BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
Faculty of Civil Engineering
Department of Construction Materials and Technologies

New scientific results of the Ph.D. thesis

Effects of Aggregate Type on Concrete Subjected to Elevated Temperatures

by

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1. Introduction

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. 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 used 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 [1–4].

During the structural design of buildings, fire resistance is an essential factor that must be considered. 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 [9,10]. 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 [11,12]. 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, reducing the concrete's strength [13].

2. Research 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 weight loss, thermal properties, including 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 at ambient temperature and after subjected to elevated temperatures.
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- Study the effect of concrete age on the properties of concrete made with different aggregate types after subjected to elevated temperatures.
7- Investigate the effect of using different aggregates derived from the same base materials on concrete's mechanical and thermal properties.
8- 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 developing more resilient and durable concrete structures under elevated temperature conditions.

3. Experimental program

A series of experimental tests were conducted using ten selected concrete composites, differing in coarse aggregate and the fibre content. Coarse aggregates used to represent different concrete categories, ordinary concrete (OC), lightweight aggregate concrete (LWAC) and recycled aggregate concrete (RAC). Five types of coarse aggregates, normal quartz aggregate, crushed andesite, expanded glass, expanded clay and recycled crushed clay bricks, Figure 3. The same amount of the ordinary Portland cement CEMI 42.5 N as a binder compatible with the European Standard EN 197–1 2011, and one type of the fine aggregates with 0-4 mm grading size, shown in Figure 3-C, were used in all mixes. Furthermore, the influence of incorporating polypropylene microfibres on each concrete mix was also examined.

The physical and chemical characteristics of the coarse aggregates used were evaluated. Concrete specimens were prepared based on EN 12390-1, using 100 mm cubes, 150 mm cubes, 200 x 100 mm diameter cylinders and 70 x 70 x 250 mm prisms, as presented in Table 2. Concrete fresh properties were evaluated, including fresh density, air content and workability, using the flow table test. Concrete physical properties were evaluated, including the concrete moisture content and the hardened density at concrete ages 28, 120 and 240 days, moreover, the weight loss due to heating were also evaluated. Concrete mechanical properties were evaluated for compressive strength, flexural tensile strength and shear strength at ambient and after subjected to elevated temperatures of 200 ℃, 400 ℃, 600 ℃, 800 ℃ and 1000 ℃ for 2 hours at ages 28, 120 and 240 days. The thermal conductivity was also evaluated for all concrete mixes at ambient and after subjected to elevated temperatures; The research flow chart is shown in Figure 9.

3.1 Mix design

3.1.1 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 38% with dosage 171 kg/m^3.

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 1. 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 1. Concrete mix proportions

Material	Mix number	*Component materials dosage 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

3.1.2 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 [14]. 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 [15] 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 1.

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 2, for 28 days, 120 days and 240 days with a temperature of 20 ± 5 °C and relative humidity of 50 ± 5 %.

Figure 1. Specimens in moulds

Figure 2. Specimens on the lab, after the initial curing, were stored for up to 240 days.

Figure 3. Aggregates used in the research, a) River quartz gravel, b) Crushed andesite, c) Quartz sand, d) Expanded clay, e) Expanded glass, and f) Crushed clay bricks

Table 2. Number and shape of concrete specimens

Test	Specimen shape and size	Specimen 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		3	-	-	-	30
Compressive strength	*Cube (150x150x150 mm)*	-	3	3	3	90
Thermal conductivity		-	3	18	-	180

3.2 Evaluations and testing methods

3.2.1 Fresh properties

The fresh properties of each concrete mix were meticulously evaluated in accordance with EN 12350-1 standard [16] and EN 1051-6 [17]. The workability of the concrete was assessed using the flow table test, following the guidelines outlined in the European standards EN 12350-5 [18]. This test provided quantitative data on the concrete's flowability and workability. The fresh concrete density was measured as outlined in EN 12350-6 [19]. Furthermore, the air content of the fresh concrete was calculated using the gravimetric method as specified in ASTM C138 [20]. 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.

3.2.2 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 [21].

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.

3.2.2.1 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 [22]. The moisture content is then calculated using the formula: Moisture Content (%) = (W1 - W2) / W1 × 100.

3.2.2.2 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 [21]. 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.

3.2.2.3 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.

3.2.3 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 [23] flexural tensile strength was tested following to EN 12390-5 [24] *w*hile the shear strength was indirectly evaluated using the push-off model with a uniaxial loading as in EN 12390-3 [23].

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 2.

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

3.2.3.1 Compressive strength

The compressive strength of the concrete was determined in accordance to EN 12390-3:2009 [23] the test was performed utilising a uniaxial compressive strength machine shown in Figure 4, 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 4. Compressive test machine

3.2.3.2 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 5. The samples were subjected to a constant loading rate of 80 N/s, following the European standard [24].

Figure 5. Three-point loading flexural tensile test machine

3.2.3.3 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 6.

