https://doi.org/10.3311/PPci.36784

Periodica Polytechnica Civil Engineering, 68(4), pp. 1073–1085, 2024

Influence of Elevated Temperatures on the Compressive Strength of Concrete Made with Different Types of Aggregate

Ahmed M. Seyam[1], Rita Nemes[1*]

[1] Department of Construction Materials and Technologies, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary

[*] Corresponding author, e-mail: nemes.rita@emk.bme.hu

Received: 29 February 2024, Accepted: 05 April 2024, Published online: 10 June 2024

Abstract

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. This study aimed to investigate the influence of elevated temperatures on the compressive strength of concrete made with different types of aggregate. A comprehensive evaluation of concrete mixes was conducted using quartz, crushed clay bricks, crushed andesite, expanded clay and expanded glass coarse aggregates. For each coarse aggregate type, concrete mixtures were made with the same amount of Portland cement, water-cement ratio, natural sand, and superplasticizer. The effective water-cement ratio and cement content were kept constant in each concrete mixture. The grading and maximum particle size were the same in all concrete mixtures. The results revealed that the type of aggregate has a significant impact on the compressive strength and thermal resistance of concrete, with andesite-containing concrete exhibiting the highest residual strength after heating up to 800 °C and clay brick-concrete displaying the highest strength under elevated temperatures up to 1000 °C. The study also found that the age of concrete affects its strength at elevated temperatures, as concrete in the early stages of hydration is more susceptible to thermal cracking than concrete that has had more time to cure. Generally, the compressive strength of normal-weight aggregates depends on the strength of the parent rock. But in the case of fire (elevated temperature), the cement paste matrix loses its strength, and the aggregates effects become more significant.

Keywords

age, aggregate, compressive strength, concrete, elevated temperature, fire, LWC

1 Introduction and background

Fire resistance stands as a critical consideration in the structural design of buildings, playing a pivotal role in ensuring the integrity of construction materials under fire exposure [1, 2]. While the construction industry offers a diverse array of materials, concrete has emerged as a preferred choice due to its inherent strength. However, comprehensive research into concrete behavior under elevated temperatures is imperative, given its widespread use [3].

Concrete's response to elevated temperatures is intricate, influenced by factors such as temperature exposure, mixture composition, moisture content, heat exposure duration, cooling methods, and the intrinsic properties of its components [2]. With aggregates constituting approximately 70% of concrete structure, their role in shaping the thermal response and mechanical properties is paramount [4]. This study delves into the compressive strength of concrete under both ambient and elevated temperatures, with a specific focus on the distinctive influence of various coarse aggregate types.

The experimental work was divided into several phases. First, it was necessary to determine the characteristic properties of the concrete mixes, which needed concrete classification for the produced specimens at the age of 28 days. The second phase involved assessing the mechanical properties of the concrete at ambient and elevated temperatures after ageing and drying for 120 days. This approach minimizes the risk of damage caused by concrete spalling during heating and provides results that are more representative of actual conditions encountered in real-world construction and serviceability.

The behaviour of concrete at high temperatures influencing by many variables; the results of the experimental tests vary depending on the test performed and their different conditions. The most significant factors influencing

Cite this article as: Seyam, A. M., Nemes, R. "Influence of Elevated Temperatures on the Compressive Strength of Concrete Made with Different Types of Aggregate", Periodica Polytechnica Civil Engineering, 68(4), pp. 1073–1085, 2024. https://doi.org/10.3311/PPci.36784

the compressive strength of concrete at high temperatures are the difference in stresses, the moisture content of the concrete, heat exposure time, and the cooling mode [5]. The hot or residual test conditions (after cooling), the rate of heating, the rate of cooling, and the period after cooling until the compression test is performed have added to the previous factors [6]; the compressive strength of concrete exposed to high temperatures are affected by a variety of factors, including the water to cement ratio, the cement to aggregate ratio, the type of aggregate used, the water content of the concrete prior to exposure to high temperatures, and the specific conditions of the fire event [7].

Literatures reported the concrete response to the heat/fire. Bažant and Kaplan [8] stated that up to temperatures of 100 °C, conventional Portland cement concrete maintains its mechanical properties unchanged. But at 200 °C the residual strength of normal strength concrete can vary between 85% and 110% of the initial strength (at room temperature). For temperatures above 200 °C, the compressive strength of concrete decreases almost linear; between 300 °C and 400 °C, a significant reduction in concrete strength begins, around 20%, and this reduction is accompanied by notoriously visible surface cracking.

The significant loss of strength in concrete due to high temperatures occurred between 400 °C and 600 °C, where dihydroxylation of the portlandite occurs, with the greatest mechanical strength loss occurring at temperatures between 500 °C and 600 °C [4, 9]. On the other hand, Passos et al. [10] showed that the exposure temperature significantly affects the compressive strength of concrete; for temperatures above 600 °C, the degradation of the concrete is more significant, and the warmer surface layers tend to separate from the cooler inner layers. Neville [5] considered the heating temperature of 600 °C as the temperature limit to guarantee the structural integrity of Portland cement concrete.

Meddah et al. [11] investigated the effects of coarse aggregate content and particle size distribution on the compressive strength of concrete. Four different mixes of concrete were produced using three types of coarse aggregate, and some mixes were modified with the use of plasticizers to decrease the water-to-cement ratio. The findings revealed that the mixture with a ternary combination of granular fractions with a maximum size of 25 mm, without admixtures, demonstrated the highest compressive strength. Additionally, the research found that a binary granular system produced the highest compressive strength at a lower water-to-cement ratio. Elices and Rocco [12] compared concretes with similar mix proportions containing four distinct coarse aggregate types. The conclusion was that higher-strength coarse aggregates typically result in higher compressive strengths. However, in normal-strength concretes, the strength of the coarse aggregate has little impact on the compressive strength.

Quayson and Mustapha [13], examined the relationship between the type of coarse aggregates and compressive strength in high-strength concrete. The investigation used two types of coarse aggregates: quartzite and crushed granite, along with quarry dust as the fine aggregate. The results showed that concrete made with quartzite aggregates displayed the highest average compressive strength, whereas concrete made with granite had better workability. The variations in compressive strength were attributed to the properties of the coarse aggregates, such as their densities and individual compressive strengths. The results highlight the importance of considering the properties of different coarse aggregates in the production of high-strength concrete.

The possibility of producing structural concrete by replacing natural aggregates with recycled materials considering the environmental factors has been studied. It was concluded that the reduction in the compressive strength of concrete is directly proportional to the increase in the percentage of substitution of natural aggregates with recycled ones and that, even with this reduction, it's still feasible to use the recycled materials and the ceramic wastes, therefore, the different constituent material characteristics used the different on the mechanical behaviour of the resulting concrete [14].

