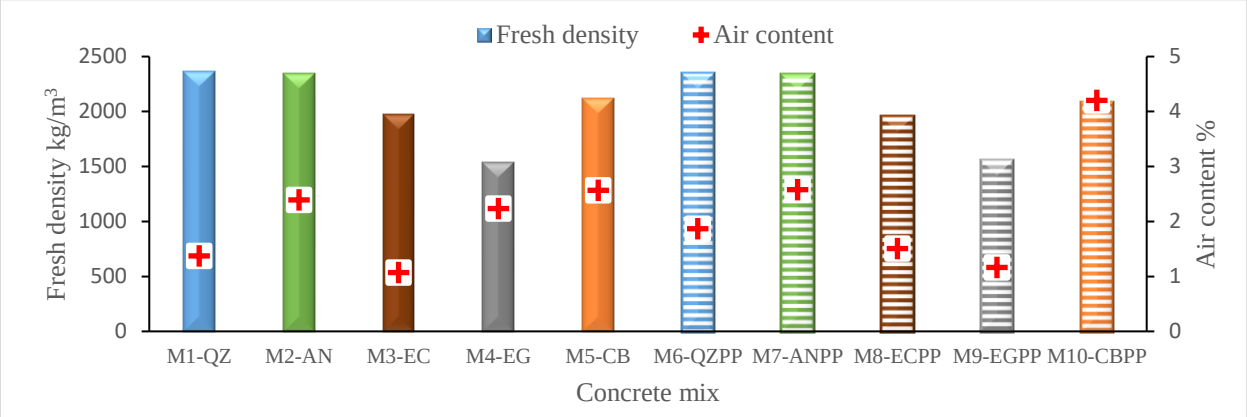


Figure 4-1. The fresh concrete density in comparison with the air content percentage

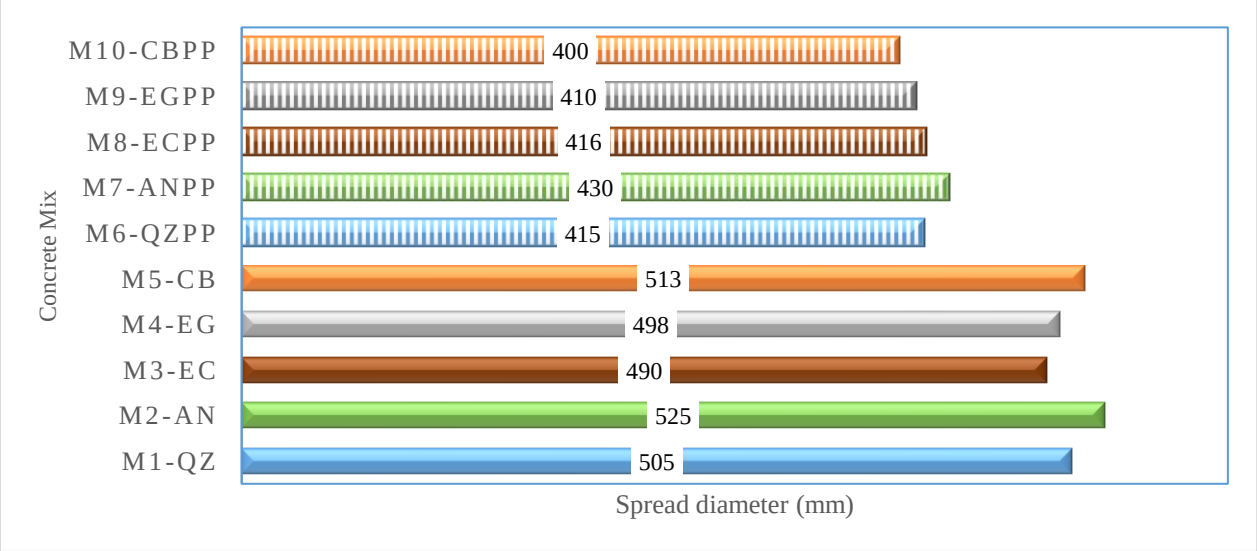


Figure 4-2. Flow table test results

4.2. Physical properties results

4.2.1. Moisture content

The moisture content percentage results before heating provide crucial insights into the initial moisture conditions of the concrete mixes at different ages: 28 days, 120 days, and 240 days as shown in Table 4.2 and Figure 4-3, shed light on the moisture characteristics of the concrete compositions before exposure to elevated temperatures, aiding in understanding their behaviour during thermal exposure. Overall, a clear trend emerges from the data, revealing a general decrease in moisture content as the concrete ages. This decline can be attributed to the concrete mixes' ongoing hydration process and maturation over time [165].

Upon examining the specific mixes, it was clear that certain compositions exhibit consistently low moisture content percentages across all ages. Notable examples include M2-AN, M3-EC, M4-EG, M5-CB, M6-QZPP, and M7-ANPP, demonstrating relatively lower initial moisture levels. These lower moisture contents suggest that these mixes had limited water content prior to thermal exposure [166].

On the other hand, mixes with lightweight aggregates and polypropylene fibres, such as M8-ECPP, M9-EGPP, and M10-CBPP, exhibit higher moisture content percentages, particularly at the earlier age of 28 days. This indicates that these mixes retained a relatively higher amount of moisture during the initial curing phase, potentially due to their composition or curing conditions [76].

Understanding the initial moisture conditions of the concrete mixes is essential for comprehending their response to elevated temperatures. Moisture content can influence phenomena such as moisture evaporation, which can impact weight loss and structural integrity during thermal exposure [167,168].

Correlating the moisture content results with other pertinent properties, such as weight loss percentages and mechanical behaviour, would provide a more comprehensive understanding of the interplay between moisture content and the performance of the concrete mixes under elevated temperature conditions [165,169–172].

Table 4.2. Moisture content before heating

Mixture	Concrete age		
	28 days	120 days	240 days
M1-QZ	2.8 %	2.1 %	0.4 %
M2-AN	0.6 %	0.3 %	0.4 %
M3-EC	2.0 %	0.6 %	0.4 %
M4-EG	2.3 %	1.0 %	0.7 %
M5-CB	1.6 %	0.9 %	0.7 %
M6-QZPP	2.7 %	2.0 %	0.4 %
M7-ANPP	3.8 %	1.4 %	0.4 %
M8-ECPP	4.2 %	3.5 %	1.9 %
M9-EGPP	2.0 %	1.2 %	0.9 %
M10-CBPP	5.6 %	2.9 %	1.2 %

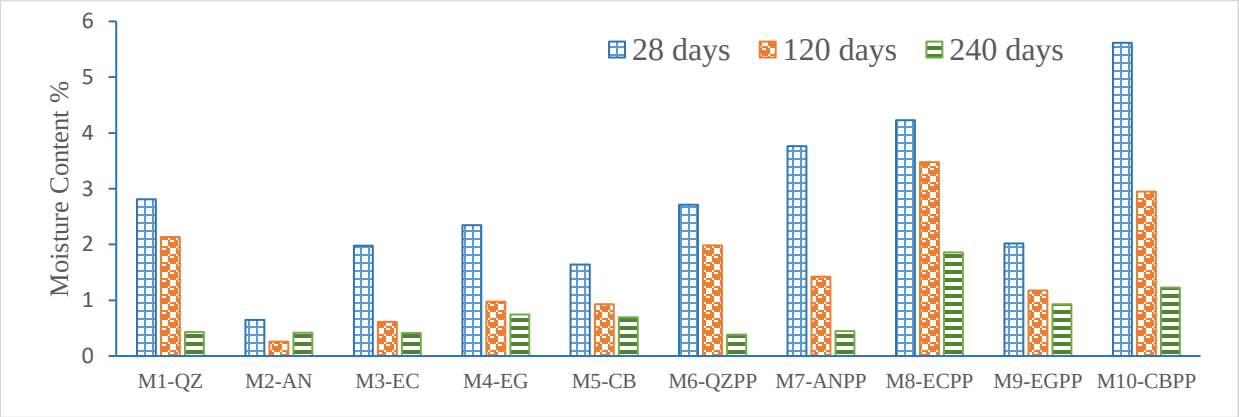


Figure 4-3. Moisture content in concrete specimen before heating

4.2.2. Hardened density

The hardened density of concrete is an important parameter that influences its structural integrity, durability, and overall performance. In this study, the hardened density of concrete mixtures was evaluated at different ages: 28 days, 120 days, and 240 days. The results are presented in Table 4.3, and Figure 4-4, illustrating the changes in density over time for each mixture.

Upon analysing the data, several observations can be made regarding the hardened density of the concrete mixes. Firstly, it is evident that the density decreases gradually as the concrete ages. This decline in density can be attributed to numerous factors, including the ongoing hydration process, moisture loss, and potential changes in the microstructure of the hardened concrete.

Examining the specific mixtures, it can be observed that most of them exhibit a consistent decrease in density as the age of the concrete increases. For instance, mix M1-QZ, which contains Quartz aggregate, shows a decrease in density from 2329.5 kg/m^3 at 28 days to 2273.7 kg/m^3 at 240 days.

Similarly, mix M4-EG, incorporating Expanded Glass aggregate, demonstrates a decline in density from 1506.3 kg/m^3 at 28 days to 1482 kg/m^3 at 240 days.

However, certain mixtures display a relatively stable density over time. Mixes such as M5-CB, M7-ANPP, and M10-CBPP show minor fluctuations in density throughout the ageing process, indicating a more consistent density profile. This suggests that the composition of the aggregates used in these mixtures may contribute to a more stable and uniform density.

The changes in hardened density are crucial to consider when evaluating the long-term performance and structural behaviour of concrete. Density directly affects properties such as strength, durability, and resistance to various external factors. The observed decrease in density over time may have implications for concrete elements' overall structural stability and load-bearing capacity.

It is important to note that the specific aggregate types used in the mixtures play a significant role in determining the hardened density [173]. Lightweight aggregates, such as Expanded Glass in mix M4-EG, generally result in lower densities due to their lower specific gravity compared to traditional aggregates. On the other hand, mixes containing Quartz aggregate, such as M1-QZ, exhibit higher densities owing to the denser nature of the Quartz particles.

Table 4.3. The hardened density of the concrete mixes through different ages

Mixture	**Density (kg/m^3)**		
Age	**28 days**	**120 days**	**240 days**
M1-QZ	2329.5	2313.4	2273.7
M2-AN	2339.2	2330.0	2333.7
M3-EC	1943.6	1916.8	1912.9
M4-EG	1506.3	1485.5	1482.0
M5-CB	2060.9	2046.0	2041.1
M6-QZPP	2281.9	2265.0	2228.6
M7-ANPP	2302.7	2248.0	2226.0
M8-ECPP	1909.7	1894.8	1863.6
M9-EGPP	1550.3	1537.1	1533.2
M10-CBPP	1987.7	1933.0	1899.3

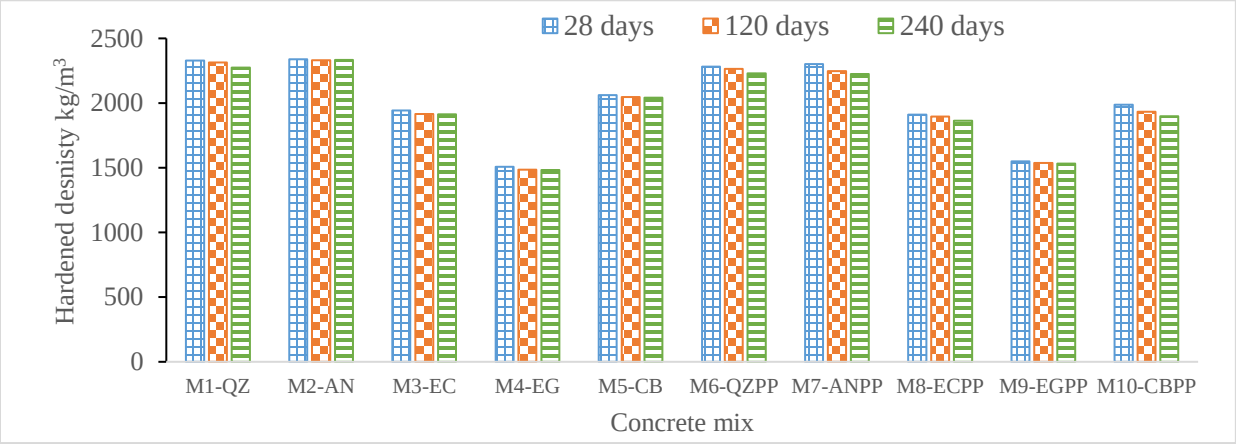


Figure 4-4. Hardened density of the concrete mixes through the different ages.

4.2.3. Weight loss due to heating

The results shown in Table 4.1 and Figure 4-5 provide significant insights into the weight loss percentages of the ten concrete mixtures when subjected to elevated temperatures from 200℃ to 1000℃ at distinct ages: 120 days and 240 days. These findings enhance the understanding of concrete behaviour under high-temperature conditions and offer implications for the design and performance of concrete structures.

The weight loss percentages exhibit a consistent upward trend as temperatures increase, elucidating the detrimental impact of elevated temperatures on concrete integrity. Notably, different concrete mixtures manifest varying levels of susceptibility to temperature-induced weight loss, reflecting their unique compositions and characteristics.

The expanded glass concrete mix (M4-EG) is particularly interesting, which displays comparatively higher weight loss percentages across all temperature levels and ages. This finding underscores the heightened vulnerability of M4-EG to weight loss and degradation when exposed to elevated temperatures. A notable observation is the increased weight loss exhibited by the M4-EG concrete mix, which incorporates expanded glass aggregate. The expanded glass aggregate, due to its lightweight nature and the expansion process involved in its production, possesses unique characteristics that influence its response to elevated temperatures. The susceptibility of expanded glass aggregate to thermal degradation, including the possibility of melting, contributes to the higher weight loss percentages observed in the M4-EG mix. Conversely, the andesite aggregate concrete mix with polypropylene fibres (M7-ANPP) and crushed clay bricks concrete mix with polypropylene fibres (M10-CBPP) demonstrate lower weight loss percentages at both 120 days and 240 days, indicating enhanced resilience in high-temperature environments. The incorporation

of polypropylene fibres in M7-ANPP and M10-CBPP emerges as a contributing factor to their improved performance.

The utilisation of crushed clay bricks in M10-CBPP provides several advantages in terms of high-temperature resistance. Clay bricks, due to their composition and manufacturing process, exhibit excellent thermal stability and resistance to weight loss when exposed to elevated temperatures. The inclusion of crushed clay bricks as an aggregate in M10-CBPP enhances its ability to withstand thermal stress and reduces weight loss compared to other mixes.

Additionally, the presence of polypropylene fibres in both M7-ANPP and M10-CBPP further enhances their performance under high-temperature conditions. The addition of polypropylene fibres improves the overall tensile strength and crack resistance of the concrete mixtures. These fibres act as reinforcement, dispersing internal stresses and inhibiting the formation and propagation of cracks caused by thermal expansion and contraction. Consequently, the weight loss percentages in M7-ANPP and M10-CBPP are lower compared to mixes without polypropylene fibres.

By combining the use of crushed clay bricks and polypropylene fibres, M10-CBPP demonstrates increased resilience to weight loss under elevated temperatures. The specific composition and properties of crushed clay bricks, in combination with the reinforcing effects of polypropylene fibres, contribute to the mix's improved performance and lower weight loss percentages.

Table 4.4. Weight loss due to heating

Age	**120 days**					**240 days**				
Mix	**200℃**	**400 ℃**	**600 ℃**	**800 ℃**	**1000 ℃**	**200 ℃**	**400 ℃**	**600 ℃**	**800 ℃**	**1000 ℃**
M1-QZ	3.7%	4.5%	7.5%	9.1%	10.4%	2.6%	3.6%	6.2%	8.3%	8.5%
M2-AN	2.0%	2.9%	5.1%	7.3%	8.5%	1.8%	1.9%	4.2%	7.6%	8.4%
M3-EC	3.0%	5.5%	9.0%	9.3%	9.7%	3.5%	5.7%	8.7%	8.3%	10.3%
M4-EG	1.4%	4.4%	8.5%	13.2%	15.6%	1.1%	6.4%	8.6%	12.1%	14.4%
M5-CB	2.4%	4.9%	8.3%	10.5%	11.1%	2.6%	4.8%	7.6%	8.9%	10.7%
M6-QZPP	2.9%	7.3%	8.6%	9.6%	10.8%	3.9%	5.7%	6.7%	8.0%	9.2%
M7-ANPP	2.0%	4.6%	6.1%	8.8%	9.9%	0.8%	3.1%	4.6%	7.3%	9.2%
M8-ECPP	3.5%	5.1%	8.6%	10.7%	12.3%	1.9%	4.6%	7.5%	11.0%	12.0%
M9-EGPP	2.1%	5.2%	9.7%	12.5%	15.8%	2.1%	6.7%	8.9%	10.1%	15.9%
M10-CBPP	3.3%	6.4%	7.6%	8.9%	9.7%	1.6%	5.0%	6.4%	6.9%	8.2%

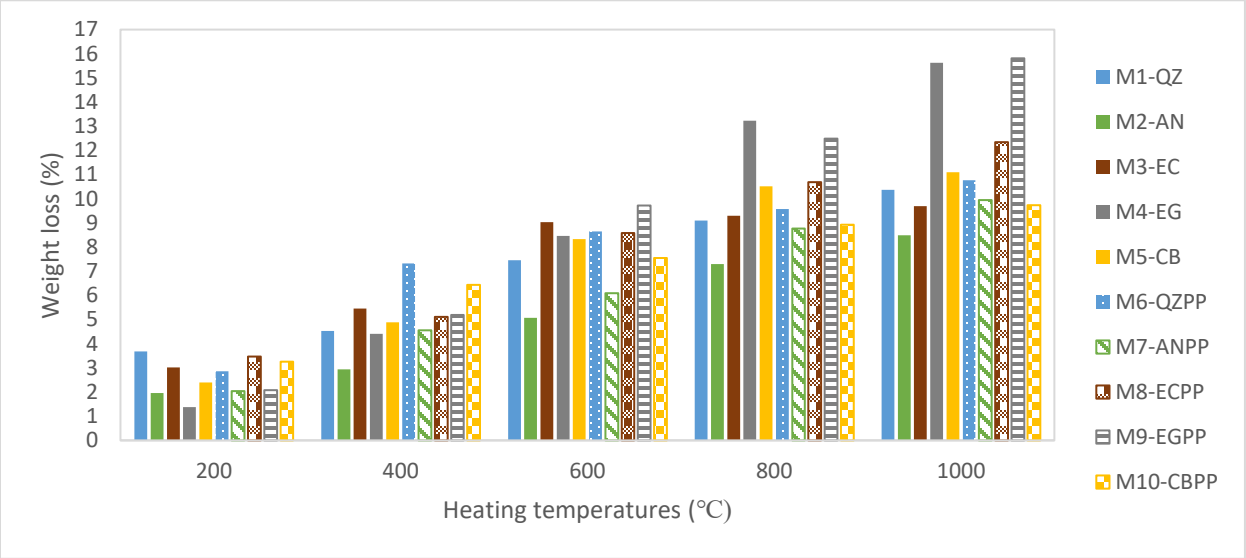


Figure 4-5. Weight loss in(%) for each concrete mixes after subjected to elevated temperatures

4.3. Mechanical Properties

4.3.1. Characteristic mechanical properties at age 28 days

At age 28 days, the mechanical properties of each concrete mixture were measured. Compressive and flexural strength tests were carried out according to the European standards [152], [153], while the shear strength test was carried out based on the Push-off model [75]; results are shown in Table 4.5.