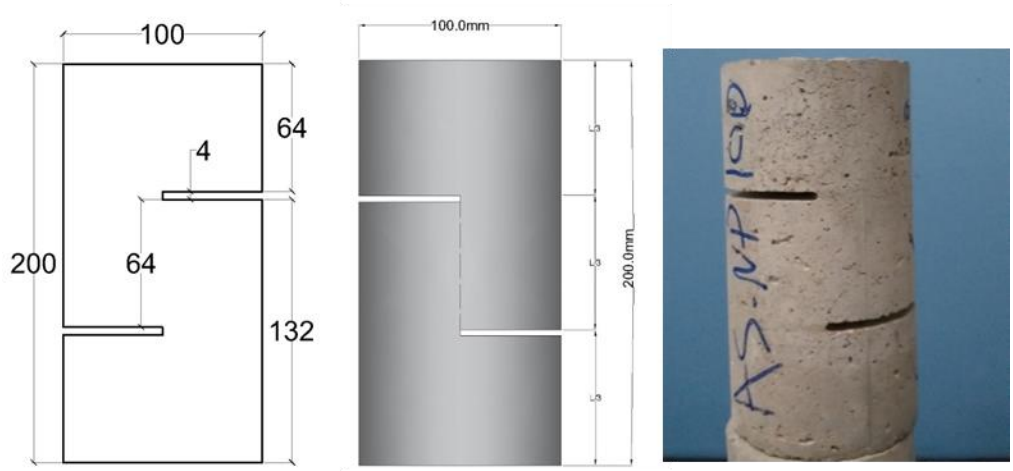

Figure 6. Schematic illustration of the dimensions adopted Push-off specimen

3.2.4 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.

3.2.5 Heating and cooling

Specimens were heated using an electric furnace, shown in Figure 8. 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 [25], 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 7, 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.

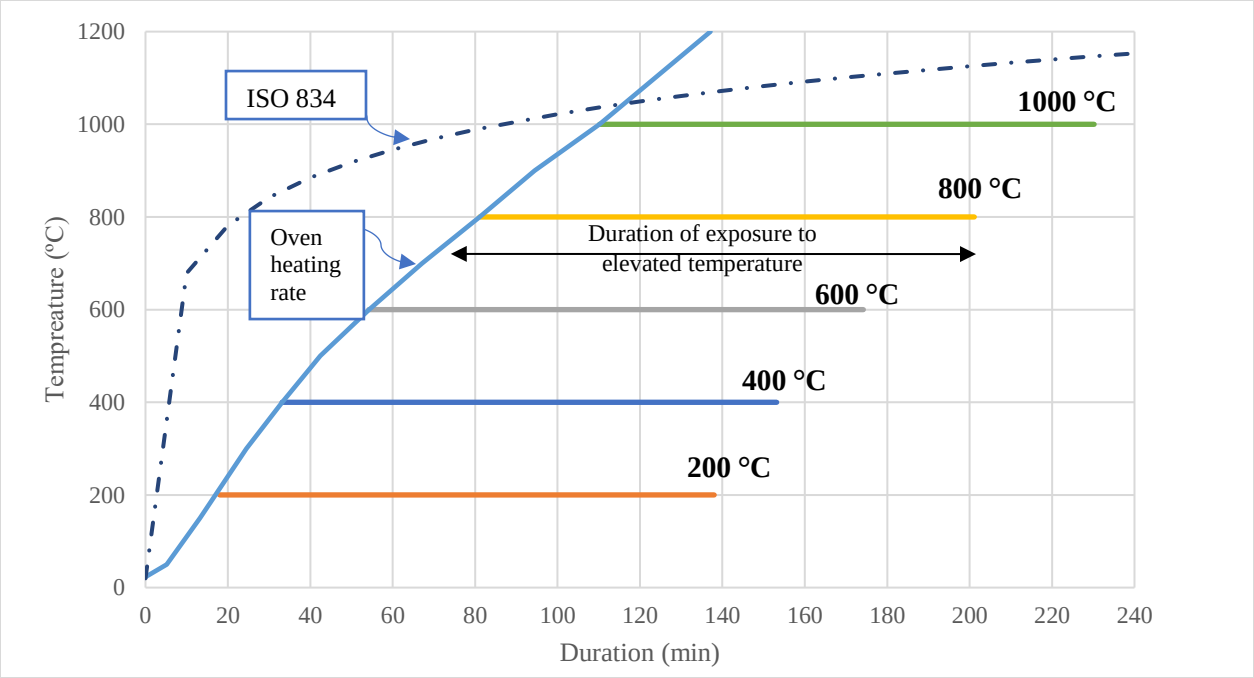

Figure 7. Rise in temperature in the furnace with heating duration at each heat level and ISO 834 fire curve