The suitability of crushed clay bricks and roof tiles as aggregates for concrete has been studied due to their exceptional resistance to high temperatures. The results have indicated that concrete made with these aggregates outperforms similar concrete mixtures containing granite aggregate [15]. The thermal stability of clay bricks and roof tiles is a key factor in their effectiveness in resisting and preventing the spread of fire. Their use as aggregates does not negatively affect the high-temperature resistance of the resulting concrete. However, it is crucial to maintain dryness to ensure optimal resistance to high temperatures, as internal steam pressure can cause spalling if the concrete is wet [16]. Furthermore, the low thermal conductivity of concrete made with crushed clay brick and roof tile aggregates provides better protection against early heating, preserving its structural integrity under high temperatures for longer than conventional concrete.

Netinger et al. [17] conducted research to determine the impact of aggregate on the mechanical properties and behaviour of concrete under high temperatures. A uniform type and amount of cement were utilized in all concrete mixtures, and the results indicated that the choice of aggregate had a substantial effect on the concrete's mechanical properties and fire resistance.

Research conducted by Bodnárová et al. [18] has shown that the compactness and load-bearing capacity of lightweight concrete with higher moisture content was impaired at a temperature of 700 °C. Additionally, the study reported that the fire resistance of the lightweight concrete rapidly decreased with decreasing moisture content, particularly for moisture content ranging from 10 to 20%. Future research could further define the optimal moisture content limit for this type of concrete. The study of Nemes and Józsa [19] evaluated the load-bearing mechanism of normal-weight concrete (NWC) and lightweight aggregate concrete (LWAC). The researchers established a correlation between the compressive strength and density of concrete, specifically in the case of various (LWAC). The main properties of lightweight aggregates were also presented. The conclusion was that the compressive strength of (LWAC) is influenced by the crushing resistance of the lightweight aggregate and the strength of the cement mortar. When the aggregate has a high strength, the behaviour of (LWAC) is similar to (NWC). The crushing resistance of the aggregate can be predicted from its particle density, which is easy to measure. This research emphasises the crucial role that the aggregate properties and moisture content play in the behaviour of (LWAC) when exposed to high temperatures.

Studies utilized the use of andesite as an aggregate in road and railway construction. They have found that andesite has favorable properties, such as high uniaxial compressive strength and resistance to abrasion, which make it suitable for pavement production. Andesite is a fine-grained volcanic rock that contains about 53–63% silica, has a grey-black color and a porphyritic texture. It is composed of plagioclase and pyroxene microliths, feldspar, pyroxene and biotite phenocrysts in a glass matrix, and small amounts of magnetite minerals. Additionally, it has a porosity range between 10% and 25%. Andesite materials show resistance to environmental factors such as cold, heat, moisture, household chemicals and impact-induced wear factors, making them suitable to be used in indoor and outdoor spaces [20].

Fernandes et al. [21] conducted research on the behaviour of concrete at high temperatures and identified several key reactions that occur as the temperature increases. They found that between 20 °C and 80 °C, there is a slow loss of capillary water due to expansion. Between 80 °C and 100 °C, ettringite dehydrates and decomposes, causing the evaporation of water physically bound in the aggregates and cement matrix, leading to an increase in capillary porosity and microcracking. From 100 °C to 200 °C, the C-S-H (calcium silicate hydrate) of the cement paste begins to dehydrate and decompose, forming αC2S. Between 120 °C and 300 °C, the cement gel layers move closer together, increasing van der Waals forces, which may lead to an increase in strength. At 350 °C, water loss intensifies, and C-S-H decomposes, causing further increases in porosity and microcracks, leading to a significant loss of strength and stiffness. From 400 °C to 600 °C, CH (portlandite) decomposes, contributing to microcracking in the cement paste, and siliceous aggregates containing quartz transform at 573 °C. The authors also noted that the selection of aggregate plays a significant role in the thermal stability of concrete at high temperatures, as it occupies 60%–80% of the concrete's volume. Niry Razafinjato et al. [22] also studied the impact of aggregate selection on the thermal behavior of concrete and found that the petrographic origin and mineralogical and chemical composition of the aggregates play a significant role in the behavior of heated concrete.

In summary, the literature suggests that concrete is generally considered to be a fire-resistant material due to the nature of its constituent materials, which are essentially inert, have low thermal conductivity, and high heat capacity. However, when exposed to high temperatures, concrete experiences slow and complex degradation caused by physical, chemical, and mineralogical transformations in the cement paste and aggregate, reducing mechanical properties. Factors that influence the compressive strength of concrete at high temperatures include the difference of stresses, the moisture content of the concrete, heat exposure time, and the cooling mode, among others. The literature reports that the significant loss of strength in concrete occurs between 400 °C and 600 °C, with the greatest mechanical strength loss occurring at temperatures between 500 °C and 600 °C. It is also noted that the heating temperature 600 °C is considered as the temperature limit to guarantee the structural integrity of Portland cement concrete. Additionally, the literature suggests that the exposure time and heating rate can also have a significant influence on the compressive strength of normal-strength concrete at high temperatures [23, 24].

2 Experimental work

2.1 Materials

In order to study the influence of aggregate type on the concrete after exposure to elevated temperatures, five mixtures of concrete were produced using five different types of coarse aggregates. These types of coarse aggregates are; Quartz Aggregate (QZ), Crushed Andesite (AN), Expanded Glass (EG), Expanded Clay (EC), and Recycled Crushed Clay Bricks (CB) (Fig. 1). All coarse aggregate types had the same size of 4–8 mm; their densities are presented in Table 1, while their gradings are shown in Fig. 2. The same type of fine aggregate with a size of 0–4 mm was used for all mixtures of concrete as well as ordinary Portland cement CEMI 42.5N as a binder compatible with CEN EN 197-1:2011 [25]. Lastly, the MasterGlenium 300 superplasticizer was used to maintain the workability of concrete. All coarse aggregates had the same size 4–8 mm; the physical characteristics of the aggregates used are presented in Table 1.

2.2 Mixtures' proportions

Five concrete mixtures were produced with the same cement amount, water-cement (*w*/*c*) ratio, and superplasticizer dose. The only difference between the concrete mixtures is the type of aggregate, where the M1-QZ mixture is the reference mixture produced with quartz aggregate.