Table 4.5. Characteristic mechanical properties at age 28 days

Mixture	Compressive strength (MPa)	Flexural strength (MPa)	Shear strength (MPa)
M1-QZ	67.6	8.4	10.3
M2-AN	85.8	10.2	10.4
M3-EC	66.0	6.3	6.2
M4-EG	23.3	3.2	3.8
M5-CB	68.7	8.5	9.0
M6-QZPP	58.9	7.2	8.8
M7-ANPP	79.1	8.8	10.5
M8-ECPP	61.5	6.0	6.0
M9-EGPP	21.5	2.9	4.0
M10-CBPP	53.6	8.2	8.5

Concerning the compressive strength classes according to EN 206-1 [174], the concrete mix (M1-QZ) and (M5-CB) can be classified as C50/60, while the concrete made with lightweight aggregates (M3-EC) and (M4-EG) can be classified as LC55/60 and LC16/18 respectively; more

over the concrete mix made with the andesite aggregate (M2-AN) can be classified as C60/75 (with the high strength concrete); taking in consideration for each concrete mix, the mean test results is the average of three specimens at least, and the distribution of the ratio of 100 mm cube to 150 mm cube specimens (fc, 100cu/fc, 150cu) for each batch of concrete is 1.01 [8]. Among all types of (M2-AN) concrete, the mix has demonstrated the highest compressive strength. The results show a variety of concrete strengths by the type of coarse aggregate, which can affect the porosity and density of the concrete. As a result, it can affect the concrete strength. Therefore, the coarse aggregate plays an essential role in the strength. The relationship between the compressive strength of concrete and the coarse aggregate agrees with results obtained in the other studies [175–177]. However, the cement matrix is the same for (M4-EG); the compressive strength is decreased by around 65% compared with the (M1-QZ) mixture in the case of using expanded glass (lightweight aggregate), which is proof of the aggregate effect in the concrete strength in the case of lower density aggregate and the surface characteristics of the aggregate. For the expanded glass aggregate the smooth spherical shape will decrease the bond between the aggregate and the mortar matrix Figure 4-6. It is well known that concrete attains a dense and impenetrable microstructure as it hardens, resulting in the cement matrix and the transition zone between the cement paste and aggregate becoming as strong as the coarse aggregate. Given that the aggregate can become the weak link in the concrete, it is crucial to select high-quality aggregate materials to achieve high-strength concrete. This is supported by research studies such as those conducted by Vishalakshi et al. [178].

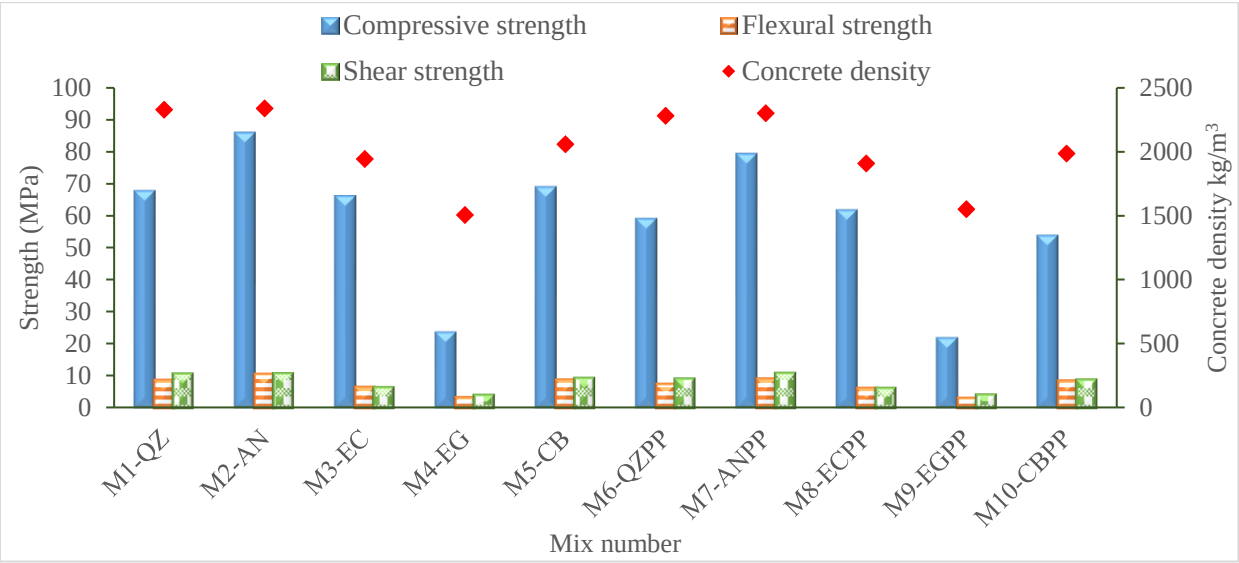


Figure 4-6. Relation between the characteristic mechanical properties at age 28 days and concrete density

4.3.2. Mechanical properties at concrete age 120 days

The comparison of mechanical properties at both 28 days and 120 days of concrete age offers valuable insights into the development and performance of the tested concrete mixes. Examining the compressive strength, it is evident that the values have generally increased from 28 days to 120 days for most mixes, as shown in Table 4.6 and Figure 4-7. For instance, mix M2-AN showed an improvement in compressive strength, increasing from 85.8 MPa at 28 days to 86.82 MPa at 120 days, while mix M9-EGPP exhibited a marginal decrease from 21.5 MPa to 20.8 MPa over the same period.

Similarly, the flexural strength and shear strength values have also demonstrated varying degrees of improvement or stability over time. Mixes such as M7-ANPP, M8-ECPP, and M10-CBPP showcased consistent or slightly enhanced flexural and shear strengths at 120 days compared to 28 days. In contrast, some mixes, like M4-EG and M9-EGPP, demonstrated limited improvement or even slight reductions in flexural and shear strengths at 120 days.

Interested observations can be made when comparing the shear strength results at 120 days with the 28-day values. Mixes such as M1-QZ, M2-AN, and M7-ANPP maintained relatively high shear strengths at 120 days, similar to their 28-day values. This suggests that the shear resistance of these mixes remains stable over time. On the other hand, mixes like M4-EG and M9-EGPP exhibited slight increases in shear strength at 120 days compared to their 28-day values. This improvement indicates that the shear performance of these mixes continues to develop with age.

The fluctuations in flexural and shear strengths observed between the concrete mixes at 28 days and 120 days can be elucidated by the inherent disparities in mechanical and chemical properties associated with the varying aggregate types employed. These differences in aggregate characteristics, such as particle shape, size distribution, mineralogy, and interfacial bonding with the cementitious matrix, substantially influence the concrete's long-term mechanical behaviour, resulting in the observed variations in strength over time [179–181].

These results indicate that the effects of curing and ageing on the mechanical properties of concrete mixes vary depending on their composition and specific characteristics. Therefore, a comprehensive understanding of the concrete's long-term behaviour is crucial for optimizing the selection and performance of concrete mixes in different applications. Additionally, including Polypropylene fibres in certain mixes, as denoted by 'PP,' appears to have influenced the mechanical properties, particularly in improving flexural and shear strengths.

Table 4.6. Ambient temperature mechanical properties at age 120 days

Mix	Compressive strength (MPa)	Flexural strength (MPa)	Shear strength (MPa)	Concrete density (kg/m^3)
M1-QZ	79.12	8.77	10.90	2313
M2-AN	86.82	10.94	11.27	2330
M3-EC	69.29	8.83	6.67	1917
M4-EG	23.02	3.30	3.83	1486
M5-CB	70.59	6.78	9.12	2046
M6-QZPP	71.4	7.3	9.7	2265
M7-ANPP	82.7	9.1	11.1	2248
M8-ECPP	64.4	6.3	6.3	1895
M9-EGPP	20.8	3.1	3.9	1537
M10-CBPP	58.3	8.6	8.6	1933

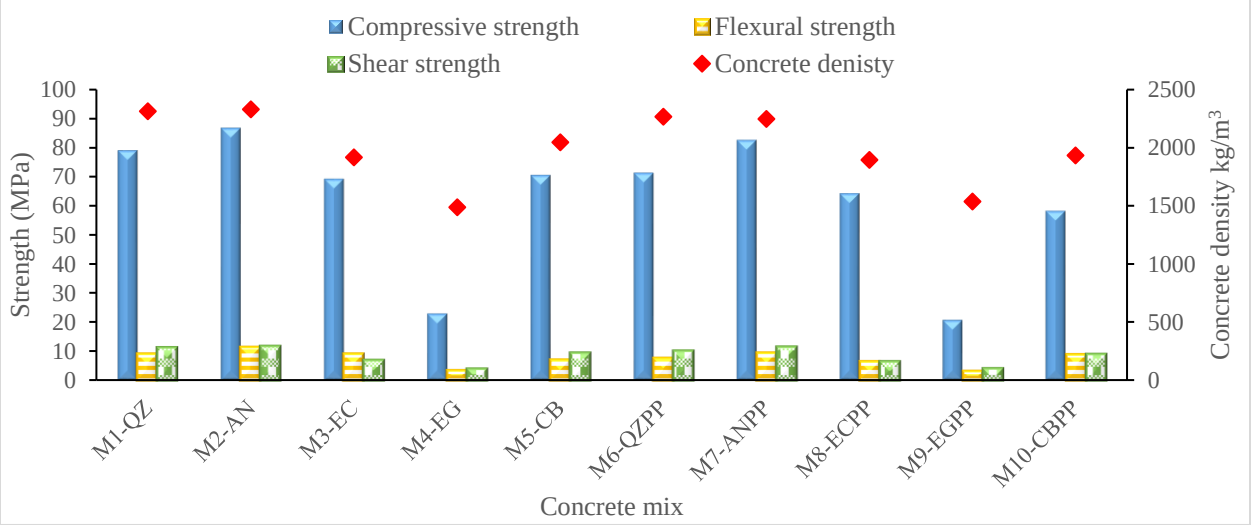


Figure 4-7. Relation between the mechanical properties at age 120 days and the concrete density

4.3.3. Mechanical at concrete age 240 days

The examination of the mechanical properties at 240 days of concrete age provides further insights into the long-term performance of the tested concrete mixes. The compressive strength values continue to show improvement over time, with most mixes demonstrating increased strength compared to the values at 28 days and 120 days. Mixes like M2-AN and M1-QZ exhibit significant increases in compressive strength, indicating the continued development and maturity of the

concrete. Other mixes, such as M4-EG and M9-EGPP, show more limited or marginal increases in compressive strength at 240 days, as presented in Table 4.7 and Figure 4-8.

Similarly, the flexural and shear strength values display varying degrees of improvement or stability at 240 days. Mixes like M7-ANPP and M10-CBPP demonstrate enhanced flexural and shear strengths, indicating the concrete's ability to withstand bending and shear forces over time. On the other hand, mixes like M4-EG and M9-EGPP show relatively modest improvements in flexural and shear strengths at 240 days.

Additionally, the concrete density values remained relatively constant for most mixes at 240 days compared to the earlier age intervals. These results highlight concrete's continued development and maturity with age, contributing to improved strength and durability. It is worth noting that the inclusion of Polypropylene fibres, as indicated by 'PP,' still appears to have influenced the mechanical properties, with certain mixes showing slightly enhanced flexural and shear strengths. Overall, these findings underscore the importance of considering the concrete's age and corresponding mechanical properties to ensure concrete structures' long-term performance and resilience.

Table 4.7. Ambient temperature mechanical properties at age 240 days

Mix	Compressive strength (MPa)	Flexural strength (MPa)	Shear strength (MPa)	Concrete density kg/m^3
M1-QZ	80.6	8.8	10.9	2273.7
M2-AN	93.8	11.0	12.2	2333.7
M3-EC	76.0	6.9	7.3	1912.9
M4-EG	24.6	3.4	4.1	1482.0
M5-CB	71.5	8.9	10.7	2041.1
M6-QZPP	71.0	7.5	9.8	2228.6
M7-ANPP	83.5	9.0	11.3	2226.0
M8-ECPP	68.7	7.1	6.3	1863.6
M9-EGPP	22.1	3.3	3.9	1533.2
M10-CBPP	59.2	8.7	8.9	1899.3

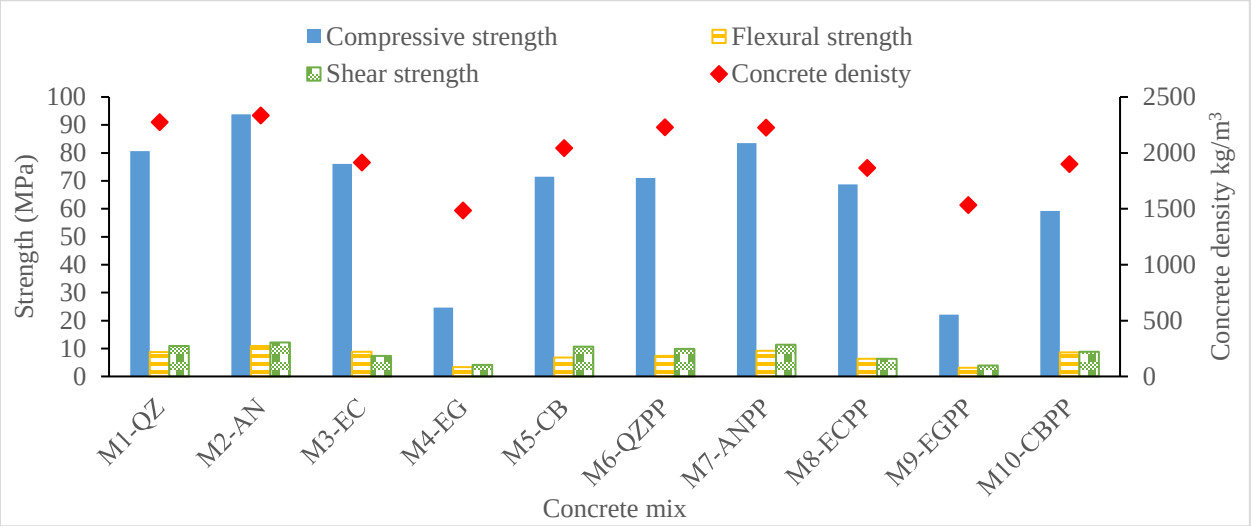


Figure 4-8. Relation between the mechanical properties at age 240 days and the concrete density

4.3.4. Microstructural analysis using SEM

Scanning Electron Microscopy (SEM) is a powerful tool for analysing the material microstructure. SEM analysis enables the correlation of the macroscopic behaviour for the different concrete mixes, underlying microstructural features, and aggregates' internal structure. SEM serves as a critical tool for connecting the relationships between composition, hydration, and mechanical properties. By integrating SEM results shown in Figure 4-9 to Figure 4-18, and the mechanical properties test results presented in Table 4.5, t the behaviour of each concrete mix becomes distinctly evident.

For instance, Mix (M1-QZ), containing quartz aggregate, exhibited a remarkable compressive strength of 67.6 MPa, attributed to adequate hydration indicated by the presence of calcium silicate hydrate (C-S-H) and a well-defined interface transition zone (ITZ). The absence of ettringite further supported its high strength. Similarly, Mix (M2-AN) demonstrated outstanding compressive strength at 85.8 MPa, coupled with robust hydration and mechanical properties.

On the other hand, Mix (M3-EC), incorporating expanded clay aggregate, achieved a compressive strength of 66 MPa, showcasing the presence of ettringite. However, the absence of ITZ indicated strong interlocking between aggregates and the cement paste, contributing to its commendable strength. In contrast, Mix (M4-EG), made with expanded glass aggregate, displayed a significantly lower compressive strength of 23.3 MPa due to the presence of pores, ettringite, and ITZ, negatively affecting its strength and suggesting limited hydration and bonding between the

aggregate and cement paste. Lastly, Mix (M5-CB), utilizing crushed clay bricks, exhibited a robust compressive strength of 68.7 MPa, attributed to thorough hydration and sound mechanical properties, supported by the presence of C-S-H and ITZ [95,182–187].