Figure 8. Electric furnaces used in the high temperature tests

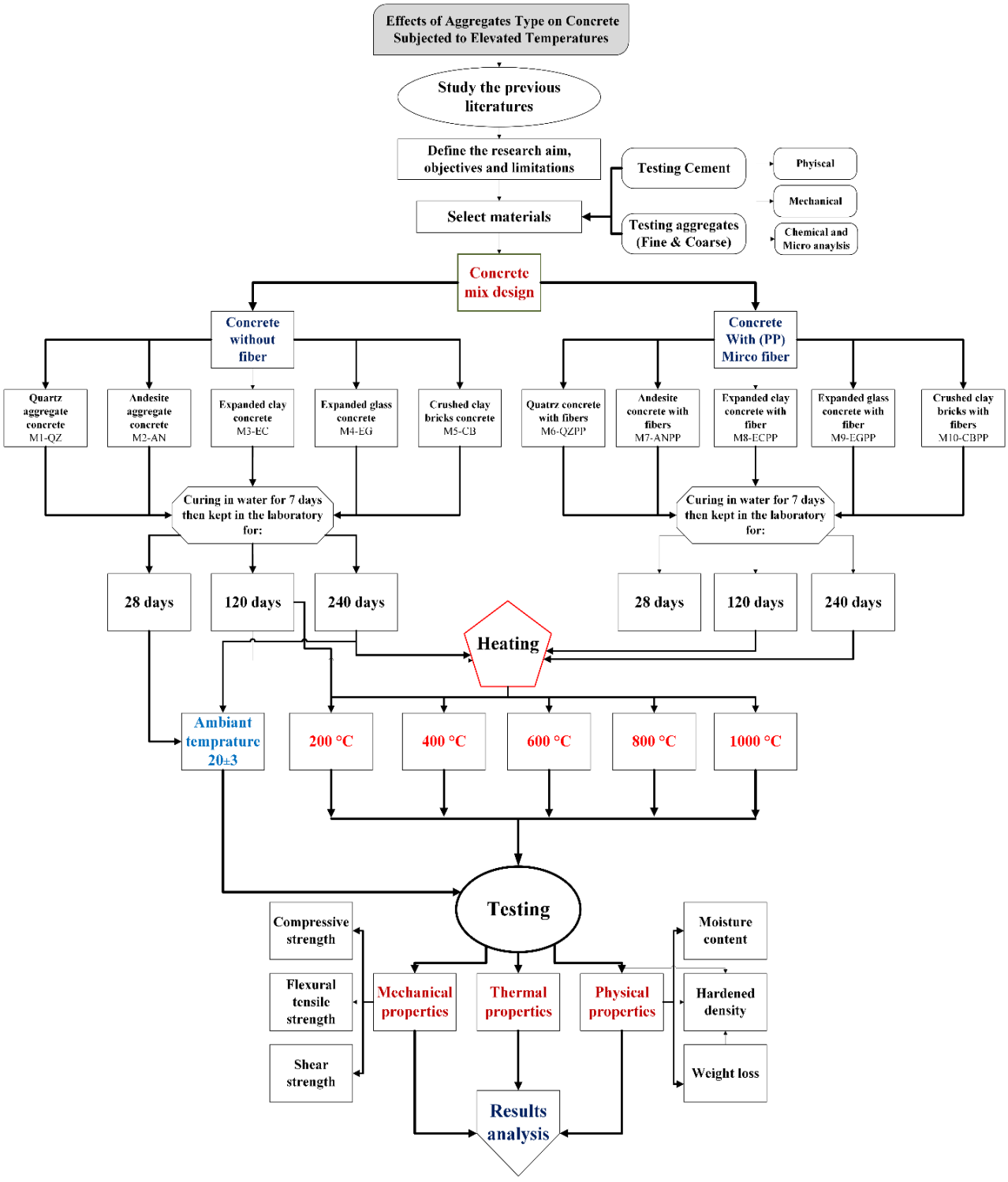

Figure 9. The full experimental program flowchart

4. 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]