Fig. 1 Aggregates used in the research, (a) River quartz aggregates, (b) Crushed andesite, (c) Quartz sand, (d) Expanded clay, (e) Expanded glass, and (f) Crushed clay bricks

Table 1 Coarse aggregate properties

Source	Type	Symbol	Density kg/m^3	Weight classification
Natural aggregate	Quartz	QZ	2590	Normal weight
Natural aggregate	Andesite	AN	2600	Normal weight
Artificial aggregate	Expanded clay	EC	1490	Lightweight
Recycled aggregate	Expanded glass	EG	380	Lightweight
Recycled aggregate	Crushed clay bricks	CB	1990	Lightweight

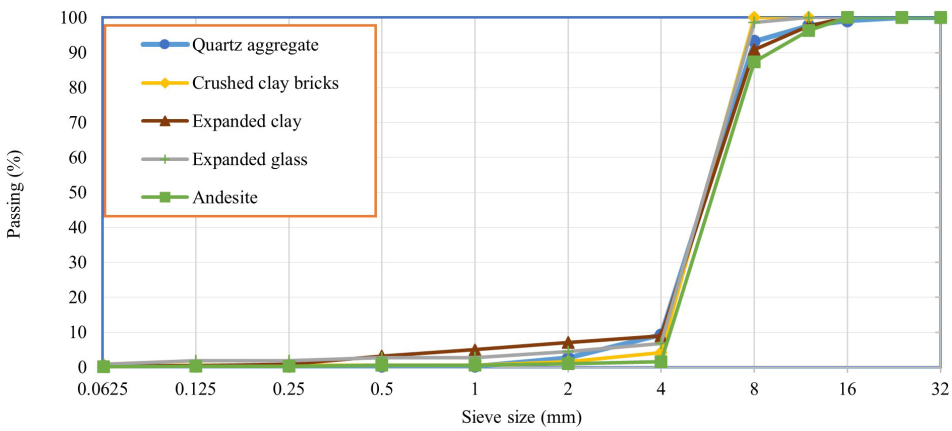

Fig. 2 Grading curve for the coarse aggregates used in the research

Mixtures M3-EC and M4-EG were produced with lightweight artificial aggregate; expanded clay and expanded glass aggregates, respectively. Mixture M5-CB was produced with crushed clay brick collected from the demolition wastes, while mixture M2-AN was produced with crushed natural andesite rocks (Table 1 and Table 2). The reason behind keeping all concrete components constant except for coarse aggregate is to comprehensively study the influence of coarse aggregate type on concrete behaviour after exposure to elevated temperatures.

2.3 Preparation and curing conditions

All specimens were prepared based on CEN EN 12390-1:2021 [26], using 100 mm cubes, 200 × 100 mm diameter cylinders and 70 × 70 × 250 mm prisms, made with different compositions as Table 2. The concrete specimens were cast and stored in steel molds for the first 24 h based on CEN EN 12390-2:2019 [27]. Concrete fresh properties tests were carried out according to CEN EN 12350-6:2019 [28] for density and based on the gravimetric method for calculating air content ASTM C138, as shown in Table 3. 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 for 28 days and 120 days with a temperature of 20 ± 5 °C and relative humidity of 50 ± 5%.

Table 2 Concrete mixtures design

Material	Component materials (kg/m^3)				
	M1-QZ	M2-AN	M3-EC	M4-EG	M5-CB
Cement	450	450	450	450	450
Water (*w/c* ratio: 0.38)	171	171	171	171	171
Aggregate 0/4	803	803	803	803	803
Aggregate 4/8	964	968	555	142	738
Superplasticiser (0.65%)	2.93	2.93	2.93	2.93	2.93

Table 3 Properties of fresh concrete

Mixture	Fresh density kg/m^3	Air content (l/m^2)
M1-QZ	2371	14
M2-AN	2350	24
M3-EC	1971	11
M4-EG	1542	22
M5-CB	2121	26

2.4 Exposing concrete specimens to elevated temperatures

At the age of 120 days, concrete specimens were exposed to elevated temperatures using an electric furnace with a specific heating rate shown in Fig. 3. Five different maximum elevated temperatures were targeted: 200, 400, 600, 800, and 1000 °C.

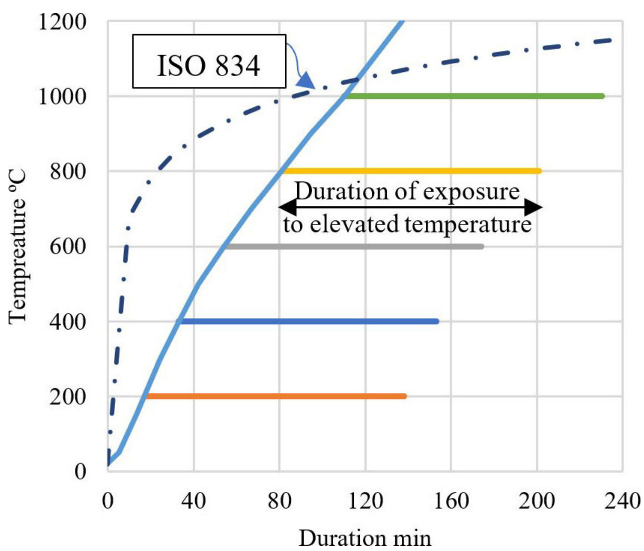

Fig. 3 Temperature rising curve in the furnace with heating duration at each heat level and ISO 834-14:2019 fire curve

However, the heating rate in the electric furnace used in this study did not fully comply with the ISO 834-14:2019 [29] standard fire curve, to ensure standardization, the ISO 834-14:2019 standard fire curve was employed for heating the specimens to elevated temperatures. The comparison of the temperature-time relationship between the ISO 834-14:2019 standard and the furnace heating rate, as shown in Fig. 3, indicates that the furnace was able to simulate the heating rate of the ISO 834-14:2019 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 specimens were allowed to cool freely for 24 hours at room temperature. This procedure aimed to simulate the fire action in real life and to evaluate the behaviour evolution with temperature when the composition and volume of cement paste and mortar remain constant in all samples [30, 31].

3 Results and discussion

3.1 Mechanical properties at ambient temperature

At age 28 days, the characteristic properties of each concrete mixture were evaluated. Compressive and flexural strength tests were carried out according to the European standards CEN EN 12390, while the shear strength test was carried out based on the Push-off model. The results are presented in Table 4. Compressive strength classes (according to European standards CEN EN 206-1:2013 [32]) for the concrete mixtures: M1-QZ and M5-CB are classified as C50/60, while M3-EC and M4-EG are classified as LC55/60 and LC16/18, respectively. However, the concrete mixture M2-AN is classified as C60/75 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 ($f_{c,100cu}/f_{c,150cu}$) for each batch of concrete is 1.01 [5].