Figure 4-9. Micrograph of M1-QZ mix

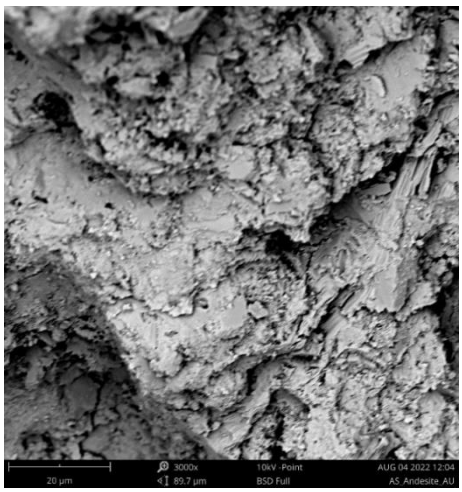


Figure 4-10. Micrograph of M2-AN mix

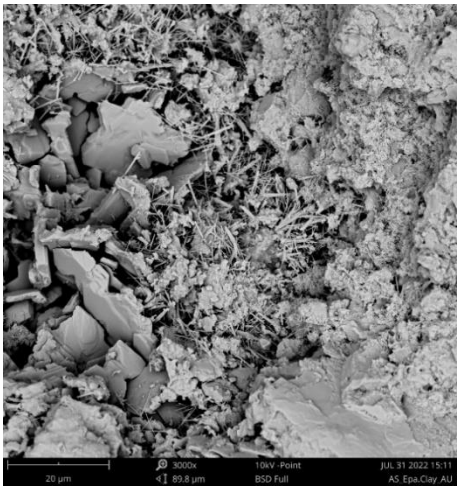


Figure 4-11. Micrograph of M3-EC mix

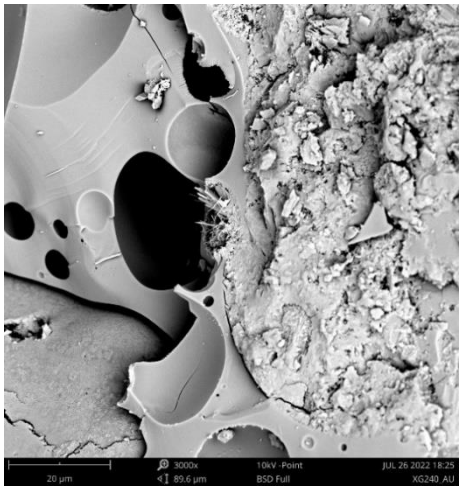


Figure 4-12. Micrograph of M4-EG mix

Figure 4-13. Micrograph of M5-CB mix

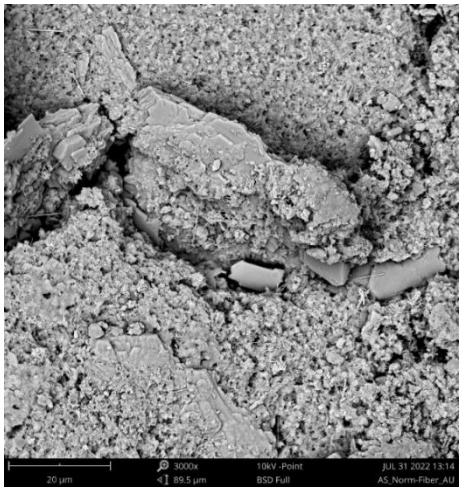


Figure 4-14. Micrograph of M6-QZPP

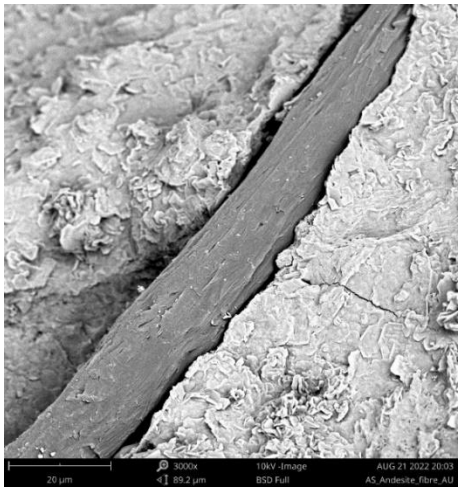


Figure 4-15. Micrograph of M7-ANPP

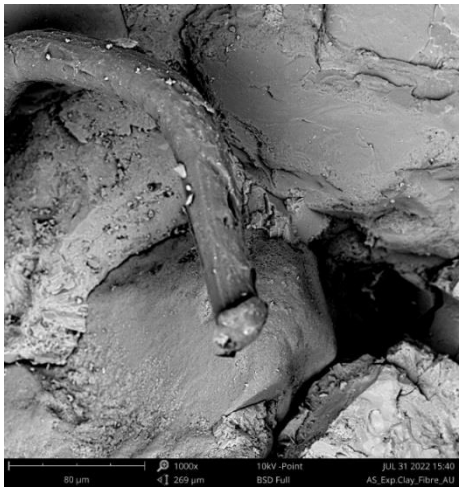


Figure 4-16. Micrograph of.M8-ECPP

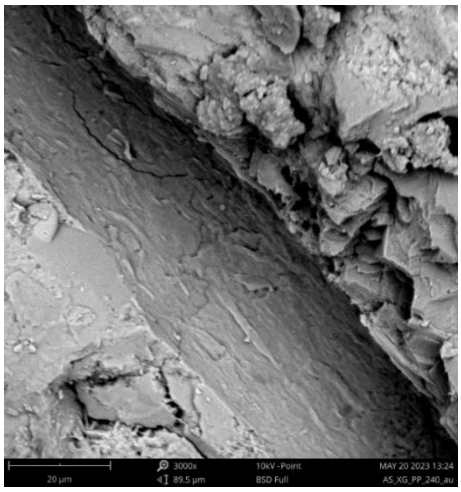


Figure 4-17. Micrograph of M9-EGPP

Figure 4-18. Micrograph of M10-CBPP

4.3.5. Conclusion on mechanical properties at different ages

In conclusion, the age of concrete significantly affects its mechanical properties, regardless of the type of aggregates used. The analysis of compressive strength, flexural strength, shear strength, and concrete density at different ages (28 days, 120 days, and 240 days) provides insights into the development and performance of concrete made with different types of aggregates.

Overall, the results indicate that most concrete mixes exhibit an improvement in compressive strength over time. This suggests that the aggregates used in the mixes continue to contribute to the development of strength as the concrete ages. However, the extent of improvement varies depending on the specific mix composition and aggregate type. For example, mixes M2-AN and M7-ANPP consistently demonstrate high compressive strength values compared to other mixes, indicating the positive influence of the Andesite aggregate.

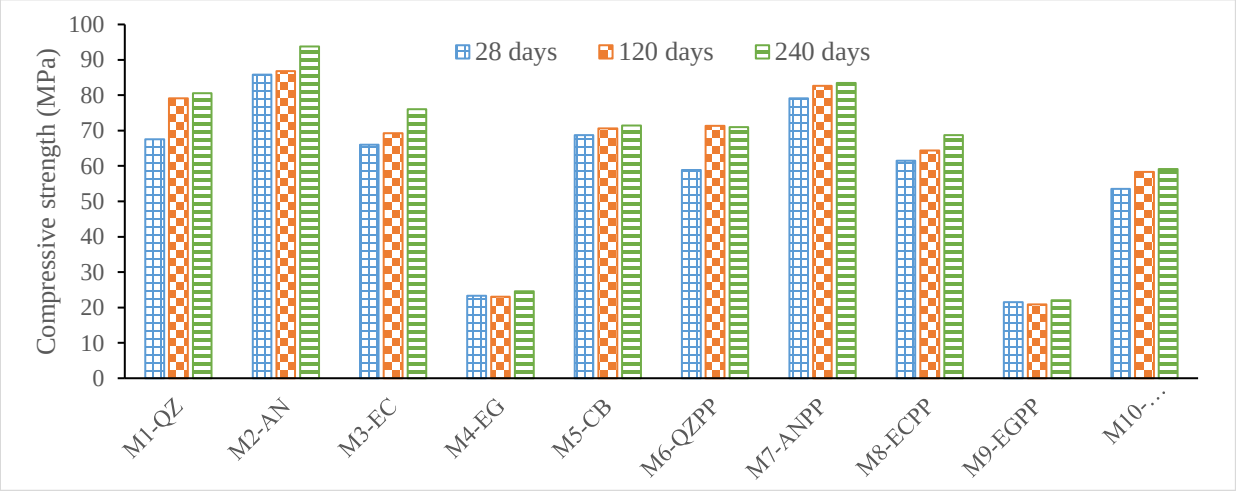


Figure 4-19. Development of compressive strength with age

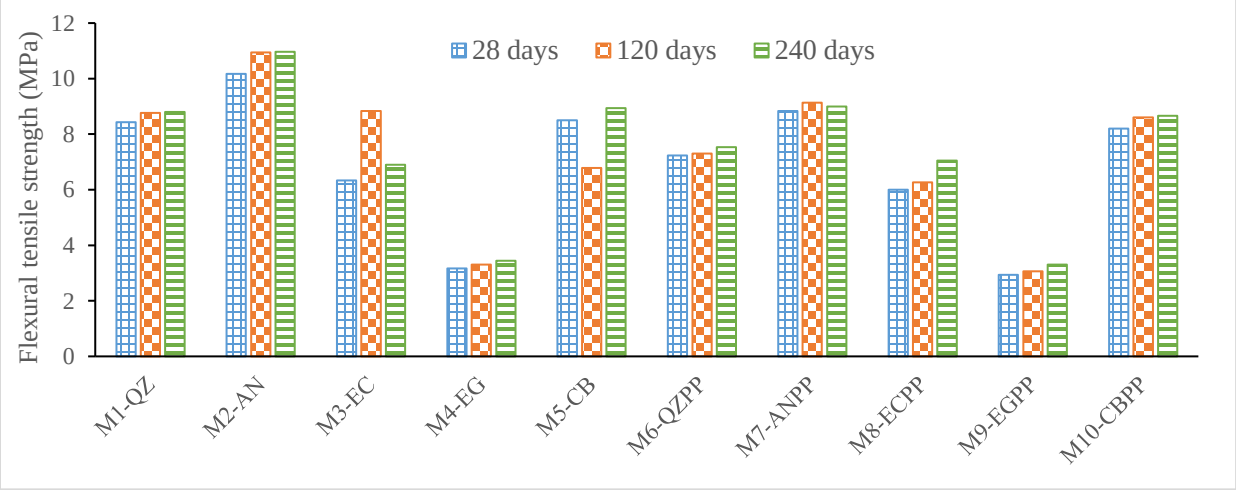


Figure 4-20. Development of flexural tensile strength with age

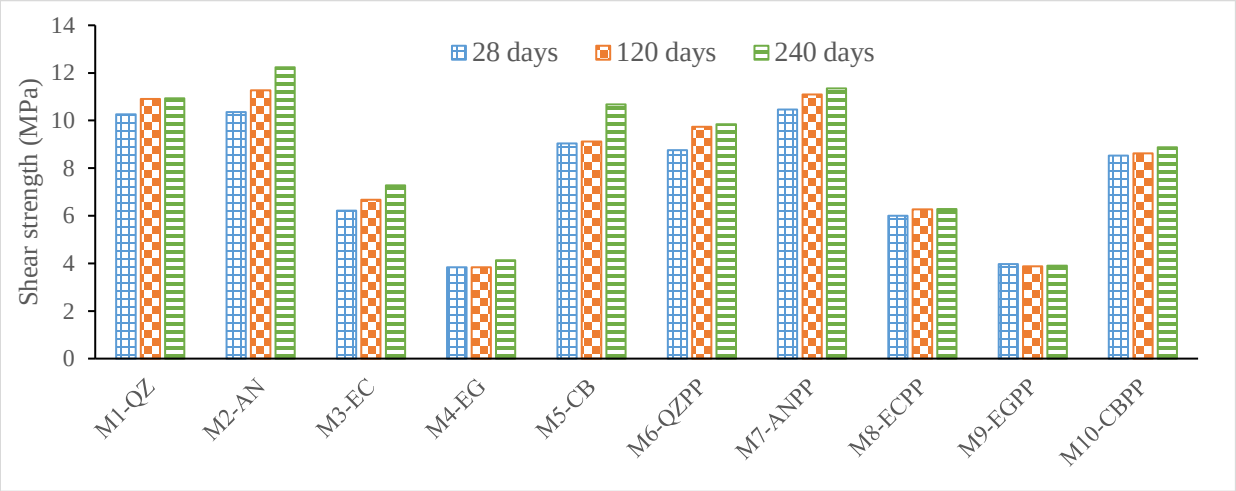


Figure 4-21. Development of shear strength with age

Regarding flexural strength and shear strength in Figure 4-20 and Figure 4-21, a similar trend can be observed. Specific mixes, such as M7-ANPP and M10-CBPP, consistently exhibit enhanced flexural and shear strengths, suggesting the beneficial impact of the aggregate types used in those mixes. Conversely, mixes like M4-EG and M9-EGPP show limited or modest improvements in these properties, indicating the potential limitations of the Expanded Glass aggregate regarding strength development. Concrete density, on the other hand, remains relatively stable for most mixes across different ages, as it shown in Figure 4-4. This suggests that the type of aggregates used has a lesser influence on concrete density over time.

In summary, while the specific type of aggregate used in concrete does play a role in determining its mechanical properties, the age of the concrete has a more pronounced effect. As concrete ages, it generally demonstrates improved mechanical properties, including compressive, flexural, and shear strength.

4.4. Mechanical properties after subjected to elevated temperatures (without fibres)

4.4.1. Compressive strength

The investigation aimed to evaluate the effect of elevated temperatures on the compressive strength of concrete specimens at two distinct ages: 120 days and 240 days. The study involved recording the average compressive strength and residual compressive strength percentages for each heating temperature and comparing them with the results obtained at ambient temperature (20 °C); results for compressive strength behaviour at age 120 and 240 days are presented in Table 4.8, Figure 4-22 and Figure 4-23 respectively.

For mix M1-QZ, at an age of 120 days and ambient temperature, the average compressive strength was measured at 79.1 MPa. As the temperature increased, a gradual decline in compressive strength was observed. At 200 °C, the average compressive strength decreased to 58.8 MPa (74% residual strength) and dropped to 13.4 MPa (17% residual strength) at 1000 °C. At the age of 240 days, the compressive strength for M1-QZ improved, with values of 80.6 MPa at 20 °C, 67.3 MPa (83.5% residual strength) at 200 °C, and 19.2 MPa (23.8% residual strength) at 1000 °C.

Similarly, for mix M2-AN, at age 120 days and ambient temperature, the average compressive strength was 86.8 MPa. As the temperature increased, a gradual decrease in compressive strength was observed. At 200 °C, the average compressive strength dropped to 79.9 MPa (92% residual strength) and decreased to 16.1 MPa (18% residual strength) at 1000 °C. while at of 240 days age, the compressive strength for M2-AN improved, with values of 93.8 MPa at 20 °C, 83.4 MPa (88.9% residual strength) at 200 °C, and 19.6 MPa (20.9% residual strength) at 1000 °C.

Conversely, the M3-EC mix, incorporating expanded clay aggregate, exhibited a decline in compressive strength with increasing heating temperature. At 400 °C, the M3-EC mix demonstrated an average compressive strength of 63.1 MPa (91% residual strength) at 120 days, which decreased to 62.4 MPa (82.1% residual strength) at 240 days. The expanded clay aggregates, known for their lightweight and porous nature, providing good insulation properties, experienced a reduction in inherent strength and potential thermal expansion at higher temperatures, resulting in an overall decrease in the compressive strength of the concrete.

The M4-EG mix, incorporating expanded glass aggregate, displayed lower average compressive strength, especially at higher heating temperatures. For instance, at 800 °C and an age of 120 days, the M4-EG mix exhibited an average compressive strength of 5.5 MPa (24% residual strength), which further decreased to 3.9 MPa (15.9% residual strength) at 240 days. The expanded glass aggregates possessed comparatively lower inherent strength, and their expansion and potential fragmentation under elevated temperature conditions contributed to the observed decline in the compressive strength of the M4-EG specimens.

Likewise, the M5-CB mix, utilizing crushed clay bricks as aggregate, demonstrated a decline in compressive strength with increasing heating temperature. At 600 °C, the M5-CB mix displayed an average compressive strength of 46.4 MPa (66% residual strength) at 120 days, slightly decreasing to 47.1 MPa (65.9% residual strength) at 240 days. This behaviour can be attributed to the vulnerability of clay bricks to thermal cracking and degradation at high temperatures. Despite

this decline, the M5-CB specimens still retained a significant proportion of their initial strength due to the inherent strength of the clay bricks.

The intriguing trend of increasing residual strength observed in specific concrete samples, such as Mix M1-QZ and Mix M3-EC, subjected to temperatures between 200 °C and 400 °C, can be attributed to a combination of factors related to the complex behaviour of concrete under high-temperature conditions. Initially, the decrease in compressive strength at 200 °C can be attributed to the aggregates properties used. For example, aggregates like expanded clay may expand at lower temperatures, leading to an initial reduction in compressive strength due to weakened aggregate-cement matrix bonding. As the temperature rises beyond 200 °C and approaches 400 °C, additional phenomena come into play. Firstly, the process of dehydration becomes significant. High temperatures cause the release of chemically bound water within the mortar matrix, contributing to a loss of strength. However, the rate of decrease in strength may slow down because much of the moisture has already been driven out during the initial heating at 200 °C [188].

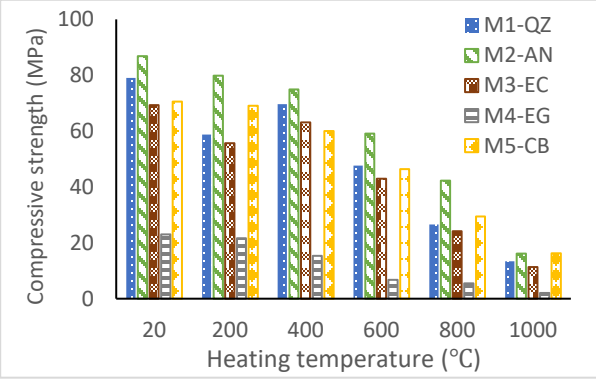


Figure 4-22. Average compressive strength results at age 120 days for concrete made with different types of aggregates

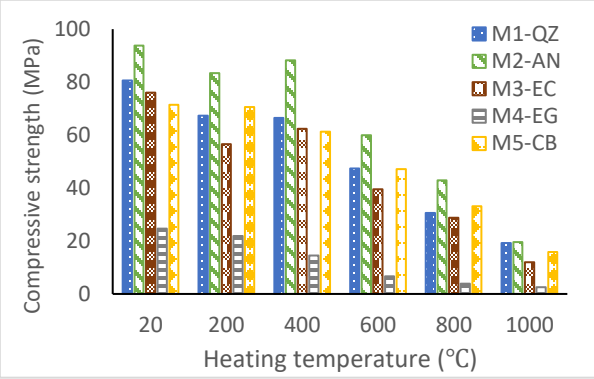


Figure 4-23. Average compressive strength results at age 240 days for concrete made with different types of aggregates

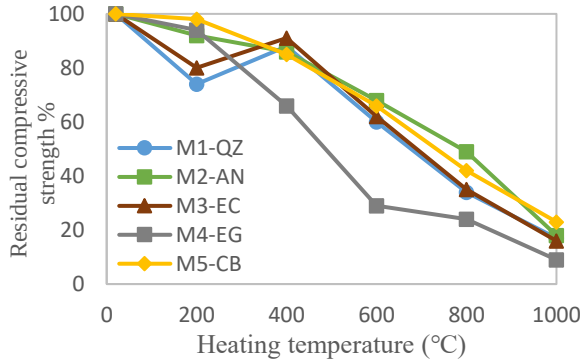


Figure 4-24. Relative residual compressive strength of concrete made with different types of aggregates at age 120 days

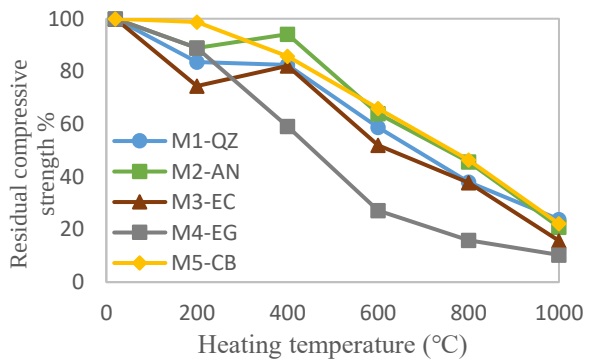


Figure 4-25. Relative residual compressive strength of concrete made with different types of aggregates at age 240 days

Table 4.8. Compressive strength results at both ages 120 and 240 days after subjected to elevated temperature

Age	120 days			240 days		
Mix – heating temperature	**Average compressive strength (MPa)**	**Residual compressive strength (%)**	**Standard deviation (σ)**	**Average compressive strength (MPa)**	**Residual compressive strength (%)**	**Standard deviation (σ)**
M1-QZ-20	79.1	100	1.4	80.6	100	1.4
M1-QZ-200	58.8	74	0.9	67.3	83.5	1.2
M1-QZ-400	69.6	88	0.3	66.5	82.4	0.3
M1-QZ-600	47.7	60	1.7	47.3	58.7	2.5
M1-QZ-800	26.6	34	1.8	30.6	38.0	1.0
M1-QZ-1000	13.4	17	3.1	19.2	23.8	1.2
M2-AN-20	86.8	100	2.7	93.8	100	0.2
M2-AN-200	79.9	92	2.0	83.4	88.9	4.2
M2-AN-400	74.9	86	3.2	88.3	94.1	2.4
M2-AN-600	59.1	68	2.9	60.0	63.9	2.2
M2-AN-800	42.3	49	2.8	42.9	45.7	4.6
M2-AN-1000	16.1	18	1.3	19.6	20.9	4.0
M3-EC-20	69.3	100	2.4	76.0	100	2.1
M3-EC-200	55.7	80	4.4	56.6	74.5	3.9
M3-EC-400	63.1	91	4.7	62.4	82.1	3.8
M3-EC-600	42.9	62	2.1	39.5	51.9	4.6
M3-EC-800	24.2	35	2.0	28.7	37.8	2.6
M3-EC-1000	11.3	16	1.3	11.9	15.7	1.5
M4-EG-20	23.0	100	0.3	24.6	100	0.3
M4-EG-200	21.7	94	1.6	21.9	88.9	0.6
M4-EG-400	15.3	66	0.5	14.6	59.1	1.7
M4-EG-600	6.8	29	0.4	6.7	27.2	0.1
M4-EG-800	5.5	24	0.8	3.9	15.9	0.0
M4-EG-1000	2.0	9	0.1	2.5	10.3	0.3
M5-CB-20	70.6	100	1.9	71.5	100	2.8
M5-CB-200	69.1	98	6.6	70.5	98.7	1.5
M5-CB-400	60.0	85	3.9	61.3	85.7	1.1
M5-CB-600	46.4	66	0.8	47.1	65.9	2.4
M5-CB-800	29.4	42	2.3	33.1	46.4	2.1
M5-CB-1000	16.3	23	1.5	15.8	22.2	1.3

4.4.2. Flexural tensile strength

In addition to the compressive strength, the flexural tensile strength of the concrete specimens was also evaluated using a 3-point loading test at ages 120 and 240 days. The average flexural strength and residual flexural strength percentages were recorded for each age and compared to the results obtained at ambient temperature, as shown in Table 4.9.