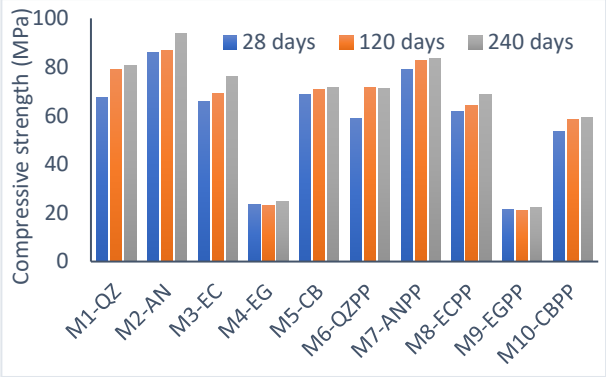

Figure 10. Compressive strength test results

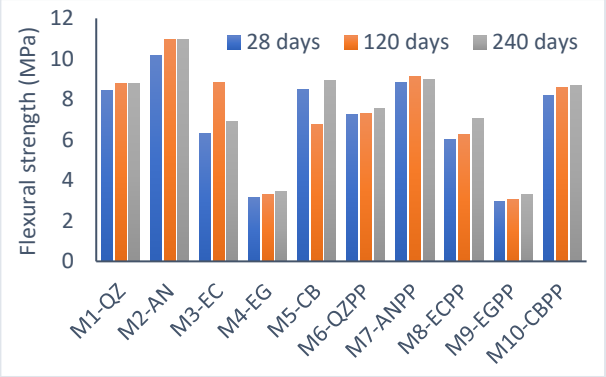

Figure 11. Flexural tensile strength test results

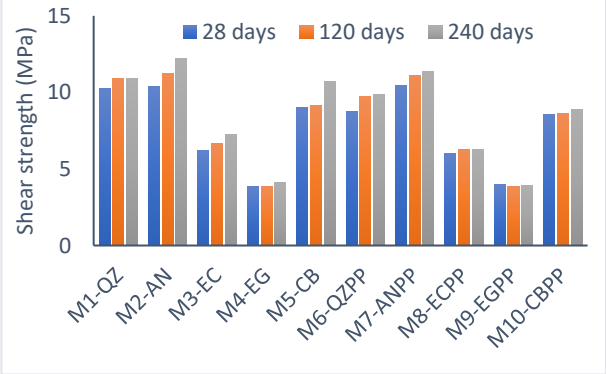

Figure 12. Shear strength test results

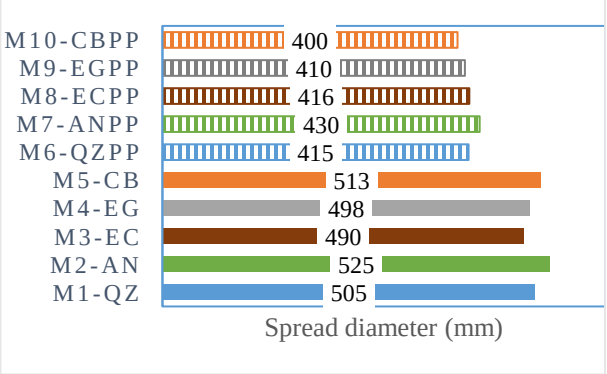

Figure 13. Flow table test results

The experimental results shown in Figure 10, Figure 11 and Figure 12 demonstrate that using Hungarian andesite extracted from (Kisnána, Mátra) as a coarse aggregate with 100% replacement for the natural quartz aggregate significantly enhances concrete's mechanical characteristics.

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 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 13. This denser mortar matrix improves load distribution and stress transfer, enhancing fresh and mechanical properties.

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 14 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 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.

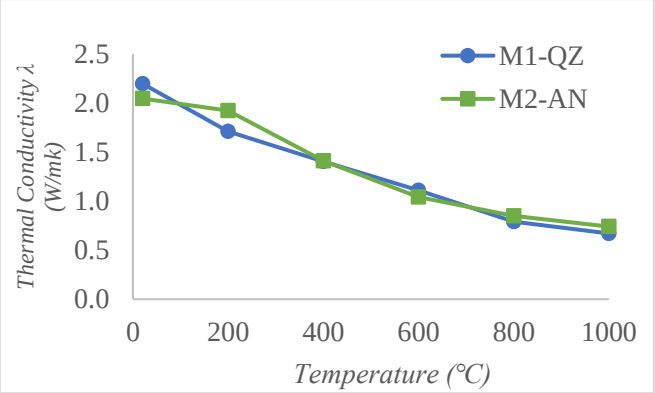

Figure 14. Concrete Thermal conductivity after subjected to elevated temperatures

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 after being subjected to elevated temperatures. The Hungarian andesite concrete consistently displayed higher residual compressive strength and higher residual shear strength values compared with concrete made with different aggregate types, including quartz as a common concrete, expanded clay and expanded glass as a lightweight concrete at various heating temperatures and ageing durations as shown in Figure 15, Figure 16, Figure 17 and Figure 18. Hungarian andesite aggregate demonstrates superior performance in structural concrete exposed to elevated temperatures, attributed to its distinctive mineral composition, thermal stability, low thermal expansion, high melting point, durable microstructure, enhanced bonding, homogeneity, lack of harmful constituents, and ample availability for construction applications. Incorporating Hungarian andesite into concrete presents a practical and effective approach to enhancing concrete's resilience under extreme thermal conditions.

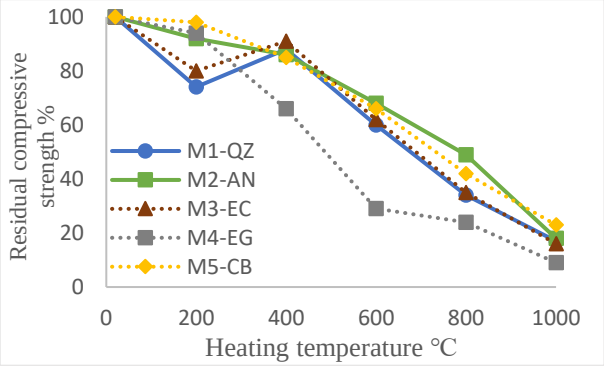

Figure 15. Residual compressive strength of concrete made with different types of aggregates at age 120 days

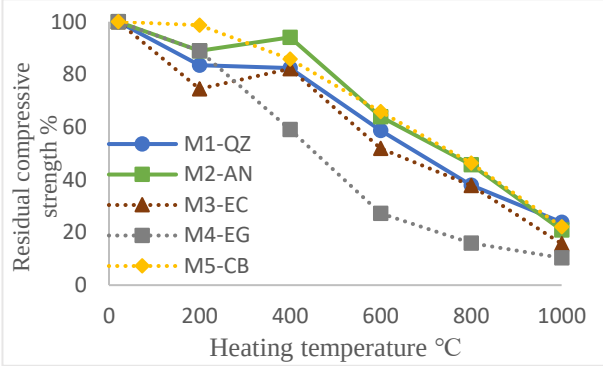

Figure 16. Residual compressive strength of concrete made with different types of aggregates at age 240 days