Table 4 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

Among all types of concrete mixtures, M2-AN has demonstrated the highest compressive strength. The results show a variety of strengths by the type of coarse aggregate, which affects the porosity and density of the concrete, as a result, affects the concrete strength. The relationship between the compressive strength and the coarse aggregate density shows in Fig. 4, agrees with the results obtained in the other studies [33, 34]. The compressive strength of M4-EG is 65% less than the compressive strength of M1-QZ as expanded glass as it is a lightweight aggregate, and its density is lower than the density of quartz aggregate. Meanwhile, the surface characteristics of the aggregate have an impact on the strength of the concrete, i.e. expanded glass aggregate has a smooth spherical shape which decreases the bond between the aggregate and the cement paste matrix. 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. [35].

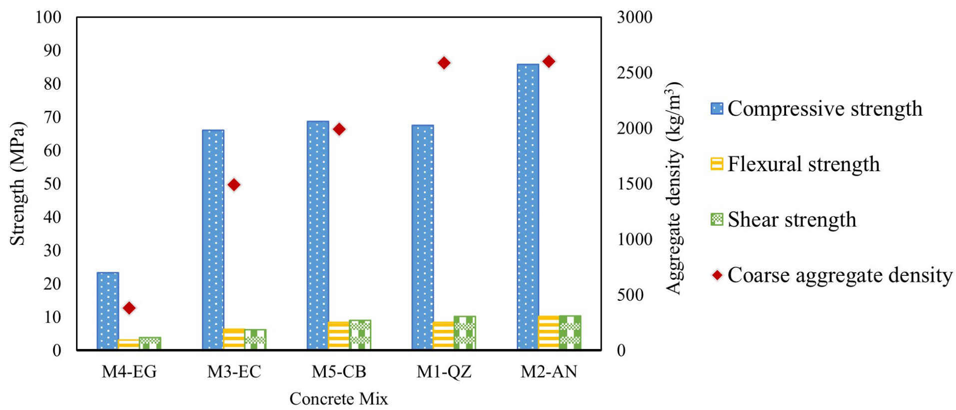

Fig. 4 Relation between the mechanical properties and the coarse aggregate density

3.2 Microstructure scanning characteristics

Scanning Electron Microscopy (SEM) is a powerful tool for analyzing the microstructure of materials. SEM was conducted on all produced concrete mixtures to examine the effect of aggregate type on concrete's microstructure (Figs. 5–9). The SEM images obtained in this study provide valuable insights into the composition and structure of these concrete mixtures and will aid in the understanding of their properties and behaviour. The results of the SEM analysis are presented and discussed in the following section. The results of the mechanical properties testing Table 4 and SEM analysis, are consistent

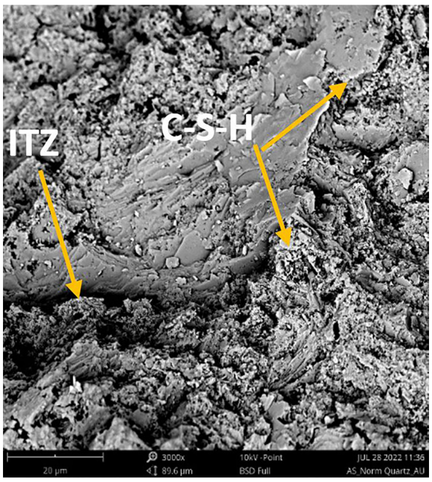

Fig. 5 Micrograph of M1-QZ mix

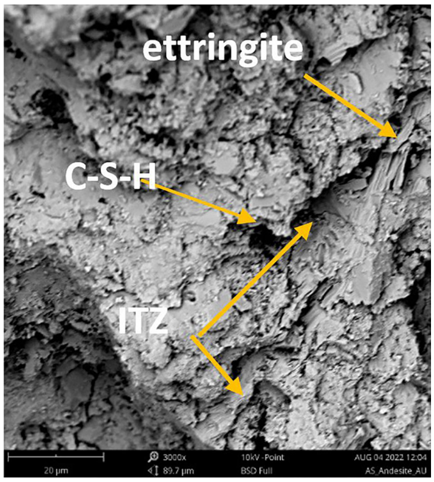

Fig. 6 Micrograph of M2-AN mix

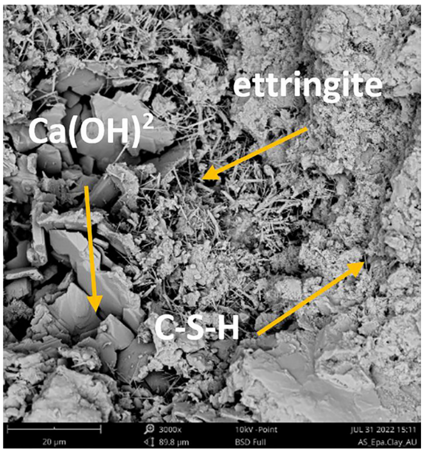

Fig. 7 Micrograph of M3-EC mix

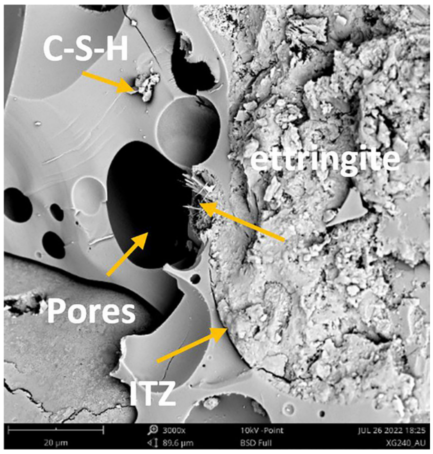

Fig. 8 Micrograph of M4-EG mix

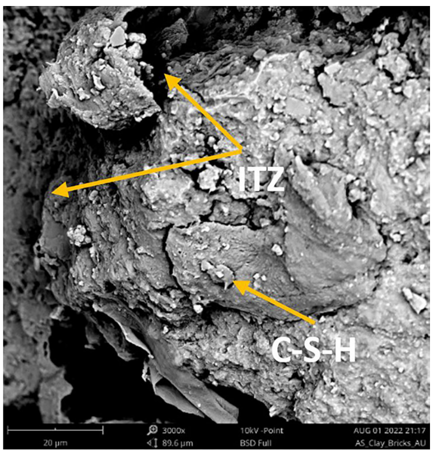

Fig. 9 Micrograph of M5-CB mix

with each other, where M-QZ that produced with quartz aggregate, had a high compressive strength of 67.6 MPa as it was well-hydrated. This can be seen clearly in Fig. 5 by the presence of calcium silicate hydrate (C-S-H) and a clear interface transition zone (ITZ) and the absence of ettringite. M-AN also had high compressive strength (85.8 MPa) and was well-hydrated with good mechanical properties. Mix (M-EC), made with expanded clay aggregate, had a compressive strength of 66 MPa and showed the presence of ettringite, but the absence of ITZ indicates good interlocking between the aggregates and cement paste, leading to its good strength. Mix M-EG, made with expanded glass aggregate, had a low compressive strength of 23.3 MPa due to the presence of pores, ettringite, and ITZ as shown in Fig. 8, which impacted its strength negatively and indicated low hydration process as well as low bonding between the aggregate and the cement paste. Mix M-CB, made with crushed clay bricks, had a compressive strength of 68.7 MPa and was well-hydrated with good mechanical properties, as indicated by the presence of C-S-H and ITZ as shown in Fig. 9 [36, 37].