For mix M1-QZ at age 120 days and ambient temperature, the average flexural strength was 8.8 MPa. The flexural strength gradually decreased as the temperature increased, with residual strength percentages ranging from 1.52% to 100% at different heating temperatures. At age 240 days, the flexural strength remained relatively consistent, with values ranging from 5.7 MPa to 8.8 MPa, corresponding to residual strength percentages of 6.06% to 100%.

Similarly, for mix M2-AN, the flexural strength decreased with increasing temperature at both ages. At age 120 days, the average flexural strength was 10.9 MPa at ambient temperature and ranged from 1.1 MPa to 10.7 MPa at elevated temperatures. At age 240 days, the flexural strength ranged from 1.1 MPa to 8.9 MPa, representing residual strength percentages of 10.05% to 100%.

Mixes M3-EC and M4-EG exhibited a similar trend, with decreasing flexural strength as the temperature increased. However, mix M5-CB demonstrated an interesting behaviour, with an increase in flexural strength at age 240 days compared to age 120 days. At age 240 days, mix M5-CB showed an average flexural strength of 11.0 MPa at ambient temperature, indicating improvement in its flexural properties.

These findings indicate that the flexural tensile strength of the concrete mixes is influenced by both age and heating temperature. The response to elevated temperatures varies depending on the mix composition, with some mixes exhibiting a decline in flexural strength while others demonstrate improved or relatively stable performance. The observed residual flexural strength percentages provide insights into the ability of the concrete mixes to withstand elevated temperatures without significant loss in strength.

Understanding the flexural behaviour of concrete under thermal exposure is essential for ensuring the structural integrity of concrete elements subjected to high-temperature conditions. The results highlight the importance of considering the age of the concrete and its corresponding flexural properties when evaluating its performance under elevated temperatures. Further research and analysis are recommended to explore the factors contributing to the observed variations in flexural strength and residual strength percentages among different concrete mixes.

Table 4.9.Flexural strength results after subjected to elevated temperatures at ages 120 and 240 days

Age	120 days			240 days		
Mix – heating temperature	**Average flexural strength (MPa)**	**Residual flexural strength (%)**	**Standard deviation (σ)**	**Average flexural strength (MPa)**	**Residual flexural strength (%)**	**Standard deviation (σ)**
M1-QZ-20	8.8	100	0.2	8.8	100	0.2
M1-QZ-200	7.7	87.6	0.2	7.8	89.0	0.2
M1-QZ-400	5.1	58.2	0.1	5.7	64.4	0.6
M1-QZ-600	2.1	24.0	0.3	2.8	31.6	0.1
M1-QZ-800	0.6	7.2	0.2	1.4	15.9	0.4
M1-QZ-1000	0.1	1.5	0.2	0.5	6.1	0.3
M2-AN-20	10.9	100	0.3	8.9	100	0.2
M2-AN-200	10.7	97.9	0.3	8.2	91.8	0.2
M2-AN-400	7.2	66.1	0.3	7.3	81.3	0.2
M2-AN-600	5.4	49.1	0.2	5.0	56.0	0.2
M2-AN-800	2.4	22.2	0.5	2.4	27.2	0.5
M2-AN-1000	1.1	10.1	0.2	1.1	12.7	0.2
M3-EC-20	8.8	100	0.1	7.05	100	0.14
M3-EC-200	8.1	91.7	0.2	6.08	86.3	0.13
M3-EC-400	7.3	82.3	0.2	3.91	55.4	0.07
M3-EC-600	4.5	50.9	0.4	2.50	35.4	0.35
M3-EC-800	1.7	19.6	0.2	1.04	14.8	0.13
M3-EC-1000	0.7	8.3	0.2	0.47	6.7	0.06
M4-EG-20	3.3	100	0.1	3.4	100	0.1
M4-EG-200	2.9	86.4	0.2	2.9	85.2	0.2
M4-EG-400	2.3	69.7	0.1	2.4	70.0	0.2
M4-EG-600	1.0	29.3	0.1	0.9	25.9	0.2
M4-EG-800	0.5	15.1	0.0	0.5	13.3	0.1
M4-EG-1000	0.1	4.2	0.0	0.2	5.3	0.0
M5-CB-20	6.8	100	0.1	11.0	100	0.1
M5-CB-200	5.6	82.1	0.4	10.4	94.5	0.4
M5-CB-400	4.7	69.2	0.1	8.9	80.9	0.3
M5-CB-600	3.5	51.6	0.5	7.4	67.2	0.4
M5-CB-800	1.3	19.3	0.0	2.7	24.6	0.5
M5-CB-1000	0.5	6.9	0.1	1.5	13.4	0.1

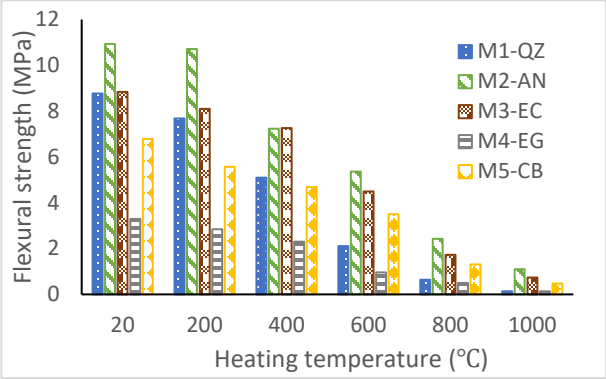


Figure 4-26. Average flexural tensile strength results at age 120 days for concrete made with different types of aggregates

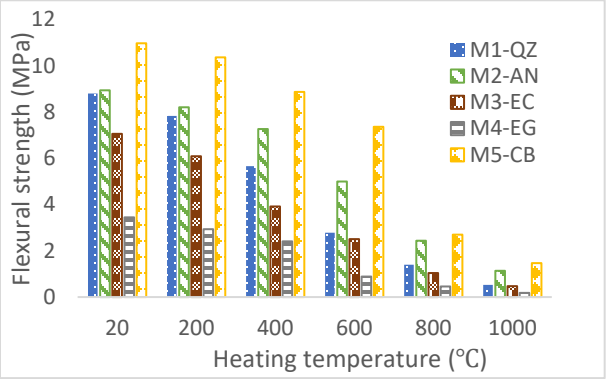


Figure 4-27. Average flexural tensile strength results at age 240 days for concrete made with different types of aggregates

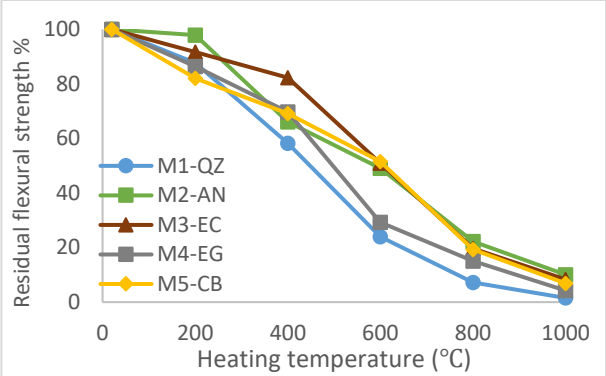


Figure 4-28. Relative residual flexural strength of concrete made with different types of aggregates at age 120 days

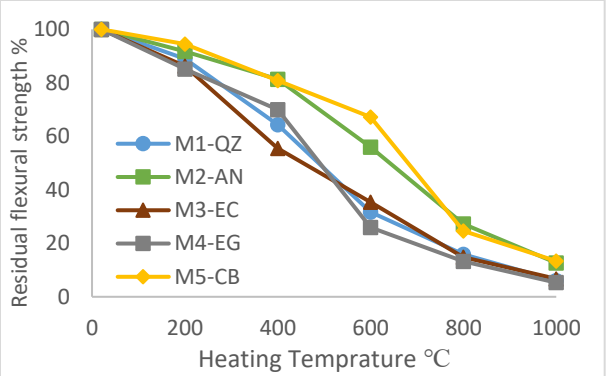


Figure 4-29. Relative residual flexural strength of concrete made with different types of aggregates at age 240 days

4.4.3. Shear strength

The shear strength of concrete mixes at elevated temperatures was evaluated using the Push-off model, considering two different ages of 120 and 240 days presented in Table 4.8 and Figure 4-30 to Figure 4-33.

Test results showed a decreased shear strength with increasing temperature at both 120 and 240-day ages for the concrete mix with quartz aggregate (M1-QZ). This indicates a progressive reduction in shear resistance over time. The residual strengths at elevated temperatures ranged from 16.8% to 66.5%. The effect of age on shear strength suggests that as concrete matures, the reduction in shear strength becomes more pronounced at elevated temperatures.

Similarly, the concrete mix with andesite aggregate (M2-AN) exhibited a decline in shear strength as the temperature increased at both 120 and 240-day ages. The residual strengths ranged from 22.6% to 92.1%. The influence of age on shear strength shows that as concrete ages, it exhibits

relatively better resistance to high temperatures, resulting in higher residual strengths compared to the 120-day age.

The concrete mix incorporating expanded clay aggregate (M3-EC) displayed a unique behaviour at both ages. At 200 °C, the shear strength slightly increased, indicating a possible beneficial effect of age and temperature interaction on shear strength. However, as the temperature continued to rise, the shear strength gradually decreased. The residual strengths at elevated temperatures ranged from 3.5% to 101.4%. The effect of age on shear strength suggests that the performance of M3-EC improves with age, but it still experiences a reduction in shear strength at high temperatures.

The concrete mixture incorporating expanded glass aggregate (M4-EG) experienced a notable decline in shear strength as temperatures rose, reaching zero at 1000 °C, indicating a complete loss of strength. This underscores that as concrete matures, it becomes increasingly vulnerable to the adverse impacts of elevated temperatures on shear strength. This interplay of factors tied to the hydration process, microstructural alterations, and responses to higher temperatures makes the influence of age on concrete shear strength a multifaceted phenomenon. While compressive strength typically rises with age, shear strength may decline due to shifts in internal cohesion and heightened susceptibility to thermal effects. In contrast, the concrete mix incorporating crushed clay bricks (M5-CB) displayed higher shear strength and better resistance to high temperatures than other mixes at both ages. The residual strengths ranged from 15.4% to 91.6%. The effect of age on shear strength suggests that as concrete ages, M5-CB exhibits improved resistance to elevated temperatures, resulting in higher residual strengths.

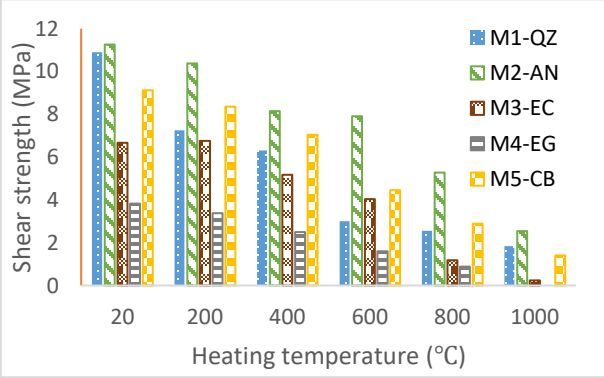


Figure 4-30. Average shear strength results at age 120 days for concrete made with different types of aggregates

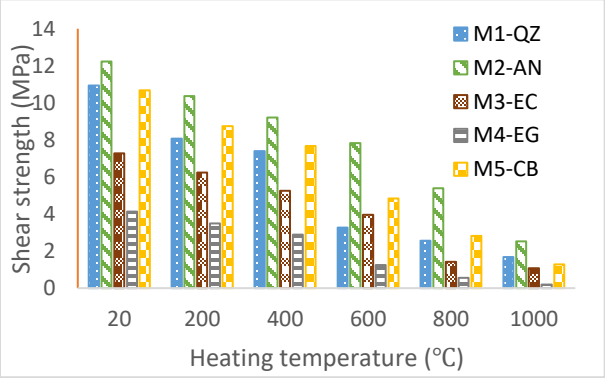


Figure 4-31. Average shear strength results at age 240 days for concrete made with different types of aggregates

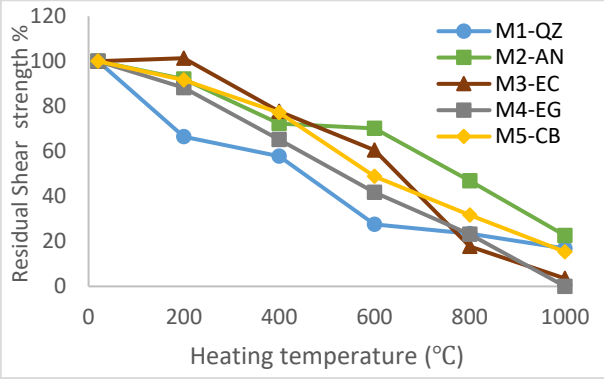


Figure 4-32. Relative residual shear strength of concrete made with different types of aggregates at age 120 days

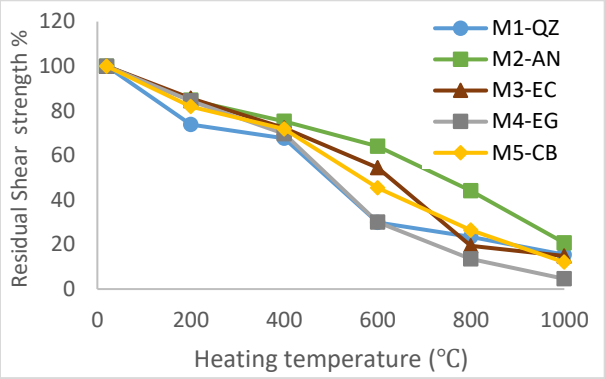


Figure 4-33. Relative residual shear strength of concrete made with different types of aggregates at age 120 days

Table 4.10. Shear strength results after subjected to elevated temperatures at ages 120 and 240 days

Age	**120 days**			**240 days**		
Mix – heating temperature	**Average shear strength (MPa)**	**Residual shear strength (%)**	**Standard deviation (σ)**	**Average shear strength (MPa)**	**Residual shear strength (%)**	**Standard deviation (σ)**
M1-QZ-20	10.9	100	0.6	10.9	100	0.1
M1-QZ-200	7.2	66.5	0.2	8.1	73.8	0.2
M1-QZ-400	6.3	57.9	0.4	7.4	67.7	0.5
M1-QZ-600	3.0	27.5	0.3	3.3	29.9	0.1
M1-QZ-800	2.6	23.5	0.1	2.6	23.4	0.3
M1-QZ-1000	1.8	16.8	0.2	1.7	15.4	0.1
M2-AN-20	11.3	100	0.3	12.2	100	0.3
M2-AN-200	10.4	92.1	0.3	10.4	84.7	0.4
M2-AN-400	8.1	72.3	0.4	9.2	75.2	0.4
M2-AN-600	7.9	70.2	0.6	7.8	64.0	0.4
M2-AN-800	5.3	46.9	0.2	5.4	44.1	0.1
M2-AN-1000	2.5	22.6	0.3	2.5	20.7	0.2
M3-EC-20	6.7	100	0.3	7.3	100	0.2
M3-EC-200	6.8	101.4	0.2	6.2	85.6	0.2
M3-EC-400	5.2	77.7	0.4	5.3	72.3	0.1
M3-EC-600	4.0	60.5	0.3	4.0	54.5	0.4
M3-EC-800	1.2	17.8	1.1	1.4	19.5	0.5
M3-EC-1000	0.2	3.5	0.4	1.1	14.9	0.2
M4-EG-20	3.8	100.0	0.1	4.1	100.0	0.6
M4-EG-200	3.4	88.3	0.2	3.5	84.4	0.1
M4-EG-400	2.5	65.2	0.3	2.9	69.7	0.0

M4-EG-600	1.6	41.7	0.2	1.2	30.0	0.3
M4-EG-800	0.9	23.1	0.1	0.6	13.5	0.1
M4-EG-1000	0.0	0.0	0.0	0.2	4.6	0.1
M5-CB-20	9.1	100	0.4	10.7	100	0.4
M5-CB-200	8.4	91.6	0.8	8.7	81.9	0.2
M5-CB-400	7.0	77.2	0.6	7.7	71.8	0.2
M5-CB-600	4.5	48.9	0.7	4.8	45.3	0.5
M5-CB-800	2.9	31.6	0.8	2.8	26.4	0.2
M5-CB-1000	1.4	15.4	0.4	1.3	12.0	0.3

4.4.4. Conclusion regarding the behaviour of concrete made with different types of aggregate under elevated temperature without the inclusion of any fibres

The age of concrete and the heating temperature are crucial factors that influence concrete's mechanical properties and performance. However, it is important to highlight that the specific type of aggregate used in the concrete mixture plays a significant role in determining its response to elevated temperatures.