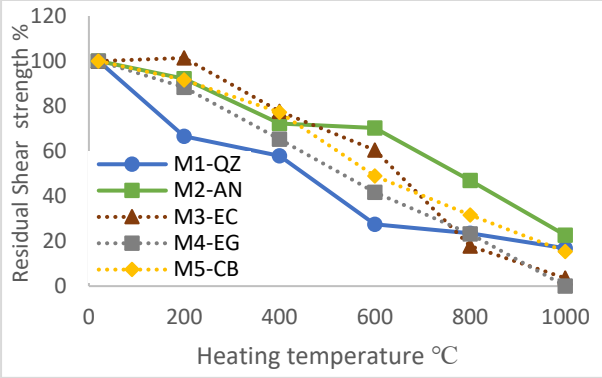

Figure 17. Residual shear strength of concrete made with different types of aggregates at age 120 days

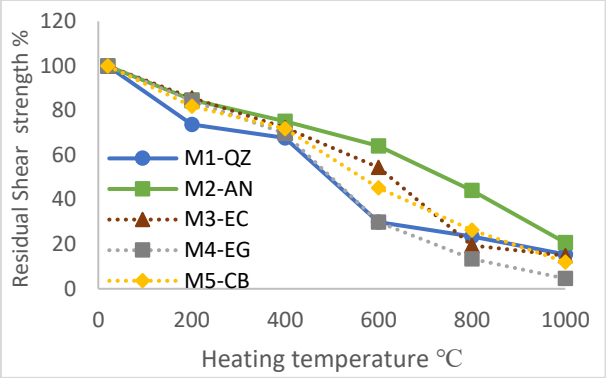

Figure 18. Residual shear strength of concrete made with different types of aggregates at age 120 days

Thesis group 2:

Using clay-based materials as a coarse aggregate for 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 equivalent compressive strength at early ages with the concrete made by normal quartz aggregate, as shown in Figure 19. 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.

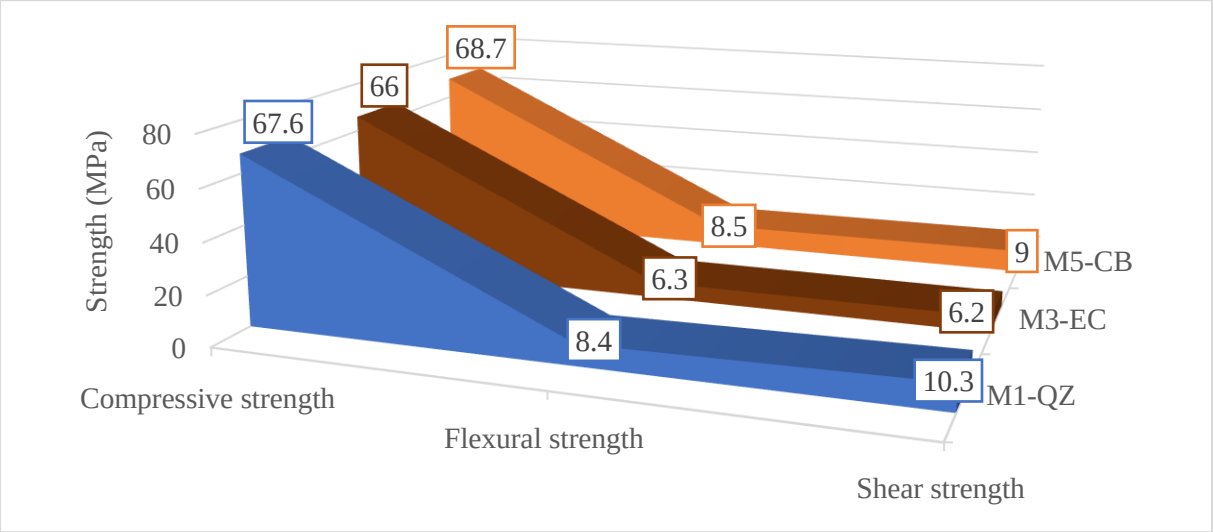

Figure 19. Characteristic mechanical properties for clay-based concrete compared with quartz concrete

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.