3.3 Compressive properties after exposure to elevated temperature

At age 120 days, the produced concrete mixture specimens were exposed to various temperatures ranging from 20 to 1000 °C. Then, after leaving the specimens in a room-temperature for 24 hours, the uniaxial compressive strength test was carried out according to the European standards CEN EN 12390-3:2019 [38] for cubes with 100 mm × 100 mm × 100 mm, and the results are presented in Fig. 10. At the ambient temperature, compressive strengths of concrete mixtures at 120 days of age were found as 58.8, 86.8, 69.3, 23, and 70.6 MPa, for M-QZ, M-AN, M-EC, M-EG, and M-CB, respectively. Based on the results, age positively influences compressive strength by 17% in the case of the mixture produced with quartz aggregate, while the increase is almost negligible in the mixtures produced with andesite and expanded glass aggregates. However, the compressive strength was slightly increased in the mixtures produced with expanded clay and crushed clay bricks, where the increases are 2.7 and 5%, respectively.

After exposure to elevated temperature, the residual compressive strength is a major concern in the fire-resistant design. The strength degradation in concrete is changeable, and there are significant variations in strength loss; this behaviour is significantly related to the aggregate type [5, 39]. As seen from the results plotted in Fig. 10 and Fig. 11, concrete produced with andesite aggregate showed the highest residual compressive strength results compared with other concrete mixtures after exposure to elevated temperatures up to 800 °C. However, the mixture produced with quartz aggregate provided the highest residual compressive strength results after exposure to elevated temperatures up to 1000 °C.

On the other hand, concrete produced with expanded glass aggregate showed the lowest residual compressive strength at all exposed temperatures. Nevertheless, the residual strength compressive strength of the mixture produced by expanded clay aggregate was the highest after exposure to 400 °C.

After exposing concrete to up to 200 °C, the highest reduction in the residual compressive strength was recorded in the quartz aggregate concrete, where the reduction reached to 25.7%. The second in the loss row was the expanded clay concrete, where the loss was recorded as 19.6%. In contrast, the concrete made by andesite (AN), expanded glass (EG), and crushed clay bricks (CB) present a marginal loss of 8%, 5.7% and 2.1%, respectively.

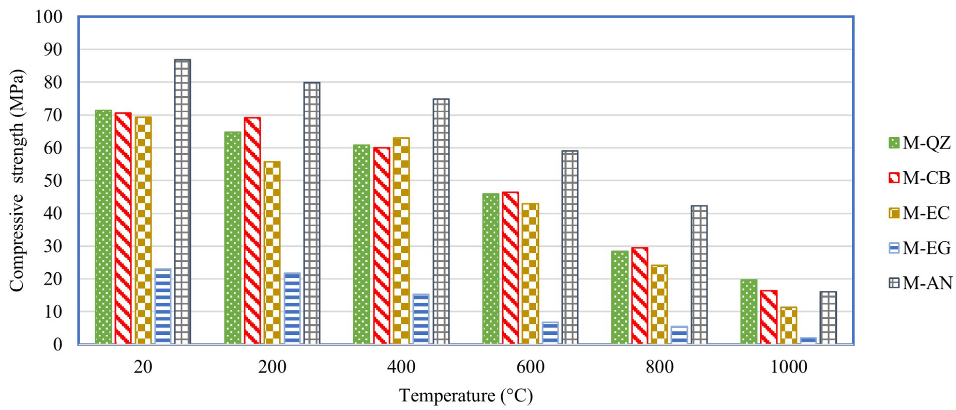

Fig. 10 Compressive strength results for concrete made with different types of aggregates

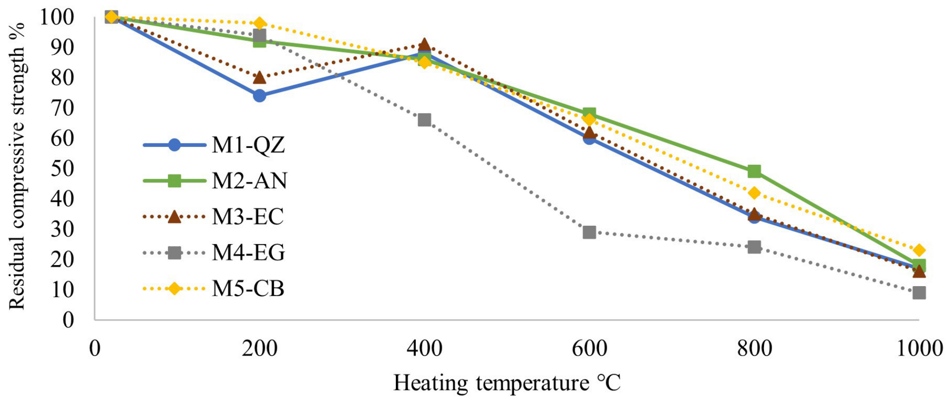

Fig. 11 Residual compressive strength of concrete made with different types of aggregates

At 400 °C, the reduction in strength is 12, 13.8, 9, 33.6 and 15.1% for concrete mixes (M-QZ), (M-AN), (M-EC), (M-EG) and (M-CB), respectively. With an increase in the temperature, the strength reduction became more noticeable; at 600 °C heating, the percentage of compressive strength reduction has been 39.7, 31.9, 37.1, 70.5 and 34.3%; the huge strength loss was observed in concrete made with expanded glass; hence less than a third of the strength remains, while the concrete made with the other type of lightweight aggregate, (EC) observe a 37% loss of strength only. At 800 °C, all the concrete mixes lose most of their strength, and the reduction of the strength exceeded 66.4, 51.3, 65.1, 75.9 and 59.3%.