The experimental results presented in the thesis demonstrate that the choice of aggregate type substantially impacts the behaviour of concrete when exposed to high temperatures. Different aggregate types, such as quartz or expanded clay, possess unique thermal properties and interlocking mechanisms, which directly influence the performance of concrete under thermal loading.

Regarding compressive strength, the age of concrete generally contributes to its improvement. However, the effect of heating temperature on compressive strength is complex and requires careful consideration. The research findings from the thesis suggest that the aggregate type significantly influences concrete compressive strength when subjected to elevated temperatures. The thermal effects on aggregate particles and their interaction with the cementitious matrix can lead to variations in compressive strength, emphasizing the importance of selecting an appropriate aggregate type to enhance the high-temperature performance of concrete.

In terms of flexural tensile strength, the thesis highlights that the choice of aggregate type has a substantial impact. The thermal effects on concrete can result in cracking and a subsequent reduction in flexural strength. Different aggregate types exhibit varying responses to elevated temperatures due to their unique properties and behaviour under thermal loading. Therefore,

understanding the specific characteristics and interlocking mechanisms of different aggregates is vital for optimizing the flexural performance of concrete subjected to high temperatures.

Similarly, the shear strength of concrete is influenced by the concrete's age and the heating temperature. The thesis's research findings indicate that the aggregate type used significantly affects the shear resistance of concrete under elevated temperatures. The thermal effects can weaken the interlocking mechanisms between aggregate particles, reducing shear strength. Thus, selecting an appropriate aggregate type becomes crucial in enhancing the shear performance of concrete exposed to high temperatures.

To summarize, the research presented in the thesis highlights the importance of aggregate type in the behaviour of concrete subjected to elevated temperatures. The findings indicate that different aggregate types exhibit varying responses to high temperatures, affecting concrete's compressive strength, flexural tensile strength, and shear strength. Selecting an appropriate aggregate type becomes critical to designing concrete structures for fire-resistant applications. Further research in this area is necessary to deepen our understanding of the thermal behaviour of different aggregate types and develop improved strategies for optimizing the performance of concrete under elevated temperature conditions.

4.5. Mechanical properties after subjected to elevated temperatures (with fibres)

4.5.1. Compressive strength

The compressive strength results presented in Table 4.11, and Figure 4-34 to Figure 4-37, provide valuable insights into the performance of concrete mixtures with polypropylene (PP) fibres after exposure to elevated temperatures. The average compressive strength values and residual compressive strength percentages demonstrate the behaviour of these mixtures under different heating temperatures and ages, shedding light on their thermal resistance and structural integrity.

The effect of heating temperature on compressive strength is evident from the data. For example, in the M6-QZPP-20 mixture, the average compressive strength at 120 days was 71.4 MPa, which decreased to 19.6 MPa at a heating temperature of 1000 °C, representing a significant reduction of approximately 72.6%. Similarly, in the M7-ANPP-20 mixture, the average compressive strength decreased from 83.5 MPa at 120 days to 16.1 MPa at a heating temperature of 1000 °C, indicating a decrease of approximately 80.7%. These findings emphasize the detrimental impact of elevated temperatures on the compressive strength of the concrete mixtures.

In terms of age, comparing the compressive strength at 120 days and 240 days reveals slight

improvements in some cases. For instance, in the M8-ECPP-400 mixture, the average compressive strength increased from 45.0 MPa at 120 days to 50.4 MPa at 240 days. However, when subjected to a heating temperature of 800 °C, the compressive strength decreased to 20.0 MPa, indicating a reduction of approximately 55.6% from the 240-day strength. These observations indicate that while the age of the concrete contributes to strength development, it offers limited protection against the adverse effects of elevated temperatures.

The choice of aggregate type also plays a significant role in the mixtures' compressive strength and thermal resistance. Lightweight aggregates, as demonstrated by the M9-EGPP-200 mixture, exhibit better thermal resistance with an average compressive strength of 20.5 MPa at 200 °C, corresponding to 98.3% of the original strength. In contrast, the M7-ANPP-200 mixture with natural aggregates shows an average compressive strength of 76.6 MPa, representing 91.7% of the original strength. These results underscore the superior thermal performance of lightweight aggregates compared to natural aggregates.

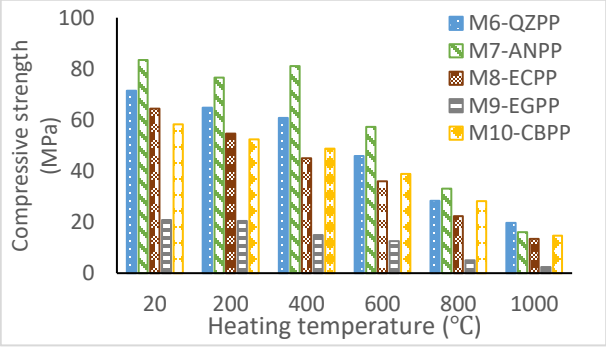


Figure 4-34. Average compressive strength results at age 240 days for concrete with PP fibres and made with different types of aggregates

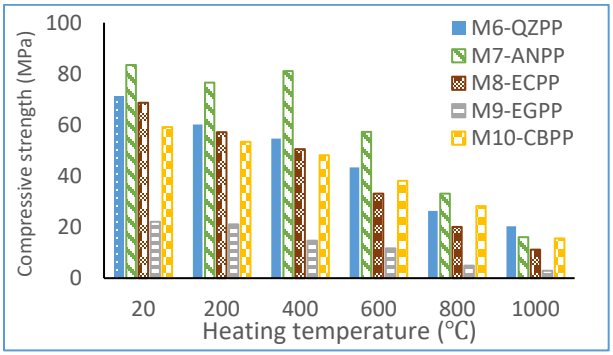


Figure 4-35. Average compressive strength results at age 240 days for concrete with PP fibres and made with different types of aggregates

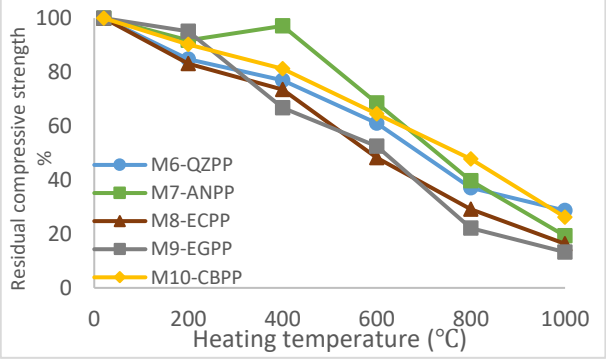


Figure 4-36. Relative residual compressive strength of concrete with PP fibres and made with different types of aggregates at age 120 days

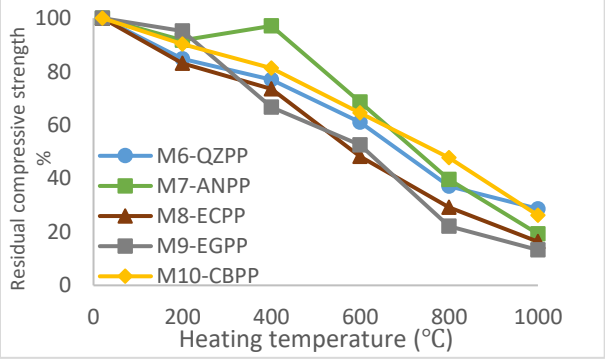


Figure 4-37. Relative residual compressive strength of concrete with PP fibres and made with different types of aggregates at age 120 days

Table 4.11. Compressive strength results for concrete with Polypropylene fibres after subjected to elevated temperatures.

Age	120 days			240 days		
Mix – heating temperature	Average compressive strength (MPa)	Residual compressive strength (%)	Standard deviation (σ)	Average compressive strength (MPa)	Residual compressive strength (%)	Standard deviation (σ)
M6-QZPP-20	71.4	100	2.4	71.0	100.0	1.5
M6-QZPP-200	64.8	90.7	3.2	60.1	84.7	1.9
M6-QZPP-400	60.7	85.1	1.9	54.6	76.9	0.7
M6-QZPP-600	45.9	64.3	0.6	43.4	61.1	1.4
M6-QZPP-800	28.3	39.7	0.6	26.3	37.1	1.0
M6-QZPP-1000	19.6	27.5	1.2	20.3	28.6	0.9
M7-ANPP-20	83.5	100	1.3	83.5	100.0	1.3
M7-ANPP-200	76.6	91.7	5.0	76.6	91.7	5.0
M7-ANPP-400	81.1	97.1	1.2	81.1	97.1	1.2
M7-ANPP-600	57.3	68.6	3.4	57.3	68.6	3.4
M7-ANPP-800	33.1	39.7	3.5	33.1	39.7	3.5
M7-ANPP-1000	16.1	19.3	2.2	16.1	19.3	2.2
M8-ECPP-20	64.4	100	1.2	68.7	100.0	1.2
M8-ECPP-200	54.6	84.8	3.3	57.1	83.1	2.9
M8-ECPP-400	45.0	70.0	3.4	50.4	73.5	2.2
M8-ECPP-600	36.0	55.9	2.2	33.1	48.3	0.7
M8-ECPP-800	22.3	34.7	2.2	20.0	29.2	0.8
M8-ECPP-1000	13.5	20.9	2.8	11.2	16.3	0.7
M9-EGPP-20	20.8	100	0.4	22.1	100.0	0.7
M9-EGPP-200	20.5	98.3	0.9	21.0	95.1	1.5
M9-EGPP-400	14.9	71.6	1.2	14.7	66.7	1.1
M9-EGPP-600	12.5	60.1	0.6	11.6	52.6	0.4
M9-EGPP-800	5.1	24.4	0.8	4.9	22.2	0.3
M9-EGPP-1000	2.5	11.8	0.6	2.9	13.3	0.7
M10-CBPP-20	58.3	100	3.5	59.2	100.0	1.4
M10-CBPP-200	52.3	89.8	2.9	53.4	90.3	1.6
M10-CBPP-400	48.7	83.6	0.5	48.1	81.3	1.3
M10-CBPP-600	38.8	66.6	0.5	38.2	64.5	1.4
M10-CBPP-800	28.2	48.3	0.9	28.3	47.8	1.2
M10-CBPP-1000	14.7	25.2	1.1	15.5	26.2	1.9

4.5.2. Flexural tensile strength

The flexural tensile strength results obtained from the experimental investigation provide valuable insights into the performance of concrete mixtures under varying heating temperatures while considering the influence of age, aggregate types, and the inclusion of polypropylene (PP) fibres.

The analysis of these results contributes to a comprehensive understanding of the complex interplay between these factors and their impact on the flexural strength characteristics of the concrete.

As observed in Table 4.12, and Figure 4-38 to Figure 4-41, an increase in heating temperature reduces flexural tensile strength for all mixtures. This decline can be attributed to several mechanisms, including the breakdown of the cementitious matrix, thermal expansion and contraction, and potential degradation of aggregate properties. The decreasing trend in flexural strength with increasing temperature highlights the challenges associated with preserving the strength of concrete under thermal stress.

An interesting observation emerges when comparing the flexural strength at different ages, namely 120 days and 240 days. In general, the flexural strength at 240 days is slightly higher than at 120 days for most mixtures, indicating ongoing strength development over time. This trend suggests that the ageing process contributes positively to the flexural strength of the concrete. However, it should be noted that the positive effects of ageing on strength development can be compromised when subjected to elevated temperatures. The combination of age and elevated temperature induces additional degradation mechanisms, resulting in reduced flexural strength compared to ambient temperature conditions.

Furthermore, the type of aggregate used in the mixtures plays a crucial role in the concrete's flexural strength and thermal performance. Mixtures incorporating natural aggregates (AN and QZ) exhibit distinct responses to heating. While AN demonstrates relatively better residual flexural strength, QZ experiences more substantial reductions, indicating the influence of aggregate properties on the thermal performance of the concrete. On the other hand, mixtures containing lightweight aggregates (EC and EG) demonstrate improved thermal performance compared to those with natural aggregates. These lightweight aggregates exhibit higher residual flexural strength and reduced strength loss at elevated temperatures, which can be attributed to their inherent properties, including lower thermal conductivity and improved thermal stability.

The inclusion of PP fibres in the mixtures offers an additional mechanism to enhance the flexural performance of the concrete. The fibres provide reinforcement and crack control, improving initial flexural strength and enhancing resistance against crack propagation. However, it is important to note that even with the inclusion of PP fibres, the flexural strength still experiences a decrease as

the heating temperature increases. This highlights the limitations of PP fibre reinforcement in preserving flexural strength under high-temperature conditions.

Overall, the results of the flexural tensile strength analysis demonstrate the complex interplay between age, temperature, aggregate types, and the presence of PP fibres in influencing the flexural behaviour of the concrete. Ageing can positively influence the concrete's initial flexural strength and crack resistance, but its long-term performance under thermal stress is affected by multiple factors. The choice of aggregate type remains significant, with natural aggregates demonstrating varying responses to heating and lightweight aggregates exhibiting improved thermal performance. The inclusion of PP fibres enhances crack control but does not eliminate the overall reduction in flexural strength under elevated temperatures.

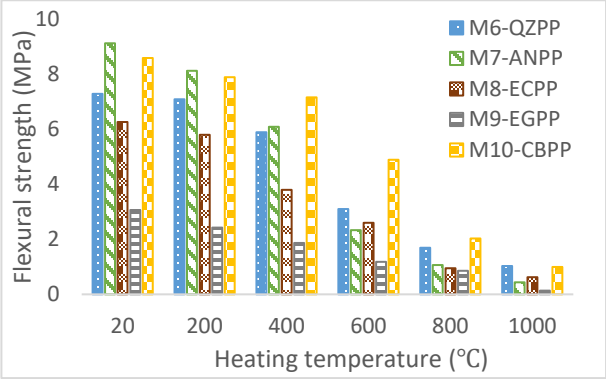


Figure 4-38. Average flexural tensile strength results at age 240 days for concrete made with different types of aggregates

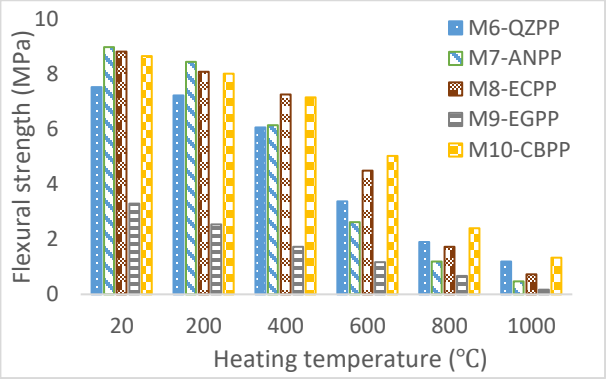


Figure 4-39. Average flexural tensile strength results at age 240 days for concrete made with different types of aggregates

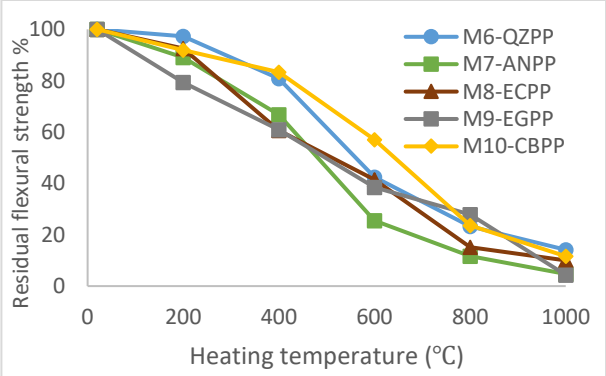


Figure 4-40. Relative residual flexural strength of concrete made with different types of aggregates at age 240 days

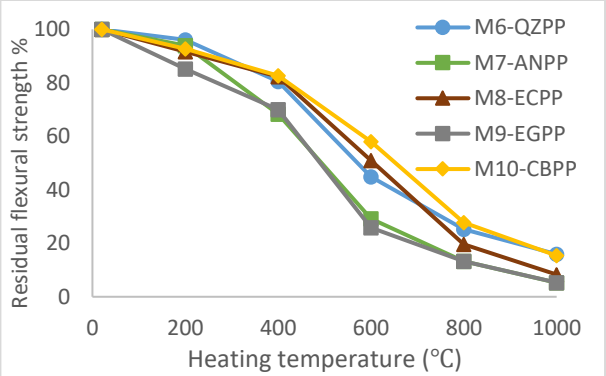


Figure 4-41. Relative residual flexural strength of concrete made with different types of aggregates at age 240 days

Table 4.12. Flexural tensile strength results for concrete mixes containing polypropylene fibres

Age	120 days			240 days		
Mix – heating temperature	Average flexural strength (MPa)	Residual flexural strength (%)	Standard deviation (σ)	Average flexural strength (MPa)	Residual flexural strength (%)	Standard deviation (σ)
M6-QZPP-20	7.3	100	0.2	7.5	100	0.25
M6-QZPP-200	7.1	97.3	0.2	7.2	96.0	0.12
M6-QZPP-400	5.9	80.8	0.3	6.1	80.5	0.25
M6-QZPP-600	3.1	42.5	0.3	3.4	44.9	0.40
M6-QZPP-800	1.7	23.3	0.3	1.9	25.2	0.17
M6-QZPP-1000	1.0	14.2	0.2	1.2	15.9	0.26
M7-ANPP-20	9.1	100	0.4	9.0	100	0.0
M7-ANPP-200	8.1	89.1	0.2	8.5	94.0	0.4
M7-ANPP-400	6.1	66.8	0.2	6.2	68.3	0.0
M7-ANPP-600	2.3	25.6	0.2	2.6	29.2	0.2
M7-ANPP-800	1.1	11.7	0.1	1.2	13.2	0.2
M7-ANPP-1000	0.4	4.7	0.1	0.5	5.3	0.0
M8-ECPP-20	6.3	100	0.25	8.8	100	0.1
M8-ECPP-200	5.8	92.6	0.17	8.1	91.7	0.2
M8-ECPP-400	3.8	60.6	0.10	7.3	82.3	0.2
M8-ECPP-600	2.6	41.5	0.40	4.5	50.9	0.4
M8-ECPP-800	1.0	15.2	0.21	1.7	19.6	0.2
M8-ECPP-1000	0.6	10.0	0.31	0.7	8.3	0.2
M9-EGPP-20	3.1	100	0.1	3.3	100	0.10
M9-EGPP-200	2.4	79.4	0.3	2.6	77.2	0.05
M9-EGPP-400	1.9	60.9	0.3	1.7	52.3	0.06
M9-EGPP-600	1.2	38.5	0.0	1.2	35.6	0.22
M9-EGPP-800	0.9	27.8	0.0	0.7	20.2	0.25
M9-EGPP-1000	0.1	4.4	0.2	0.2	5.1	0.06
M10-CBPP-20	8.6	100	0.2	8.7	100	0.15
M10-CBPP-200	7.9	91.9	0.2	8.0	92.7	0.29
M10-CBPP-400	7.2	83.3	0.1	7.2	82.7	0.15
M10-CBPP-600	4.9	57.0	0.2	5.0	58.1	0.31
M10-CBPP-800	2.0	23.6	0.3	2.4	27.7	0.10
M10-CBPP-1000	1.0	11.6	0.2	1.3	15.4	0.15

4.5.3. Shear strength

The shear strength results for concrete specimens with five different aggregate types and the inclusion of polypropylene fibres (PP) have been evaluated under elevated temperatures ranging

from 200 °C to 1000 °C. A comparison has been made between the results obtained at ambient temperature and those obtained at two different ages, namely 120 and 240 days.