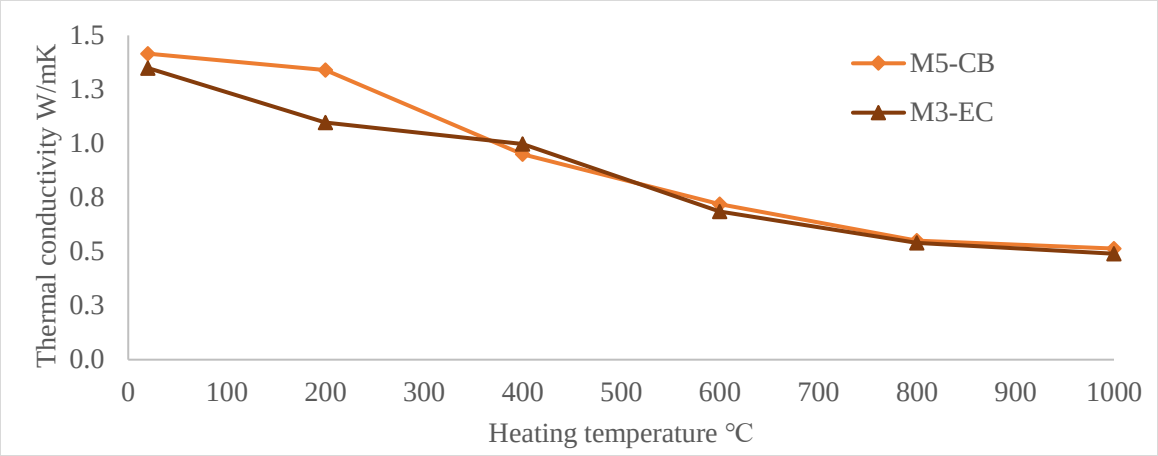

Figure 20. Thermal conductivity for two different clay-based materials mixes

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 400 ℃, 600 ℃, 800 ℃ and 1000 ℃ as shown in Figure 20 proof this finding. 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 Figure 21 and Figure 22, 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 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.

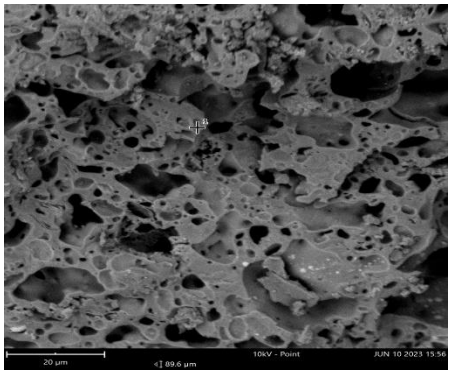

Figure 21.Microstructural photo for expanded clay

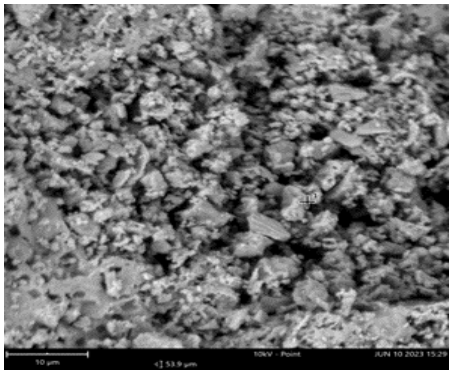

Figure 22.. Microstructural photo for clay bricks

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 available literatures [26–30]. The clay-based aggregate concrete consistently displayed higher residual compressive strength and flexural tensile strength after subjected to heating temperatures up to 1000 °C, as shown in the following figures.

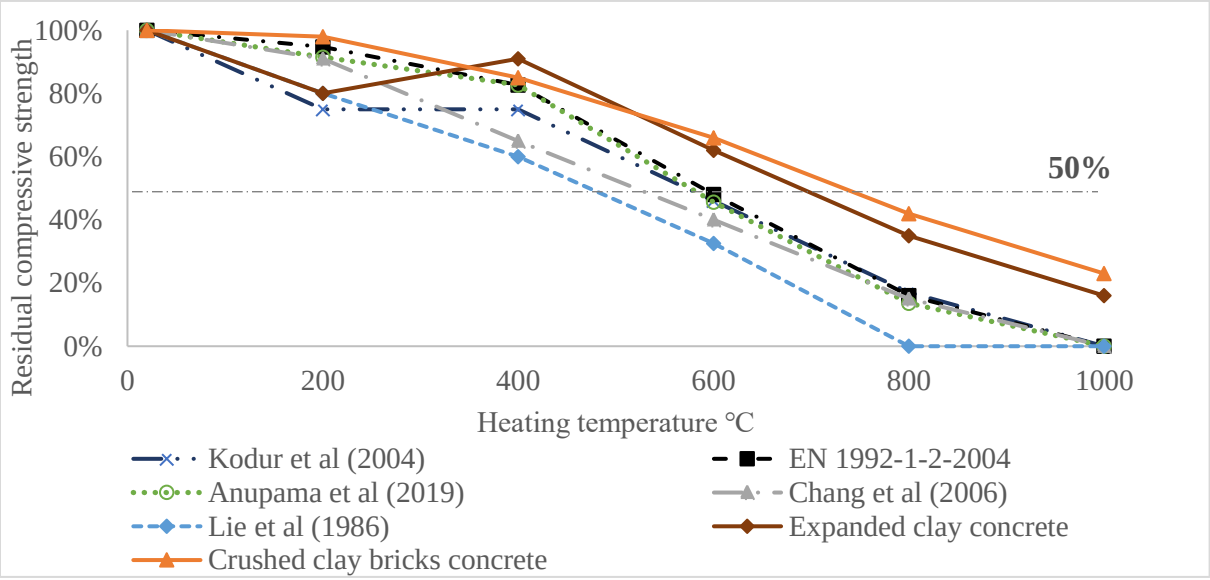

Figure 23.. Residual compressive strength for the clay-based aggregates concrete in comparison to previous literature