The results of the study indicate that the type of aggregate used in the concrete mixture can greatly impact performance of concrete after elevated temperature exposer. Concrete mixtures made with Andesite aggregates (M-AN) showed best performance in terms of resisting elevated temperature, with conserving half of the initial strength after 800 °C expose. In contrast, concrete mixes made with quartz aggregates (M-QZ) only retained a third of their initial strength at the same temperature. At the highest temperature of 1000 °C, all of the concrete mixtures (M-QZ), (M-AN), and (M-CB) experienced a significant loss of strength, with losses ranging from 81–83%. The concrete mix made with expanded glass aggregate (M-EG) had the lowest performance, with a 91.4% loss in strength. The results show that the type of aggregate used in the concrete mixture can significantly affect the concrete's compressive strength at ambient and elevated temperatures, which agrees with the literature findings [5, 24].

3.4 Relationship between the aggregate type and the concrete behaviour

The type of aggregate used in the concrete mixture can significantly impact the concrete's compressive strength at ambient and elevated temperatures. Results of an experimental study show that concrete made with andesite aggregate had the highest compressive strength at both ambient and elevated temperatures up to 800 °C. The superior strength of andesite concrete can be attributed to several factors; andesite is a type of volcanic rock known for its high strength and durability, its angular shape and low porosity of andesite aggregate also contribute to its high compressive strength [40, 41]. However, at elevated temperatures, the structural integrity of the andesite is compromised, leading to a reduction in strength. The high coefficient of thermal expansion of andesite also causes the material to expand and become less dense [42], further reducing strength. High temperatures can also cause phase changes such as melting or vaporization, further diminishing strength. Additionally, the low water absorption of andesite aggregate helps to preserve the concrete's strength even at high temperatures. Concrete made with crushed clay bricks had the highest residual compressive strength after being subjected to a temperature of 1000 °C. This is due to the properties of clay bricks. Clay bricks are made from natural materials, mainly clay and shale, which are fired at high temperatures (typically around 1000 °C); the brick particles retain their strength and durability even after being exposed to high temperatures; The clay minerals in the bricks may also help to protect the concrete from thermal damage by absorbing and releasing heat slowly, thus reducing the thermal stress on the concrete [43]. In contrast, the lowest compressive strength in all cases with and without subjecting to elevated temperatures for concrete made with expanded glass aggregate (M-EG), the behaviour can be attributed to several factors, including the lower strength of the aggregate, having a less favorable shape with a smooth circular shape, which could reduce matrix interlocking and the overall strength of the concrete, and higher porosity [44]. On the other hand, the behaviour of concrete made with expanded clay aggregate and concrete made with quartz aggregate when subjected to elevated temperatures is distinct due to the inherent properties of the aggregates utilized. Expanded clay aggregate, which is a lightweight aggregate derived from clay that has been heated to high temperatures, exhibits a lower thermal conductivity and a higher insulation value. This results in the concrete made with expanded clay aggregate displaying a lower decrease in compressive strength at low temperatures 200 °C and a higher increase in compressive strength at higher temperatures 400 °C than traditional concrete [18]. Conversely, quartz aggregate, a hard mineral aggregate that is relatively resistant to thermal expansion, displays a high thermal conductivity, leading to a loss of moisture at high temperatures and a corresponding decrease in compressive strength. Additionally, the high coefficient of thermal expansion of quartz aggregate causes the concrete to expand more at high temperatures resulting in a decrease in compressive strength. As a result, it can be inferred that concrete made with expanded clay aggregate is more resistant to thermal expansion than concrete made with quartz aggregate.

3.5 Relationship between the aggregate type and the concrete thermal conductivity

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 [45, 46].

The thermal conductivity was measured based on the analysis of the temperature response of the material analyzed to heat flow impulses. The presented thermal conductivity results in Fig. 12, showed a decreasing trend in thermal conductivity as temperature increases. This

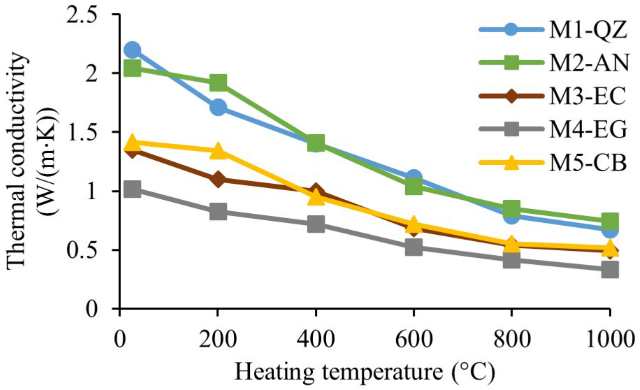

Fig. 12 Thermal conductivity values of concrete made with different types of aggregates

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 and M2-AN exhibit relatively higher thermal conductivity value. 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 and M5-CB demonstrate moderate thermal conductivity values. Incorporating expanded clay and crushed clay bricks, i.e. clay based aggregates in these mixtures contributes to their intermediate heat transfer characteristics.

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. Results revealed that concrete with the same category of coarse aggregate has a similar thermal behaviour after subjected to elevated temperature as that's clearly shown in case on natural aggregates represented by the mixes contains quartz aggregates and andesite aggregates M1-QZ and M2-AN; and in case of clay-based aggregates as expanded clay and crushed clay bricks M3-EC and M5-CB.

4 Conclusions

In conclusion, this study investigated the effect of coarse aggregate type on concrete's compressive strength and fire resistance. The results showed that the type of aggregate used in the concrete mixture significantly impacted mechanical and thermal properties characteristics. The SEM analysis provided further insights into the microstructure of each concrete mix and the relationship between aggregate type and concrete properties. Based on the results of this study, it can be concluded that the selection of high-quality aggregate materials is crucial for achieving high-strength concrete with good fire resistance.

A decrease in strength at 200 °C, followed by a further increase at 400 °C, was observed for quartz aggregate only in the case of expanded clay aggregate among the other aggregate types tested. The relative decrease of expanded clay gravel was similar to, but not more significant than, that of quartz aggregate.

The expanded glass aggregate concrete had different characteristics and was significantly weaker than the other aggregates tested. This concrete does not even belong to the group of load-bearing concretes (LC16/18), and therefore, the comparison cannot be evaluated from this point of view.

For andesite and crushed brick, the rate of relative decrease is similar to that of quartz gravel, typically slightly greater, but not less at any of the temperatures tested. Therefore, andesite, expanded clay, and crushed brick can be considered for fire sizing in the same way as quartz pebbles with aggregate tested at C50/60-C60/70 or equivalent lightweight concrete strength class using pure Portland cement.