For the M6-QZPP specimens, it was observed that the average shear strength remained relatively constant at ambient temperature and both age intervals, with values ranging from 9.7 MPa to 9.8 MPa, indicating no significant variation. However, when subjected to elevated temperatures, a gradual decrease in the average shear strength was observed, accompanied by a decrease in the residual shear strength percentage. At 200 °C, the average shear strength reduced to 9.1 MPa (92.98% residual shear strength) at 120 days and recovered to 9.9 MPa (100.95% residual shear strength) at 240 days. As the temperature increased to 1000 °C, the average shear strength further declined to 1.9 MPa (19.18% residual shear strength) at 120 days and 1.7 MPa (17.45% residual shear strength) at 240 days.

Similarly, for the M7-ANPP specimens, the average shear strength remained consistent at ambient temperature, with values of 11.1 MPa and 11.35 MPa at 120 and 240 days, respectively. Under elevated temperatures, a gradual reduction in the average shear strength and a decrease in the residual shear strength percentage were observed. At 200 °C, the average shear strength decreased to 9.7 MPa (87.69% residual shear strength) at 120 days and recovered slightly to 10.00 MPa (88.13% residual shear strength) at 240 days. The average shear strength further decreased as the temperature increased to 1000 °C, reaching 2.1 MPa (19.22% residual shear strength) at 120 days and 2.42 MPa (21.33% residual shear strength) at 240 days.

For the M8-ECPP specimens, the average shear strength at ambient temperature was 6.27 MPa and 6.3 MPa at 120 and 240 days, respectively. Under elevated temperatures, a gradual reduction in the average shear strength was observed, accompanied by a decrease in the residual shear strength percentage. At 200 °C, the average shear strength decreased to 5.80 MPa (92.55% residual shear strength) at 120 days and recovered slightly to 6.0 MPa (96.02% residual shear strength) at 240 days. The average shear strength continued to decrease as the temperature rose to 1000 °C, reaching 1.16 MPa (18.51% residual shear strength) at 120 days and 0.8 MPa (13.45% residual shear strength) at 240 days.

For the M9-EGPP specimens, the average shear strength at ambient temperature was 3.88 MPa and 3.9 MPa at 120 and 240 days, respectively. Under elevated temperatures, a gradual reduction in the average shear strength and a decrease in the residual shear strength percentage were observed. At 200 °C, the average shear strength decreased to 3.41 MPa (87.90% residual shear

strength) at 120 days and slightly recovered to 3.5 MPa (90.94% residual shear strength) at 240 days. The average shear strength continued to decrease with increasing temperature, reaching 0.13 MPa (3.43% residual shear strength) at 120 days and 0.2 MPa (5.98% residual shear strength) at 240 days when subjected to 1000 °C.

Lastly, for the M10-CBPP specimens, the average shear strength at ambient temperature was 8.63 MPa and 8.9 MPa at 120 and 240 days, respectively. Under elevated temperatures, a gradual reduction in the average shear strength was observed, accompanied by a decrease in the residual shear strength percentage. At 200 °C, the average shear strength decreased to 7.8 MPa (90.42% residual shear strength) at 120 days and further decreased to 7.2 MPa (81.13% residual shear strength) at 240 days. The average shear strength continued to decrease as the temperature rose to 1000 °C, reaching 1.57 MPa (18.16% residual shear strength) at 120 days and 1.6 MPa (18.02% residual shear strength) at 240 days.

In conclusion, the results demonstrate that the shear strength of concrete specimens with different aggregate types and the inclusion of polypropylene fibres (PP), is adversely affected by elevated temperatures. The average shear strength progressively decreases as the temperature rises, and the residual shear strength percentage decreases accordingly. These findings provide valuable insights into the performance of concrete under high-temperature conditions.

Table 4.13. Shear strength results for mixtures containing Polypropylene PP fibres.

Age	**120 days**			**240 days**		
Mix – heating temperature	**Average shear strength (MPa)**	**Residual shear strength (%)**	**Standard deviation (σ)**	**Average shear strength (MPa)**	**Residual shear strength (%)**	**Standard deviation (σ)**
M6-QZPP-20	9.7	100	0.5	9.8	100	0.23
M6-QZPP-200	9.1	93.0	0.4	9.9	101.0	0.25
M6-QZPP-400	6.7	68.5	0.2	6.9	70.0	0.29
M6-QZPP-600	5.7	58.2	0.2	5.7	57.8	0.46
M6-QZPP-800	2.2	22.3	0.2	3.0	30.7	0.37
M6-QZPP-1000	1.9	19.2	0.3	1.7	17.5	0.08
M7-ANPP-20	11.1	100	0.6	11.3	100	1.13
M7-ANPP-200	9.7	87.7	0.2	10.0	88.1	0.40
M7-ANPP-400	7.0	63.4	0.2	7.0	61.7	0.47
M7-ANPP-600	5.4	48.7	0.1	5.6	49.5	0.28
M7-ANPP-800	4.2	37.5	0.2	4.5	39.3	0.25
M7-ANPP-1000	2.1	19.2	0.3	2.4	21.3	0.39
M8-ECPP-20	6.3	100	0.3	6.3	100	0.29

M8-ECPP-200	5.8	92.6	0.2	6.0	96.0	0.15
M8-ECPP-400	5.0	80.3	0.3	5.1	80.6	0.06
M8-ECPP-600	3.7	59.0	0.6	3.5	55.7	0.26
M8-ECPP-800	1.7	26.3	0.5	1.4	23.0	0.63
M8-ECPP-1000	1.2	18.5	0.3	0.8	13.5	0.36
M9-EGPP-20	3.9	100	0.1	3.9	100	0.05
M9-EGPP-200	3.4	87.9	0.2	3.5	90.9	0.05
M9-EGPP-400	3.0	78.1	0.1	3.3	85.5	0.61
M9-EGPP-600	1.6	41.6	0.1	1.2	31.8	0.29
M9-EGPP-800	0.9	22.0	0.0	0.8	20.9	0.10
M9-EGPP-1000	0.1	3.4	0.2	0.2	6.0	0.06
M10-CBPP-20	8.6	100	0.5	8.9	100	0.33
M10-CBPP-200	7.8	90.4	0.4	7.2	81.1	0.19
M10-CBPP-400	6.8	78.8	0.4	6.3	71.1	0.33
M10-CBPP-600	5.0	58.2	0.2	5.2	58.1	0.08
M10-CBPP-800	4.0	46.8	0.3	3.1	34.4	0.49
M10-CBPP-1000	1.6	18.2	0.3	1.6	18.0	0.14

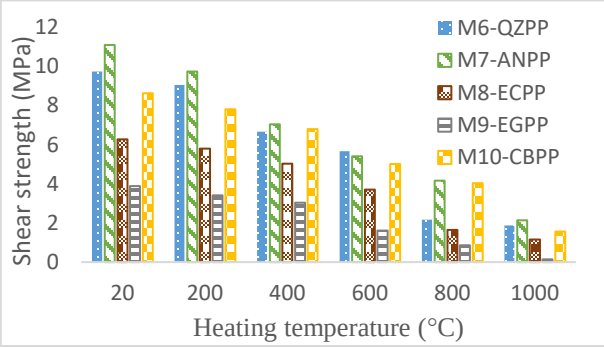


Figure 4-42. Average shear strength results at the age of 120 days for concrete with PP made with different types of aggregates

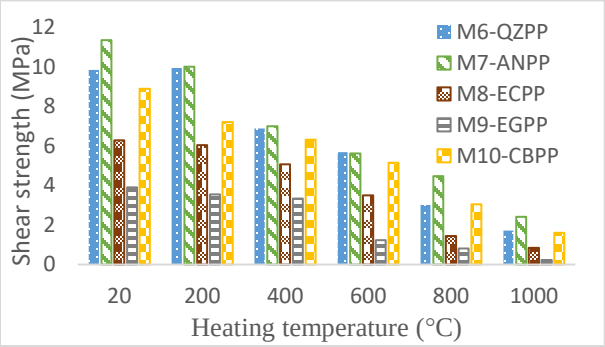


Figure 4-43. Average shear strength results at the age of 240 days for concrete made with different types of aggregates

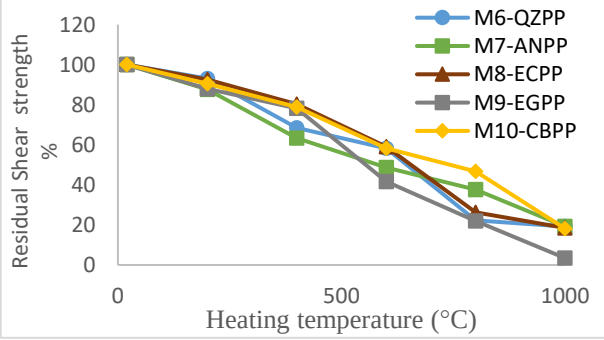


Figure 4-44. Relative residual shear strength of concrete with PP made with different types of aggregates at the age of 120 days

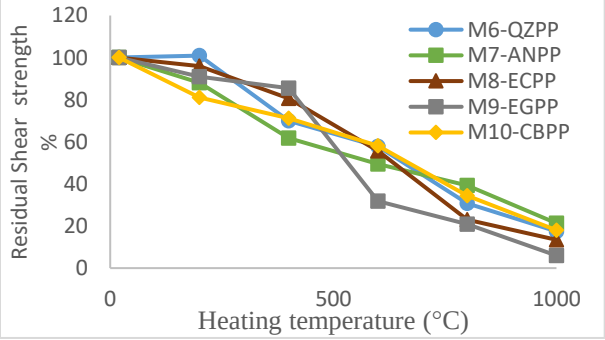


Figure 4-45. Relative residual shear strength of concrete made with different types of aggregates at the age of 120 days

4.6. Thermal conductivity

The presented thermal conductivity results in Table 4.14 and Figure 4-46 offer valuable insights into the heat transfer characteristics of various concrete mixtures. Thermal conductivity is a critical property in construction materials, as it determines their ability to transmit heat. Understanding thermal conductivity is crucial for optimizing energy efficiency and ensuring thermal comfort in buildings and structures.

Generally, as temperature increases, there is a decreasing trend in thermal conductivity. This behaviour can be attributed to the expansion of air voids within the concrete structure at higher temperatures, resulting in improved insulation properties and reduced heat transfer.

Mixtures M1-QZ, M2-AN, and M6-QZPP exhibit relatively higher thermal conductivity values. These mixtures incorporate aggregates such as quartz and andesite, which are known for their good thermal conductivity properties. The presence of these aggregates contributes to higher heat transfer rates within the concrete.

Mixture M4-EG, on the other hand, displays lower thermal conductivity values. This is attributed to the use of expanded glass aggregate, which exhibits insulating properties, thereby reducing heat transfer within the concrete.

Mixtures M3-EC, M5-CB, M7-ANPP, M8-ECPP, M9-EGPP, and M10-CBPP demonstrate moderate thermal conductivity values. Incorporating expanded clay, crushed clay bricks, and polypropylene fibres in these mixtures contributes to their intermediate heat transfer characteristics.

Table 4.14. Thermal conductivity results after subjected to elevated temperature

Mixture	20℃	200℃	400 ℃	600 ℃	800 ℃	1000 ℃
M1-QZ	2.20	1.71	1.40	1.11	0.79	0.67
M2-AN	2.05	1.92	1.41	1.04	0.85	0.74
M3-EC	1.35	1.10	1.00	0.69	0.54	0.49
M4-EG	1.01	0.82	0.72	0.52	0.41	0.33
M5-CB	1.42	1.34	0.95	0.72	0.55	0.51
M6-QZPP	2.06	1.69	1.30	0.99	0.75	0.60
M7-ANPP	1.85	1.62	1.11	0.87	0.81	0.70
M8-ECPP	1.25	1.01	0.85	0.61	0.51	0.46
M9-EGPP	1.10	0.78	0.62	0.45	0.36	0.23
M10-CBPP	1.36	1.17	0.90	0.61	0.52	0.38

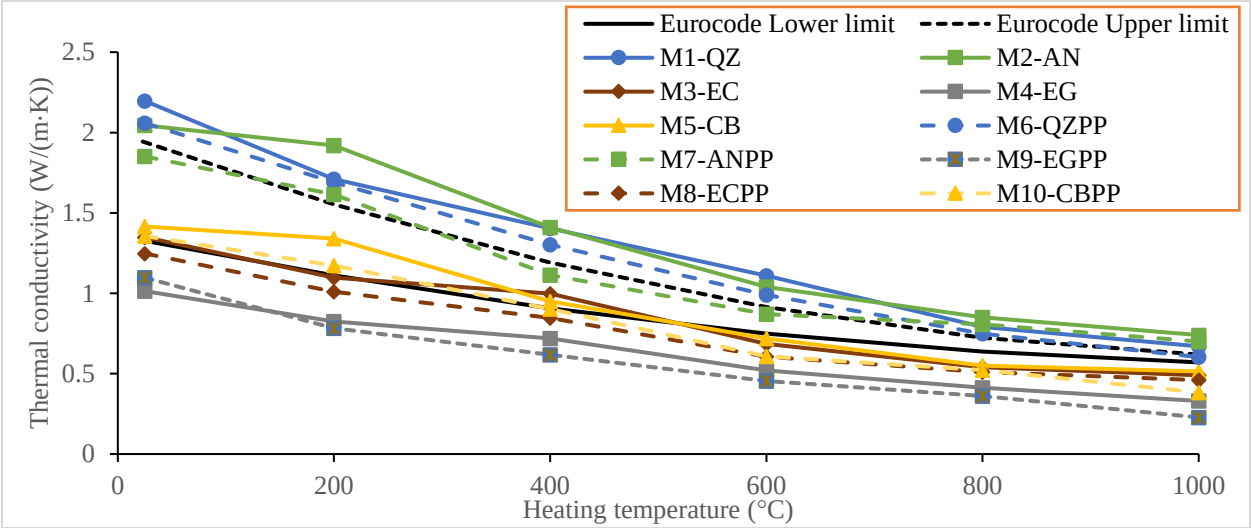


Figure 4-46. Thermal conductivity results in comparison with the Eurocode limits

Regarding to the thermal conductivity values of the different concrete mixes, it can be noted that concrete made with expanded glass aggregate exhibited the lowest thermal conductivity value of 1.0 W/mK, followed by concrete made with expanded clay aggregate at 1.3 W/mK. On the other hand, concrete made with crushed clay bricks and andesite aggregates had higher thermal conductivity values of 1.4 W/mK and 2.0 W/mK, respectively. Concrete made with natural quartz aggregate had a thermal conductivity value of 2.2 W/mK.

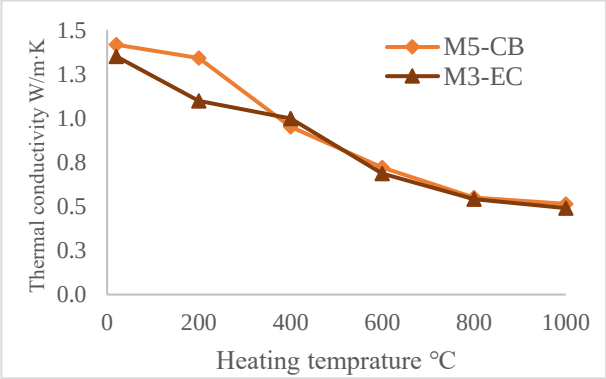


Figure 4-47. Thermal conductivity for two different clay-based materials mixes

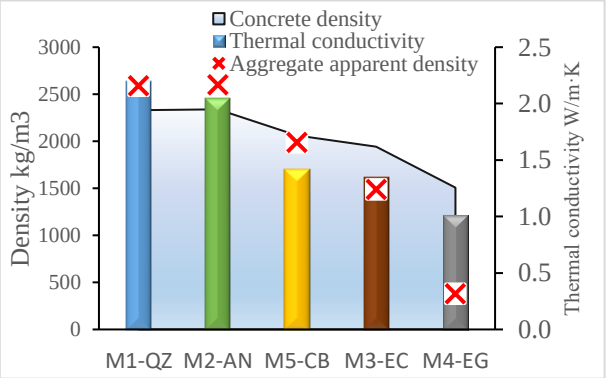


Figure 4-48. Thermal conductivity in comparison with concrete density and aggregate density

As it is shown in Figure 4-46 and Figure 4-47, provide a comprehensive understanding of the thermal behaviour of clay-based aggregates in concrete has been established through the use of Expanded clay aggregate on (M3-EC) and crushed clay bricks aggregates (M5-CB). The findings reveal that aggregates with the same clay-based material exhibit consistent thermal behaviour,

irrespective of their shape or the presence of porous structures. This emphasizes the dominant influence of the clay-based material on the aggregates' thermal properties, suggesting that factors such as shape and porosity have minimal impact in this regard, especially after subjected to elevated temperatures over 400 ℃.

Moreover, based on the experimental results, it can be observed that the thermal conductivity of concrete is influenced by the type of aggregate used. The thermal conductivity values for concrete made with different aggregates demonstrate distinct differences, indicating that aggregate type significantly affects the thermal conductivity of the resulting concrete, as shown in Figure 4-46 and Figure 4-48. Additionally, results revealed that concrete with the same category of coarse aggregate has a similar thermal behaviour after subjected to elevated temperature.

These results indicate that the choice of aggregate has a noticeable impact on the thermal conductivity of concrete. The lower thermal conductivity values observed for concrete made with expanded glass and expanded clay aggregates suggest that these aggregates contribute to better thermal insulation properties compared to the other aggregates evaluated. This can be attributed to these aggregates' lower density and potentially more porous structure, which can hinder heat transfer through the concrete.

Furthermore, the relationship between concrete density and thermal conductivity is evident from the provided results. Lower concrete density values were associated with lower thermal conductivity values, reinforcing the understanding that a more porous structure contributes to improved thermal insulation properties. Concrete made with expanded glass, which had the lowest density among the tested aggregates, exhibited the lowest thermal conductivity.

Chapter 5 : CONCLUSIONS AND FUTURE RESEARCHS

An extensive dataset of over 2700 concrete samples was generated and tested. Concrete specimens were designed to incorporate fully replaced coarse aggregates, utilising various types such as natural, lightweight, and recycled aggregates. Additionally, the investigation considered different fibre contents in the concrete mixtures.