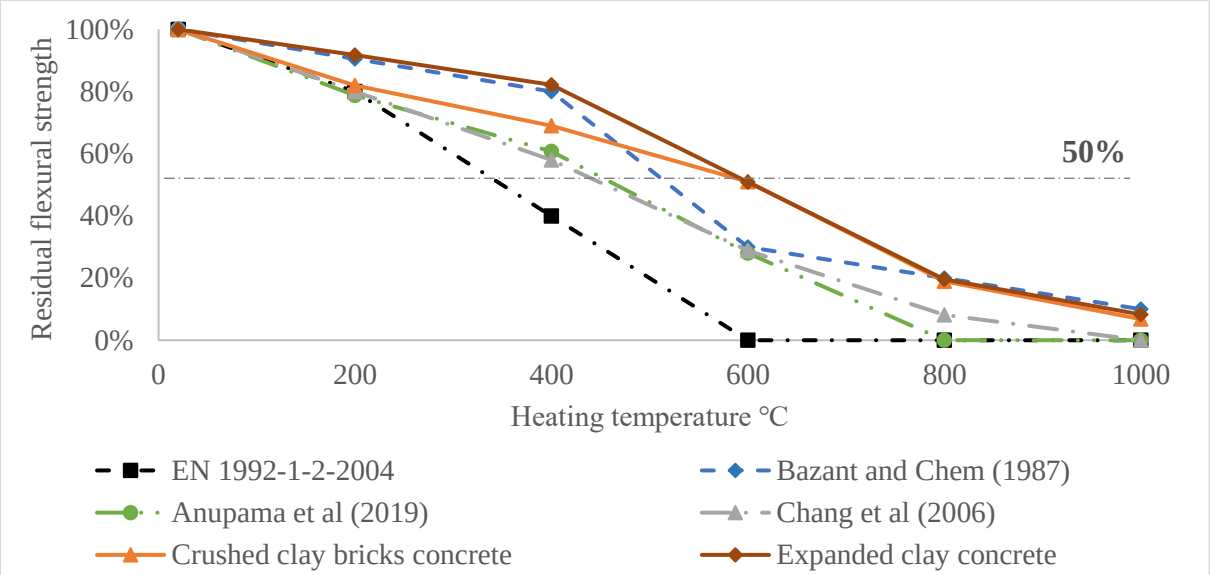

Figure 24. Residual flexural tensile strength for the clay-based aggregates concrete in comparison to previous literature

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]**

The experimental results showed that aggregate type significantly impacts thermal conductivity, as shown in Figure 25. I experimentally demonstrated that concrete with the same category of coarse aggregate exhibits similar thermal behaviour when exposed to elevated temperatures, as shown in Figure 26. Concrete compositions utilising natural aggregates, such as quartz or andesite M1-QZ and M2-AN, respectively, showcased similar thermal conductivity values after exposure to 400 °C and higher elevated temperatures. This indicates a consistent thermal behaviour among

concretes made with these types of aggregates under such conditions. Additionally, my experiments revealed a similar behaviour among lightweight aggregates. Despite their distinct compositions, expanded clay and expanded glass M3-EC and M4-EG exhibited similar thermal conductivity patterns when incorporated into concrete and subjected to elevated temperatures. 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 exciting possibilities for designing concrete mixtures with targeted thermal conductivity values.

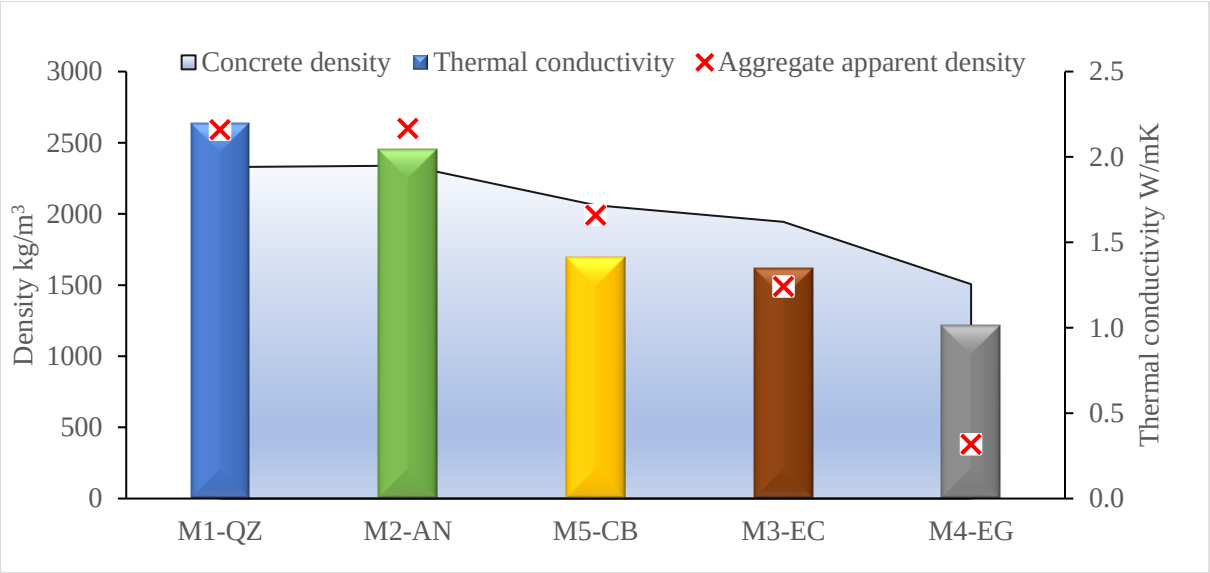

Figure 25. Concrete thermal conductivity in comparison with concrete density and aggregates density