Additionally, for the tested aggregates (andesite and crushed brick), the temperature-relative compressive strength curve characteristics were different from those of quartz aggregate. With increasing temperature, the compressive strength decreased steadily. This is a more favorable behaviour than in the case of reference quartz gravel aggregate concrete.

No significant loss of strength at 200 degrees and no increase at 400 °C was observed for the expanded glass aggregate concrete. However, at 400 degrees, the relative decrease in compressive strength is much greater (65%) than for the standard quartz gravel or the other aggregates tested. At 600 °C, it is around 40%, which is already a failure rate for a load-bearing structure. In this case, however, it cannot consider load-bearing concrete (LC16/18), but it may still be functional in a supplementary structure (e.g. slope layer). There has also been no explosive failure at 1000 °C, so the concrete will not directly damage other structures by failing in such use.

The thermal conductivity of concrete 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, the concrete with the same category of coarse aggregate has a similar thermal behaviour trend after being subjected to elevated temperatures.

Thermal conductivity results proved that concrete coarse aggregates base material played the significant role on the thermal response in case of the same cement matrix, as 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.

References

[1] Kodur, V., Kumar, P., Rafi, M. M. "Fire hazard in buildings: review, assessment and strategies for improving fire safety", PSU Research Review, 4(1), pp. 1–23, 2020. https://doi.org/10.1108/PRR-12-2018-0033

[2] Rahla, K. M., Mateus, R., Bragança, L. "Selection Criteria for Building Materials and Components in Line with the Circular Economy Principles in the Built Environment—A Review of Current Trends", Infrastructures, 6(4), 49, 2021. https://doi.org/10.3390/infrastructures6040049

[3] Fletcher, I. A., Welch, S., Torero, J. L., Carvel, R. O., Usmani, A. "Behaviour of concrete structures in fire", Thermal Science, 11(2), pp. 37–52, 2007. https://doi.org/10.2298/TSCI0702037F

[4] Khoury, G.A. "Effect of fire on concrete and concrete structures", Progress in Structural Engineering and Materials, 2(4), pp. 429–447, 2000. https://doi.org/10.1002/pse.51

[5] Neville, A. M. "Properties of concrete", Prentice Hall, 2012. ISBN 978-0273755807

[6] Khoury, G. A., Majorana, C. E., Pesavento, F., Schrefler, B. A. "Modelling of heated concrete", Magazine of Concrete Research, 54(2), pp. 77–101, 2002. https://doi.org/10.1680/macr.54.2.77.40895

[7] Lublóy, É., Balázs, G. L. "Concrete properties in fire depending on types of cement, aggregate and fibre", In: Balázs, G. L., Nehme, S. G. (eds.) Innovative Materials and Technologies for Concrete Structures: Proceedings of the fib Congress, Budapest, Hungary, 2007, pp. 327–332. ISBN 978-963-420-923-2

[8] Bažant, Z. P., Kaplan, M. F. "Concrete at High Temperatures: Material Properties and Mathematical Models", Longman Group Limited, 1996. ISBN 0-582-08626-4

[9] Ma, Q., Guo, R., Zhao, Z., Lin, Z., He, K. "Mechanical properties of concrete at high temperature—A review", Construction and Building Materials, 93, pp. 371–383, 2015. https://doi.org/10.1016/j.conbuildmat.2015.05.131

[10] Passos, L., Moreno Jr., A. L. Souza, A. A. A. "Lightweight concrete with coarse aggregate from ceramic waste at high temperatures", Revista IBRACON de Estruturas e Materiais, 13(2), pp. 433–454, 2020. https://doi.org/10.1590/s1983-41952020000200012

[11] Meddah, M. S., Zitouni, S., Belâabes, S. "Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete" Construction and Building Materials, 24(4), pp. 505–512, 2010. https://doi.org/10.1016/j.conbuildmat.2009.10.009