The study was supported by an in-depth review of more than 200 research papers, books, and standards. Extracts from these sources were utilised in the preparation of this thesis, making it a valuable resource for researchers in this field. The research examines the concretes' constituent materials and paste components, thoroughly analysing their key fresh and hardened properties. The study thoroughly investigated the fresh properties, physical characteristics, thermal behaviour, and mechanical performance of ten distinct concrete mixtures at three different ages. Additionally, these mixtures were subjected to elevated temperatures across six different levels. The extensive dataset generated and the comprehensive literature review provide a solid foundation for understanding concrete mixtures' fresh and hardened properties incorporating different coarse aggregates and fibre contents. The main research findings are given below:

5.1 Aggregates

- Quartz aggregate shown in Figure 3-5 exhibits favourable properties, including well-defined particle size distribution, low water absorption, excellent thermal stability, and resistance to heat-induced alterations, making it a reliable choice for concrete mixtures.
- Andesite aggregate excavated from Hungary, (Kisnána, Mátra) shown in Figure 3-9, with approximately 53-63% silica content, displays favourable properties, such as porphyritic texture and chemical stability, making it suitable for concrete mixtures.
- Expanded clay aggregate (Liapor 8F) shown in Figure 3-12, possesses low density, high strength, and thermal efficiency, making it suitable for lightweight concrete and insulation systems in construction.
- Expanded glass aggregate (Stikloporas) shown in Figure 3-15, showcases beneficial properties such as low density, high insulation value, and durability.
- Crushed clay brick aggregates shown in Figure 3-18, sourced from demolition wastes undergo meticulous cleaning and crushing processes, resulting in controlled particle size distribution.

5.2 Fresh properties

- The fresh density measurements of concrete mixtures (Figure 4-1) show significant variations influenced by the specific aggregate types used. Lightweight aggregates result in lower fresh concrete densities, while quartz aggregate exhibits relatively higher fresh density. The addition of polypropylene (PP) fibres has a slight impact on fresh density.
- The air content results (Table 4.1) of the concrete mixtures indicate variations ranging from 1.07% to 4.20%. The mixtures without fibres (M1 to M5) exhibited air content values between 1.07% and 2.57%, while the mixtures with polypropylene fibres (M6 to M10) showed slightly higher air content values ranging from 1.17% to 4.20%.
- The flow table test results (Figure 4-2) for the mixtures without fibres andesite demonstrated good workability, while Quartz and Crushed Clay Bricks also exhibited favourable flow characteristics. The mixtures with PP fibres maintained acceptable workability by increasing the percentage of superplasticizers.

5.3 Physical properties

- The analysis of moisture content in the concrete mixtures (Figure 4-3) indicates a significant decrease in moisture content as the concrete ages, with values ranging from 5.6% at 28 days to 1.2% at 240 days, shedding light on their initial moisture conditions and providing valuable insights into their behaviour during thermal exposure.
- The analysis of hardened density (Figure 4-4) remains relatively stable for most mixes across different ages, with a gradual decrease observed as concrete ages.
- The analysis of weight loss percentages in the concrete mixtures exposed to elevated temperatures (Figure 4-5) reveals a clear trend of increasing weight loss as temperatures rises, with values ranging from 1.1% to 15.9% at 240 days. Mixtures incorporating expanded glass aggregate, such as M4-EG, exhibit higher weight loss percentages, while those incorporating polypropylene fibres and crushed clay bricks, like M7-ANPP and M10-CBPP, demonstrate lower weight loss percentages, emphasising the influence of aggregate composition and fibre inclusion on high-temperature performance.
- The physical properties results, highlight the influence of factors such as hydration, moisture loss, and potential changes in microstructure on the density of hardened concrete.

5.4 Mechanical properties

- The age of concrete has a significant effect on its mechanical properties, regardless of the type of aggregates used. The analysis of compressive strength, flexural strength, shear strength, and concrete density at different ages (28 days, 120 days, and 240 days) provides insights into the development and performance of concrete made with different types of aggregates, as shown on Figure 4-6, Figure 4-7 and Figure 4-8.
- The concrete mixes M1-QZ and M5-CB can be classified as C50/60, indicating a high-strength concrete. Mixtures M3-EC and M4-EG, made with lightweight aggregates, can be classified as LC55/60 and LC16/18, respectively, highlighting their lower strength compared to the C50/60 mixes. Lastly, the concrete mix made with andesite aggregate, M2-AN, can be classified as C60/75, representing a high-strength concrete.
- Andesite aggregates are suitable for structural concrete due to their higher compressive strength.
- The compressive strength results exhibit an improvement over time. This observed that the aggregates used in the mixes continue to contribute to the development of strength as the concrete ages.
- Mixtures incorporating expanded glass aggregates show a decline in compressive strength due to their lightweight and porous nature as it clearly shown in Figure 3-16, resulting in reduced inherent strength and potential fragmentation under high-temperature conditions.
- Crushed clay bricks as aggregates reveal an environmentally friendly solution by utilising the clay brick's demolition wastes as coarse aggregates for structural concrete.
- The type of aggregate used in the mixtures significantly affects flexural strength and thermal performance. Mixtures with natural aggregates (andesite and quartz) exhibit distinct responses to heating. While andesite concrete demonstrates relatively better residual flexural strength, as shown in Figure 4-28 and Figure 4-29.
- The flexural tensile strength at different ages (120 days and 240 days) observed a slight increase in strength at the age of 240 days for most mixtures. This behaviour demonstrates an ongoing strength development over time. However, the positive effects of ageing from 120 to 240 days on strength development can be compromised when exposed to elevated temperatures. Ageing, in combination with high temperature, induces additional

degradation mechanisms, resulting in reduced flexural strength compared to ambient temperature conditions.

- Mixtures containing expanded glass aggregates (e.g., M4-EG and M9-EGPP) show limited or modest improvements in flexural strength, highlighting potential limitations of the Expanded Glass aggregate.
- The age of concrete and its corresponding flexural properties play a significant role in evaluating performance under elevated temperatures.
- Lightweight aggregates demonstrate better shear strength performance at elevated temperatures compared to natural aggregates, as shown in Figure 4-44 and Figure 4-45.
- The inclusion of polypropylene fibres enhances crack control and initial shear strength but does not prevent reduction at high temperatures as shown in Figure 4-44 and Figure 4-45.
- Ageing can provide slight improvements in flexural and shear strength but does not fully preserve strength under elevated temperatures.

5.5 Thermal properties

- Thermal conductivity in concrete is influenced by temperature and aggregate type. Higher temperatures result in decreased thermal conductivity due to the expansion of air voids within the concrete structure.
- Quartz and andesite aggregates exhibit higher thermal conductivity, while expanded glass aggregate shows lower values due to its insulating properties.
- Concrete with expanded clay aggregate demonstrates intermediate thermal conductivity, while crushed clay bricks and polypropylene fibre inclusion contribute to moderate heat transfer characteristics.
- The choice of aggregate significantly affects thermal conductivity, with expanded glass and expanded clay aggregates providing better thermal insulation properties.
- Lower concrete density is associated with lower thermal conductivity, indicating improved thermal insulation in more porous structures.

5.6 Possible Directions for Future Research

The extensive investigation into concrete behaviour under various conditions and with different aggregates and fibre contents opens up avenues for future research in several key areas:

- Advanced Aggregate Characterization: In-depth investigations into different aggregates' microstructural and chemical properties can provide a deeper understanding of their influence on concrete behaviour.
- Sustainable Materials: Further research on developing sustainable concrete materials, such as exploring innovative ways to utilize recycled aggregates and alternative binders.
- Fibre Reinforcement: Detailed studies on the effects of various types and dosages of fibres, including their interaction with different aggregates, can enhance our knowledge of fibre-reinforced concrete's performance under various conditions.
- Numerical Modeling: Utilizing advanced numerical models and simulations can help predict the behaviour of concrete mixtures under diverse scenarios, aiding in optimizing mix designs.
- Long-Term Durability: Evaluating the long-term durability of concrete mixtures exposed to elevated temperatures is crucial. Research on the effects of concrete age and extended exposure to high temperatures can inform maintenance and rehabilitation strategies for existing structures.
- Environmental Impact: Assessing the environmental impact of different concrete mixtures, including embodied carbon emissions and energy consumption, is vital for sustainable construction. Future research can focus on quantifying and minimizing the environmental footprint of concrete under varying conditions.
- Innovative Applications: Exploring novel applications for specialized concrete mixtures, such as those incorporating lightweight aggregates, can open up new possibilities in construction and infrastructure.
- Multi-Objective Optimization: Investigating multi-objective optimization techniques to balance multiple properties, such as strength, thermal performance, and sustainability, can lead to the development of more versatile and efficient concrete mixtures for diverse applications.

These future research directions aim to advance our knowledge of concrete materials and their performance in challenging environments and severe conditions, ultimately contributing to developing more resilient, sustainable, and efficient construction practices.

CHAPTER 6 : NEW SCIENTIFIC RESULTS

In this chapter, a comprehensive investigation has been carried out to analyse the influence of aggregate type on concrete's thermal, mechanical, and physical properties. The study encompasses a range of parameters, including various types of coarse aggregates, multiple concrete ages, fibre content, and elevated temperature levels. The following key findings have emerged through an extensive experimental program and analytical study, highlighting the new scientific results.

Thesis group 1:

Utilising the use of the Hungarian andesite as a coarse aggregate for structural concrete

1.1 I experimentally proved that using Hungarian andesite as a 100% coarse aggregate showed an enhanced mechanical and durability performance of concrete in terms of compressive strength, flexural tensile strength, and shear strength, compared with five different concrete mixes having 100% coarse aggregate as natural quartz aggregate (the most used aggregate in ordinary concrete), expanded clay aggregates (one of the most used aggregates in structural lightweight concrete), expanded glass and recycled clay bricks in case of the same cement matrix. **[P2, P6]**

The experimental results shown in Figure 4-6, Figure 4-7 and Figure 4-8, clearly demonstrate that using Hungarian andesite excavated from (Kisnána, Mátra) as a coarse aggregate with 100% replacement for the natural quartz aggregate significantly enhances concrete's mechanical characteristics. The concrete's compressive strength improved by 27%, 9.7% and 16.3% at ages 28 days, 120 days, and 240 days, respectively. The concrete flexural tensile strength enhanced by 20%, 25% and 25% at the same ages. While the shear strength at ages 120 and 240 days, increased by 3 and 12% of the strength in the case of quartz gravels.

The superior strength of concrete made with andesite aggregate is attributed to the nature of andesite as a dense, hard volcanic rock, providing higher strength properties. The rough and angular texture of andesite particles enhances the bond with the cement paste, resulting in increased mechanical properties. Moreover, the presence of pozzolanic materials as shown in Figure 4-10 in the andesite, can contribute to the long-term strength development of concrete as it reacts with the calcium hydroxide produced during cement hydration. Additionally, using andesite

aggregate allows for better particle packing, reducing voids and increasing concrete density as well as better workability, as shown in Figure 6-4. This denser mortar matrix improves load distribution and stress transfer, enhancing fresh and mechanical properties.

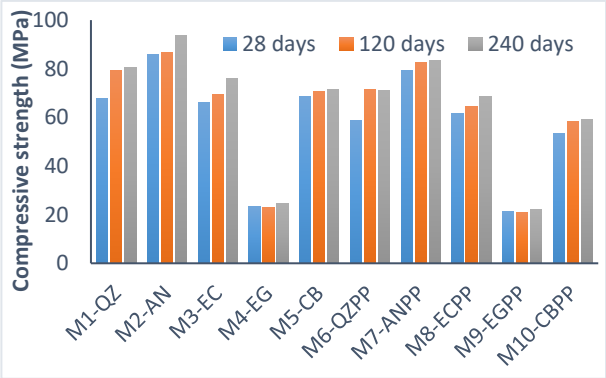


Figure 6.1. Compressive strength test results

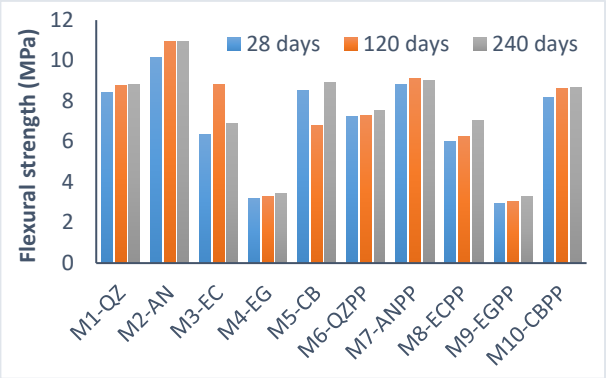


Figure 6.2. Flexural tensile strength test results

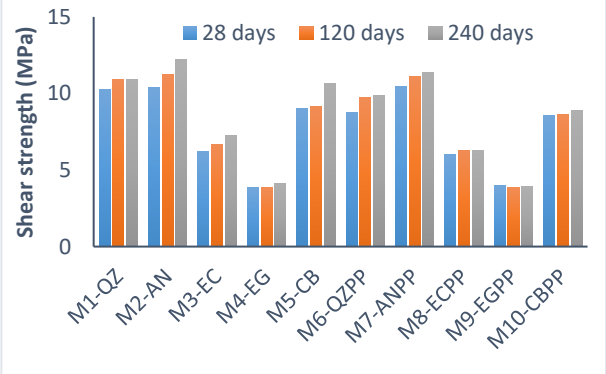


Figure 6.3. Shear strength test results

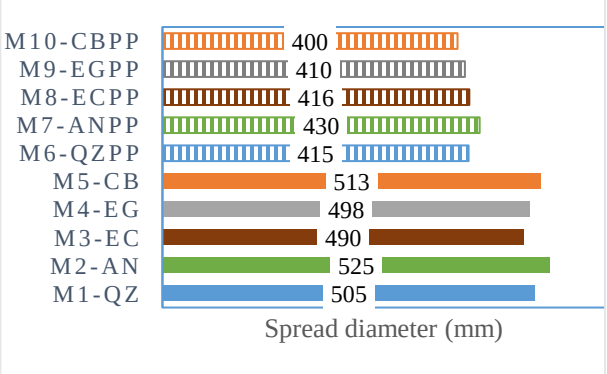


Figure 6-4. Flow table test results

1.2 ***I experimentally proved that the thermal conductivity for concrete made using Hungarian andesite as 100% coarse aggregate showed similar behaviour to the concrete made with normal quartz aggregate at ambient and elevated temperatures.*** **[P2, P6]**

The experimental results shown in Figure 6-5 indicate that using Hungarian andesite in concrete compared with concrete made with normal quartz aggregate exhibits similar thermal conductivity across various temperatures. At room temperature, the thermal conductivities of the two concretes showed a minimal difference, suggesting that the choice of coarse aggregate has a negligible impact on initial thermal conductivity. As

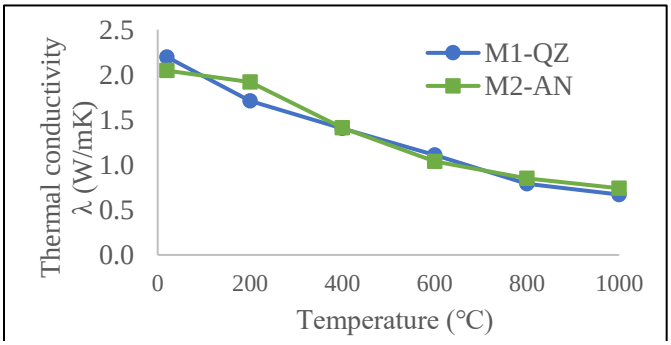


Figure 6.5. Thermal conductivity for andesite and quartz concrete after subjected to elevated temperature

the temperature increased, both concretes displayed similar decreases in thermal conductivity. Both concretes maintained similar thermal insulation properties even at higher temperatures of 400 °C and above. It is worth noting that the Hungarian andesite concrete had a slightly higher density and significantly higher compressive strength compared to the quartz aggregate concrete. However, these factors do not detract from the overall finding that the thermal conductivity remains similar between the two concrete types.

***1.3 I experimentally proved that using Hungarian andesite (Kisnána, Mátra) as a coarse aggregate with 100% replacement of the natural quartz gravel for structural concrete showed a higher residual compressive strength and higher residual shear strength for concrete after being subjected to elevated temperatures up to 1000 °C at both ages 120 and 240 days.* [P2, P4, P6]**

The experimental results demonstrate that using Hungarian andesite as a coarse aggregate in structural concrete significantly improves the mechanical performance of concrete subjected to elevated temperatures. The Hungarian andesite concrete consistently displayed higher residual compressive strength and higher residual shear strength values compared to the normal quartz concrete at various heating temperatures and ageing durations as shown in Figure 4-22 to Figure 4-33. Hungarian andesite concrete demonstrates superior performance in structural concrete exposed to elevated temperatures, attributed to its mineral composition, thermal stability, low thermal expansion, high melting point, durable microstructure and enhanced bonding.