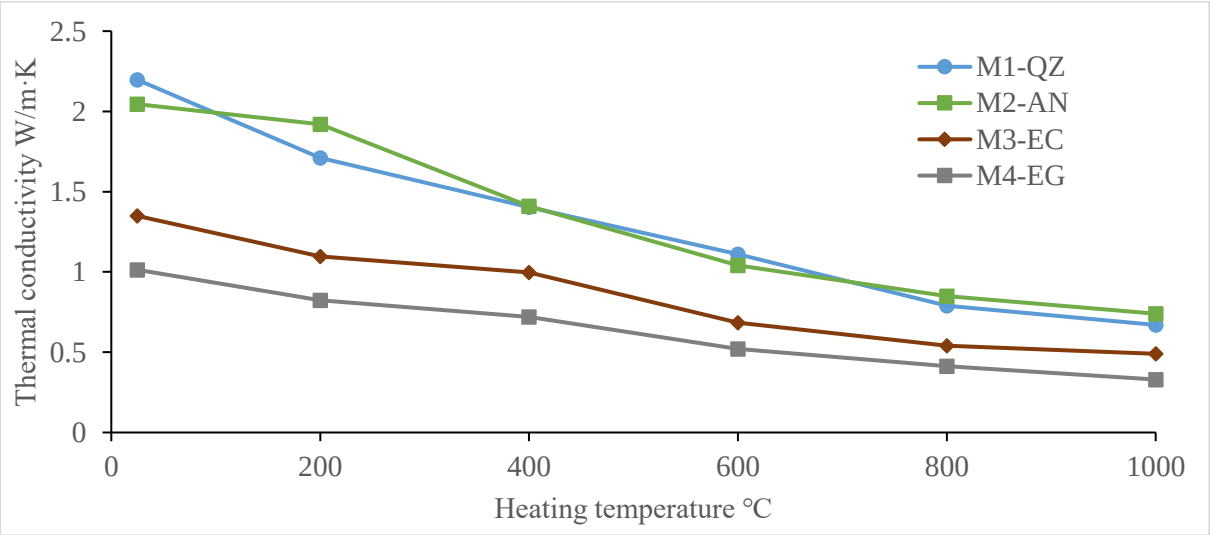

Figure 26. Thermal conductivity for concrete with the same aggregates category

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]**

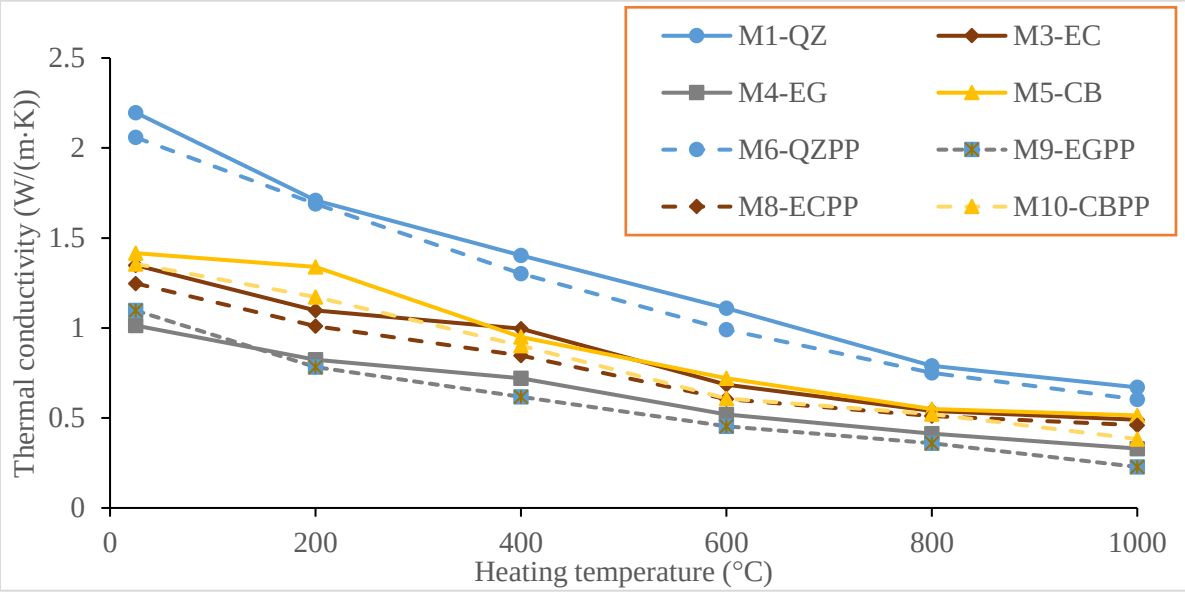

Figure 27. Thermal conductivity results for both mixes with and without PP micro fibres

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 27. 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.

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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) 104–111. 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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