[12] Elices, M., Rocco, C. G. "Effect of aggregate size on the fracture and mechanical properties of a simple concrete", Engineering Fracture Mechanics, 75(13), pp. 3839–3851, 2008. https://doi.org/10.1016/j.engfracmech.2008.02.011
[13] Quayson, J. H., Mustapha, Z. "Impact of Coarse Aggregate on Compressive Strength of Concrete", Built Environment Journal, 16(1), pp. 49–58, 2019.
[14] Mueller, A., Schnell, A., Ruebner, K. "The manufacture of lightweight aggregates from recycled masonry rubble", Construction and Building Materials, 98, pp. 376–387, 2015. https://doi.org/10.1016/j.conbuildmat.2015.07.027
[15] Khalaf, F. M., DeVenny, A. S. "Performance of Brick Aggregate Concrete at High Temperatures", Journal of Materials in Civil Engineering, 16(6), pp. 556–565, 2004. https://doi.org/10.1061/(asce)0899-1561(2004)16:6(556)
[16] Hansen, T. C. (ed.) "Recycling of Demolished Concrete and Masonry", CRC Press, 1992. ISBN 9780429081675 https://doi.org/https://doi.org/10.1201/9781482267075
[17] Netinger, I., Kesegic, I., Guljas, I. "The effect of high temperatures on the mechanical properties of concrete made with different types of aggregates", Fire Safety Journal, 46(7), pp. 425–430, 2011. https://doi.org/10.1016/j.firesaf.2011.07.002
[18] Bodnárová, L., Hela, R., Hubertová, M., Nováková, I. "Behaviour of Lightweight Expanded Clay Aggregate Concrete Exposed to High Temperatures", International Journal of Civil and Environmental Engineering, 8(12), pp. 1210–1213, 2014. https://doi.org/10.5281/zenodo.1096883
[19] Nemes, R., Józsa, Z. "Differences in mix designs of lightweight and conventional concretes", In: Balázs G. L., Nehme S. G. (eds.) Innovative Materials and Technologies for Concrete Structures: Proceedings of the fib Congress, Budapest, Hungary, 2007, pp. 61–66. ISBN 978-963-420-923-2
[20] Sariişik, A., Sariişik, G. "Tarihi aniitlariin restorasyonunda (Dalyan-Kaunos) kullaniilan mermerlerin çevre etkileşim özellikleri" (Environmental Interaction Properties of Marble Used in the Restoration of Historical Monuments (Dalyan-Kaunos), Ekoloji, 20(79), pp. 12–20, 2011. (in Turkish) https://doi.org/10.5053/ekoloji.2011.792
[21] Fernandes, B., Carré, H., Mindeguia, J.-C., Perlot, C., La Borderie, C. "Effect of elevated temperatures on concrete made with recycled concrete aggregates - An overview", Journal of Building Engineering, 44, 103235, 2021. https://doi.org/10.1016/j.jobe.2021.103235
[22] Niry Razafinjato, R., Beaucour, A. L., Hebert, R. L., Ledesert, B., Bodet, R., Noumowe, A. "High temperature behaviour of a wide petrographic range of siliceous and calcareous aggregates for concretes", Construction and Building Materials, 123, pp. 261–273, 2016. https://doi.org/10.1016/j.conbuildmat.2016.06.097
[23] Fehérvári, S. "The Effect of Elevated Temperature on Ordinary Portland Cements", Periodica Polytechnica Civil Engineering, 67(1), pp. 224–231, 2023. https://doi.org/10.3311/PPci.20519
[24] Gyurkó, Z., Nemes, R. "Specimen Size and Shape Effect on the Compressive Strength of Normal Strength Concrete", Periodica Polytechnica Civil Engineering, 64(1), pp. 276–286, 2020. https://doi.org/10.3311/PPci.15338
[25] CEN "CEN EN 197–1:2011 Cement - Part 1: Composition, specifications and conformity criteria for common cements", European Committee for Standardization, Brussels, Belgium, 2011.
[26] CEN "CEN EN 12390-1:2021 Testing hardened concrete – Part 1: Shape, dimensions and other requirements for specimens and moulds", European Committee for Standardization, Brussels, Belgium, 2021.
[27] CEN "CEN EN 12390-2:2019 Testing hardened concrete - Part 2: Making and curing specimens for strength tests", European Committee for Standardization, Brussels, Belgium, 2019.
[28] CEN "CEN EN 12350-6:2019 Testing fresh concrete - Part 6: Density", European Committee for Standardization, Brussels, Belgium, 2019.
[29] ISO "ISO 834-14:2019 Fire-resistance tests-Elements of building construction: Part 14: Requirements for the testing and assessment of applied fire protection to solid steel bar", International Organization for Standardization, Geneva, Switzerland, 2019.
[30] Abed, M., Nemes, R., Lublóy, É. "The impact of time on the heat resistance of self-compacting high-performance concrete incorporated with recycled martials", Journal of Thermal Analysis and Calorimetry, 138(1), pp. 35–45, 2019. https://doi.org/10.1007/s10973-019-08263-z
[31] Seyam, A. M., Nemes, R. "Age influence on compressive strength for concrete made with different types of aggregates after exposed to high temperatures", Materials Today: Proceedings, 2023. https://doi.org/10.1016/j.matpr.2023.06.403
[32] CEN "CEN EN 206-1:2013 Concrete - Part 1: Specification, performance, production and conformity", European Committee for Standardization, Brussels, Belgium, 2013.
[33] Ćosić, K., Korat, L., Ducman, V., Netinger, I. "Influence of aggregate type and size on properties of pervious concrete", Construction and Building Materials, 78, pp. 69–76, 2015. https://doi.org/10.1016/j.conbuildmat.2014.12.073
[34] Hlavička, V., Hlavicka-Laczák, L. E., Lublóy, É. "Residual fracture mechanical properties of quartz and expanded clay aggregate concrete subjected to elevated temperature", Construction and Building Materials, 328, 126845, 2022. https://doi.org/10.1016/j.conbuildmat.2022.126845
[35] Vishalakshi, K. P., Revathi, V., Sivamurthy Reddy, S. "Effect of type of coarse aggregate on the strength properties and fracture energy of normal and high strength concrete", Engineering Fracture Mechanics, 194, pp. 52–60, 2018. https://doi.org/10.1016/j.engfracmech.2018.02.029
[36] Hilal, A. A. "Microstructure of Concrete", In: Yilmaz, S., Özmen, H. B. (eds.) High Performance Concrete Technology and Applications, IntechOpen, 2016. ISBN 978-953-51-2651-5 https://doi.org/10.5772/64574
[37] Bravo, M., Santos Silva, A., de Brito, J., Evangelista, L. "Microstructure of Concrete with Aggregates from Construction and Demolition Waste Recycling Plants", Microscopy and Microanalysis, 22(1), pp. 149–167, 2016. https://doi.org/10.1017/S1431927615015512
[38] CEN "CEN EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens", European Committee for Standardization, Brussels, Belgium, 2019.

[39] Ghadzali, N. S., Ibrahim, M. H. W., Mohd Sani, M. S. H., Jamaludin, N., Desa, M. S. M., Misri, Z. "Properties of concrete containing different type of waste materials as aggregate replacement exposed to elevated temperature - A review", IOP Conference Series: Earth and Environmental Science, 140, 012139, 2018. https://doi.org/10.1088/1755-1315/140/1/012139

[40] Özkan, Ș, Ceylan, H. "The effects on mechanical properties of sustainable use of waste andesite dust as a partial substitution of cement in cementitious composites", Journal of Building Engineering, 58, 104959, 2022. https://doi.org/10.1016/j.jobe.2022.104959

[41] Seyam, A. M., Nemes, R. "Using Hungarian andesite as a coarse aggregate for concrete", Építőanyag - Journal of Silicate Based and Composite Materials, 75(1), pp. 38–43, 2023. https://doi.org/10.14382/epitoanyag-jsbcm.2023.06

[42] Heap, M. J., Kushnir, A. R. L., Vasseur, J., Wadsworth, F. B., Harlé, P., Baud. P, Kennedy, B. M., Troll, V. R., Deegan, F. M. "The thermal properties of porous andesite", Journal of Volcanology and Geothermal Research, 398, 106901, 2020. https://doi.org/10.1016/j.jvolgeores.2020.106901

[43] Aliabdo, A. A., Abd-Elmoaty, A.-E. M., Hassan, H. H. "Utilization of crushed clay brick in concrete industry", Alexandria Engineering Journal, 53(1), pp. 151–168, 2014. https://doi.org/10.1016/j.aej.2013.12.003

[44] Nemes, R., Józsa, Z. "Strength of Lightweight Glass Aggregate Concrete", Journal of Materials in Civil Engineering, 18(5), pp. 710–714, 2006. https://doi.org/10.1061/(ASCE)0899-1561(2006)18:5(710)

[45] Blackstone, J. "Thermal Performance of Precast Concrete Connections Exposed to Fire", MSc Thesis, The University of North Carolina at Charlotte, 2019.

[46] Ramachandran, V. S., Paroli, R. M., Beaudoin, J. J., Delgado, A. H. "Handbook of thermal analysis of construction materials", Noyes Publications, 2002. ISBN 0-8155-1487-5