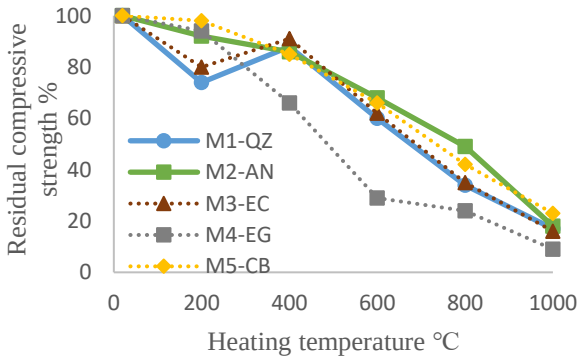


Figure 6-6. Relative residual compressive strength of concrete made with different types of aggregates at age 120 days

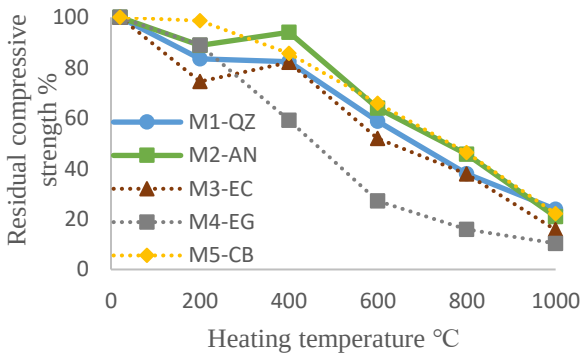


Figure 6-7. Relative residual compressive strength of concrete made with different types of aggregates at age 240 days

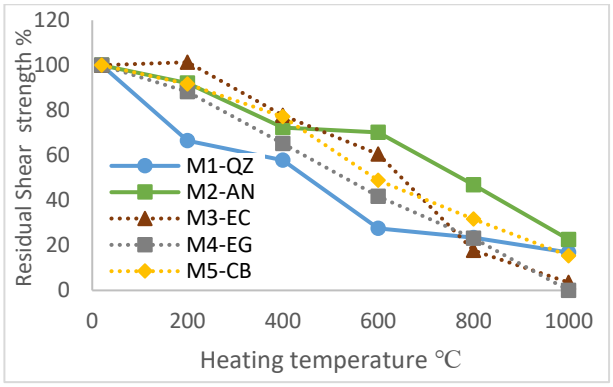


Figure 6-8. Relative residual shear strength of concrete made with different types of aggregates at age 120 days

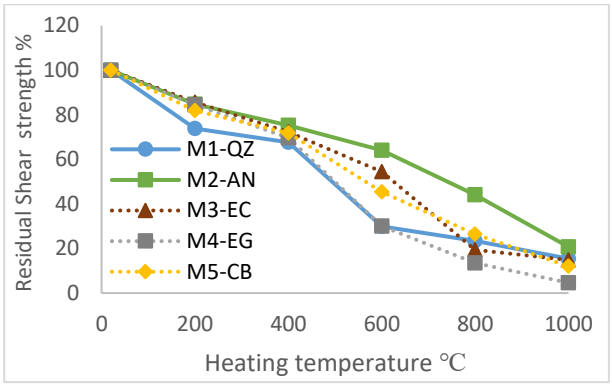


Figure 6-9. Relative residual shear strength of concrete made with different types of aggregates at age 120 days

Thesis group 2:

Using clay-based materials as a coarse aggregate for the structural concrete

2.1 I experimentally utilised using clay-based aggregates as a coarse aggregate with 100% replacement for the natural quartz aggregate to produce high-quality structural concrete, I successfully demonstrated that using crushed clay bricks as a recycled aggregate and expanded clay aggregate as the most used clay-based aggregate, with 100% replacement of the coarse aggregate for concrete showed almost similar characteristic compressive strength, compared with ordinary quartz aggregate concrete. Additionally, the clay-based aggregate concrete exhibited equivalent flexural tensile strength and shear strength levels to those of ordinary quartz aggregate concrete. **[P3, P4, P5, P6]**

The experimental utilisation of crushed clay bricks derived from cladding demolishing waste as a full replacement for the coarse aggregate in the concrete mix resulted in suitable characteristics for the structural concrete C50/60 and LC55/60 in addition to the favourable properties as lightweight concrete. The concrete made with recycled clay bricks showed similar

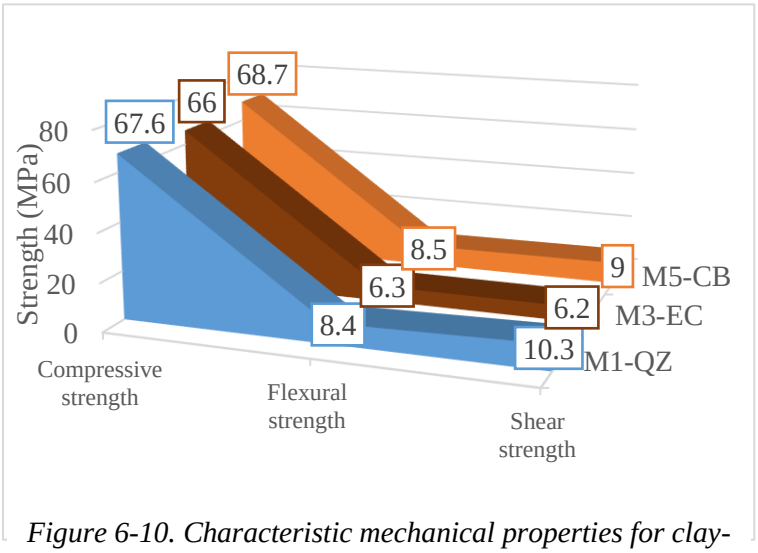


Figure 6-10. Characteristic mechanical properties for clay-based concrete compared with quartz concrete

compressive strength at early ages with the concrete made using normal quartz aggregate, as shown in Figure 6-10. However, the concrete with normal quartz aggregate developed superior strength as the curing time progressed. The flexural tensile strength and the shear strength exhibited minimal variation between the crushed clay bricks concrete and the quartz aggregate concrete. In contrast, the concrete with normal quartz aggregate displayed higher flexural tensile strength and higher shear strength in the case of expanded clay concrete; this behaviour was attributed to the lightweight aggregate's circular shape, affecting its interlocking properties with the cement paste.

2.2 I experimentally demonstrated that using crushed clay bricks as a recycled aggregate and expanded clay aggregate as the most used clay-based aggregate, with 100% replacement of the coarse aggregate for concrete subjected to elevated temperatures, showed a high similarity of the concrete thermal behaviour, irrespective to the aggregate shape or the porous structures; Results proved that concrete coarse aggregates base material played the significant role on the thermal response in case of the same cement matrix. **[P6]**

I successfully demonstrated that aggregates made with the same base material exhibit similar thermal behaviour, regardless of the aggregate shape or the presence of porous structures. The thermal characteristics of the aggregates remained consistent despite variations in their physical properties. These findings emphasise the base material's importance in determining aggregates' thermal behaviour, suggesting that other factors, such as shape and porosity, have a minimal impact on the overall thermal response.

The similar thermal conductivity for concrete made with recycled clay bricks and concrete made with expanded clay aggregates at ambient temperature and after subjected to elevated temperatures up to 1000 ℃ as shown in Figure 6-11. The finding that aggregates with the same base material exhibit consistent thermal behaviour in concrete, irrespective of their shape or the presence of porous structures, as shown in Figures 6-12 and 6-13, carries significant importance. This discovery highlights the base material's dominant influence on aggregates' thermal properties. It suggests that factors such as shape and porosity have minimal impact. This understanding is crucial in selecting and designing

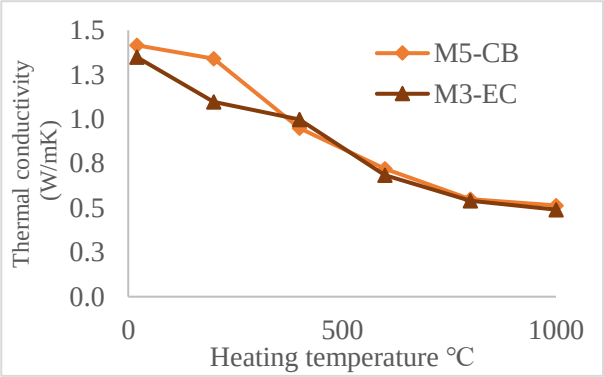


Figure 6-11. Thermal conductivity for two different clay-based materials mixes

concrete mixes with specific thermal requirements, as it allows for selecting aggregates based on factors such as availability and cost without compromising the desired thermal performance. Additionally, this finding opens up opportunities for developing advanced concrete formulations tailored to specific thermal requirements. By utilising aggregates with the same base material, construction practices can benefit from sustainable solutions, including recycled aggregates and reduced waste generation.

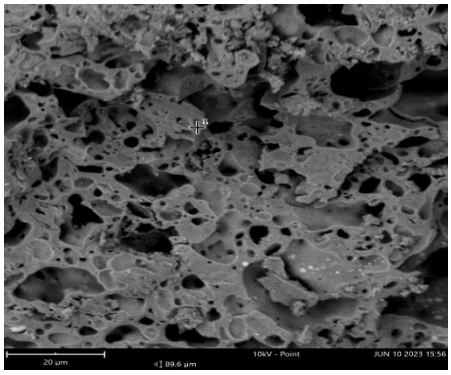


Figure 6-12. Microstructural photo for expanded clay

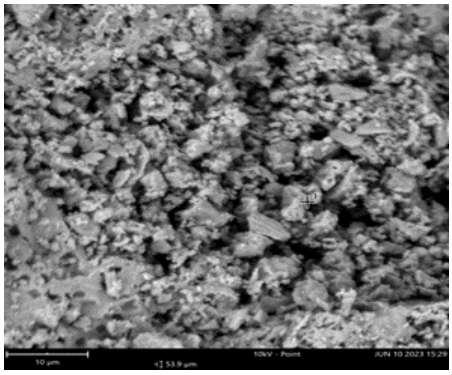


Figure 6-13. Microstructural photo for clay bricks

2.3 I experimentally proved that using the clay-based aggregates as 100% of the coarse aggregate in concrete showed high residual compressive and flexural tensile strengths after being subjected to elevated temperatures. I successfully demonstrated that using crushed clay bricks (recycled clay aggregate) and expanded clay aggregate (the most used clay-based aggregate) as 100% of the coarse aggregate of concrete exhibits superior behaviour in terms of residual compressive and residual flexural tensile strengths after subjected to elevated temperatures from 400 °C to 1000 °C. Compared to the Eurocode standards (EN 1992-1) and the available literature results for the natural aggregates concrete. **[P3, P4, P5, P6]**

The experimental results demonstrate that incorporating crushed clay bricks as a recycled clay aggregate and expanded clay aggregate as a clay-based aggregate in concrete coarse aggregates with full replacement of coarse aggregate showed a high residual mechanical property when the concrete subjected to elevated temperatures compared with the current literatures [33,34,36–39]. The clay-based aggregate concrete consistently displayed higher residual compressive strength and flexural tensile strength after subjected to heating temperatures up to 1000 ℃, as shown in the following figures.

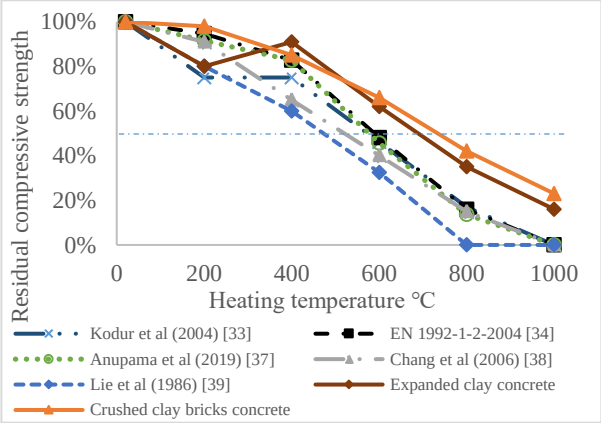


Figure 6-14. Residual compressive strength for the clay-based aggregates concrete in comparison to previous literature

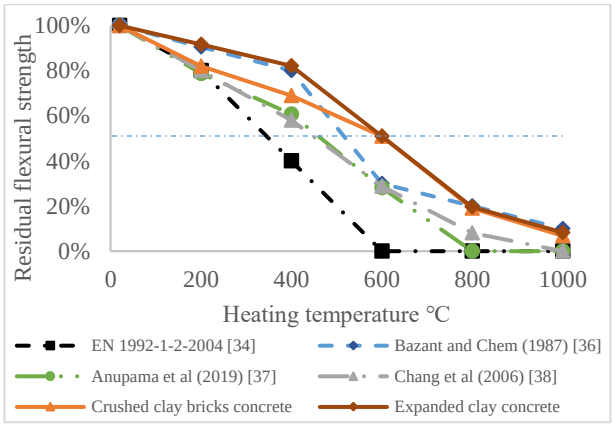


Figure 6-15. Residual flexural tensile strength for the clay-based aggregates concrete in comparison to previous literature

The utilisation of crushed clay bricks as a recycled clay aggregate and expanded clay aggregate as the commonly used clay-based aggregate offers a sustainable approach to concrete production. The successful demonstration of their performance as a 100% replacement for coarse aggregate further highlights their potential as environmentally friendly alternatives.

Thesis group 3:

Thermal conductivity for concrete made with different types of aggregate after subjected to elevated temperature.

***3.1 I experimentally proved that concrete thermal conductivity is directly connected to the aggregate category in terms of normal or lightweight aggregates as well as concrete, with less dependency on the mortar matrix or concrete class. Moreover, I experimentally proved that concrete with the same category of coarse aggregate has a similar thermal behaviour trend after being subjected to elevated temperatures.* [P6]**

Concrete is a composite material comprising various components, including aggregates and a cementitious matrix. The experimental results showed that aggregate type significantly impacts thermal conductivity. I experimentally demonstrated that concrete with the same category of coarse aggregate exhibits similar thermal behaviour when exposed to elevated temperatures. Concrete compositions

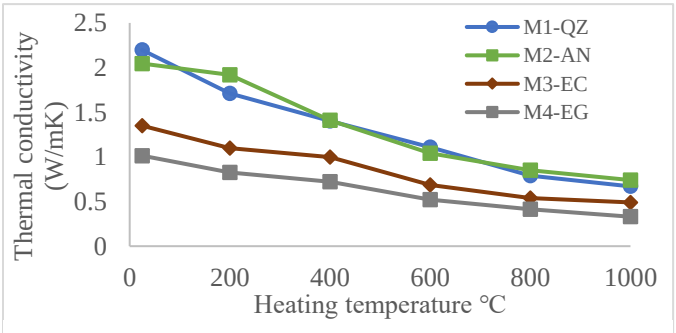


Figure 6.16. Thermal conductivity for concrete with the same aggregates category

utilizing natural aggregates, such as quartz (M1-QZ) or andesite (M2-AN), similar thermal conductivity values after exposure to elevated temperatures. This indicates a consistent thermal behaviour among concretes made with these types of aggregates under such conditions. Additionally, experiments revealed a similar behaviour among lightweight aggregates. Despite their distinct compositions, expanded clay (M3-EC) and expanded glass (M4-EG) exhibited similar thermal conductivity trends when incorporated into concrete and subjected to elevated temperatures, as shown in Figure 6-16. These significant findings shed light on the crucial role of aggregate selection in determining the thermal properties of concrete, especially in environments with high temperatures. Consistent thermal behaviour within the same aggregate category opens up exciting possibilities for designing concrete mixtures with targeted thermal conductivity values.

3.2 ***I experimentally proved that the inclusion of polypropylene micro-fibre in concrete has a minimal effect on the thermal behaviour after being subjected to elevated temperatures. Concrete mixtures utilising various coarse aggregates, including quartz aggregate, expanded clay, expanded glass, and crushed clay bricks, exhibited negligible changes in thermal conductivity when polypropylene micro-fibres were included. Consequently, a single thermal conductivity measurement suffices to represent both fibre-included and fibre-free concrete mixes, streamlining assessment procedures for enhanced construction applications.*** **[P1, P6]**

The thermal conductivity results of concrete mixtures with and without polypropylene fibres showed similar or slightly lower thermal conductivity values for mixtures containing fibres as shown in Figure 4-46. This suggests that the presence of polypropylene fibres has a limited impact on the overall thermal behaviour of concrete in terms of heat transfer properties. In contrast, PP fibres in the concrete mixture contribute to crack control and improved reinforcement, leading to a more compact structure. This denser structure can hinder heat transfer and result in slightly lower thermal conductivity values.

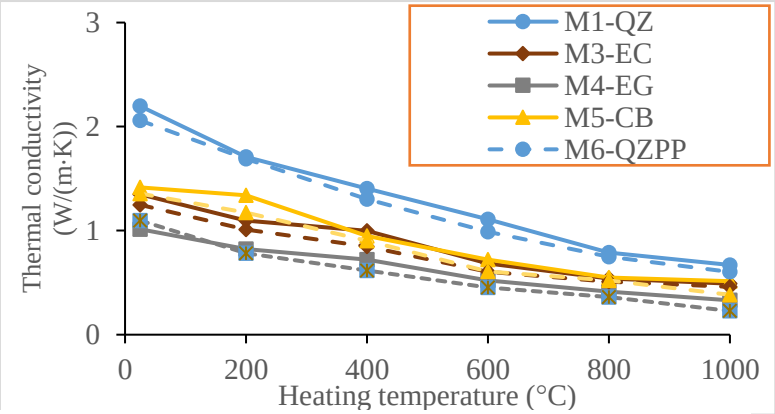


Figure 6.17. Thermal conductivity for concrete with the same aggregates category

List of publications related to the new scientific results

P1. A.M. Seyam, S. Shihada, R. Nemes, Effects of polypropylene fibers on ultra high performance concrete at elevated temperature, Concrete Structures. 21 (2020) 11–16. https://doi.org/10.32970/cs.2020.1.2.

P2. A.M. Seyam, R. Nemes, Using Hungarian andesite as a coarse aggregate for concrete, Epitoanyag - Journal of Silicate Based and Composite Materials. 75 (2023). https://doi.org/10.14382/epitoanyag-jsbcm.2023.06.

P3. A.M. Seyam, R. Nemes, Age influence on compressive strength for concrete made with different types of aggregates after exposed to high temperatures, Mater Today Proc. (2023). https://doi.org/10.1016/j.matpr.2023.06.403.

P4. A.M. Seyam, R. Nemes, Shear Strength Behavior for Lightweight Aggregate Concrete Subjected to Elevated Temperature, in: Stokkeland Stine, Braarud Henny Cathrine (Eds.), 6th Fib International Congress, Concrete Innovation for Sustanbaility, Oslo, 2022: pp. 595–603.

P5. A.M. Seyam, R. Nemes, Impacts of Aggregate Type and Elevated Temperature on Flexural Tensile Strength of Concrete, in: M. di Prisco, A. Meda, G.L. Balazs (Eds.), Proceeding of the 14th Fib International PhD Symposium in Civil Engineering, Rome, 2022.

P6. A.M. Seyam, R. Nemes, Influence of Elevated Temperatures on the Compressive Strength of Concrete Made with Different Types of Aggregate, Periodica Polytechnica Civil Engineering. (2024), *Accepted*.

List of other publications

P7. R. Nemes, M.A. Abed, A.M. Seyam, É. Lublóy, Behavior of structural lightweight concrete produced with expanded clay aggregate and after exposure to high temperatures, J Therm Anal Calorim. 147 (2022) 8111–8118. https://doi.org/10.1007/s10973-021-11167-6.

P8. A.M. Seyam, S. Shihada, R. Nemes, Effects of using polypropylene and steel fibres on Ultra High Performance Concrete subjected to elevated temperatures, in: F. Gatuingt, J.M. Torrenti (Eds.), 13th Edition of the Fib International PhD Symposium in Civil Engineering, International Federation for Structural Concrete, fib, Paris, 2020: pp. 25–32.

P9. A.M. Seyam, G.L. Balázs, A Review in Technologies, Definitions, Properties and Applications of Ultra High-performance Concrete (UHPC), Concrete Structures. (2023) 105–111. https://doi.org/10.32970/CS.2023.1.15

P10. A.M. Seyam, R. Nemes, Comparing the European Standards and the American Standards for Testing Concrete Mechanical Properties, Concrete Structures. (2023) 97–104. https://doi.org/10.32970/CS.2023.1.14

P11. A.M. Seyam, G.L. Balázs, A Review in Technologies, definitions and Mechanical Properties of Ultra High-Performance Concrete (UHPC), in: M. Salamak (Ed.), 13th Central European Congress on Concrete Engineering CCC 2022, Next Generation of Concrete Engineering for Post-Pandemic Europe, nbi media, Kraków, 2022: pp. 93–100.

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