Challenge Journal of Structural Mechanics

Research Article

Effect of elevated temperatures on mechanical properties of hydraulic lime-based mortar in historical structures

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ABSTRACT

Historic masonry structures are subjected to various negative effects from the time they are built. As a result, these structures suffer damage, leading to restoration and reinforcement efforts. Hydraulic lime-based mortars (HLMs), which are compatible with the nature of historic structures, are used in restoration and reinforcement. This study investigated the fire resistance of hydraulic lime-based mortars. Within the scope of this study, HLMs were prepared in accordance with restoration standards, and prism specimens were prepared with HLMs. These specimens were exposed to high temperatures ranging from 200 °C to 700 °C, and bending and compression tests were conducted on the specimens exposed to temperature. During the elevated temperature tests (ETTs), a total of 27 specimens were prepared, including three test specimens, one temperature monitoring specimen for each temperature, and three reference specimens. While the reference specimens were tested at room temperature, the other specimens were kept until they reached room temperature after the ETTs were completed and then tested under the same conditions as the reference specimens. No tests were performed on the temperature monitoring specimens, and these specimens were only used to monitor the temperatures inside the specimens with thermocouples placed inside. As a result of the experimental studies and evaluations, it was determined that the HLMs began to lose their mechanical properties with increasing temperature, but even after 700 °C, they still exhibited mechanical properties observed in low-grade mortars.

ARTICLE INFO

Article history:
Received – April 8, 2025
Revision requested – May 6, 2025
Revision received – May 23, 2025
Accepted – June 2, 2025

Keywords:
Hydraulic lime-based mortar
Elevated temperature test
Mechanical properties
Compression strength
Flexural strength

Citation: Kara AF, Cakir F, Calis M (2025). Effect of elevated temperatures on mechanical properties of hydraulic lime-based mortar in historical structures. *Challenge Journal of Structural Mechanics*, 11(4), 184–200.

1. Introduction

Historic masonry structures are subjected to a multitude of adverse conditions, enduring ravages of time, natural disasters, and human interventions. In addition to their behavior against atmospheric conditions and aging, historic mortars are also exposed to harsh conditions during natural disasters, such as earthquakes, landslides, air pollution, extreme temperatures, floods, and fires. Fire poses a particularly formidable threat to these architectural treasures, capable of erasing centuries of history in hours and causing irreversible damage. In addition to architectural and cultural value loss, fires can lead to costly and destructive situations in historical structures. The performance of structural elements during and after a fire is crucial for the future of a building. In particular, the thermal behavior of construction materials during and after a fire and the changes in their physical and mechanical properties are critical for structural performance. The mortar in joint areas, considered the weakest link in the chain, is the construction material that most significantly affects the fire performance of historical structures. It is known that even the smallest weaknesses occurring at the connection points can lead to ir-

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2025.04.002

reversible damage throughout the entire structure. Although the composition of mortar varies depending on the era, historical mortars primarily consist of lime-based materials, including air lime mortars, lime-pozzolan mortars, natural hydraulic lime mortars, and ternary mortars.

Although the fire resistance and physical and mechanical performance of hydraulic lime-based mortars HLM after a fire are significant topics, studies conducted in the literature are quite limited. Studies in the literature have primarily focused on cement-based mortars. For example, Neto et al. (2022) investigated the impact of post-fire curing on the mechanical behavior of cement-lime based masonry mortars, which are often overlooked in contemporary structures. Three mortar mixes were subjected to fire tests and cured at different post-fire ages. Mechanical tests revealed that longer post-fire curing led to reduced mechanical properties and increased deformability, particularly in mortars with higher lime content. The mortars exhibited progressive deterioration and became more ductile over time during the post-fire curing. Additionally, a theoretical model with correlations accurately predicted the post-fire mechanical behavior of masonry mortars. Bamonte et al. (2021) focused on the behavior of three bed-fixing cement-lime based mortars at high temperatures (up to 900 °C) to understand their mechanical properties and thermal diffusivity. This study aimed to expand knowledge on this subject and develop stress-strain relationships for potential use in masonry structure design. Their study emphasized that while the mechanical decay at high temperatures is similar to that of ordinary concrete, they exhibit higher mass loss, lower thermal diffusivity, and greater ductility. This led to the calibration of an analytical stress-strain law for compression, which considered the specific characteristics of the mortars.

Pachta et al. (2021) conducted a study on the use of brick residues in historic mortars to enhance pozzolanicity and resistance to humidity, as well as to assess their performance at elevated temperatures. Three mortar series were tested: lime, lime with natural pozzolan, and lime with natural pozzolan and brick dust. Physico-mechanical properties were tested at 28 and 90 days, and mortars were exposed to temperatures ranging from 200 °C to 1000 °C. The study suggested that the 90-day age is more representative, and the inclusion of crushed brick and brick dust improves the structural integrity at extreme temperatures. Rais et al. (2019) discussed how high temperatures affect the fresh and aged strengths, as well as the microstructure properties of fly ash mortars. Various blends were tested, and after exposure to temperatures ranging from 100 °C to 500 °C, compression strengths was measured and compared between blended and plain mortars. Mortars with 10% fly ash exhibited superior performance at 500 °C. The proposed model accurately predicted the aged strength of blended mortar after heating, offering potential benefits for concrete construction and sustainability. Pachta et al. (2018) examined the impact of elevated temperatures on lime-based mortars used in historical restoration. Mortar specimens were exposed to temperatures from 200 °C to 1000 °C, and their properties were tested before and after exposure. The results indicated that lime-based mortars generally retain their structure and characteristics after exposure to high temperatures, with the lime-pozzolan matrix displaying particularly high resistance. Zhang et al. (2018) investigated the impact of heat treatment on fly ash (FA) cement mortar, focusing on color and thermal conductivity changes. Different FA replacement percentages (10%, 20%, and 40%) were examined across 45 samples exposed to temperatures ranging from room temperature to 800 °C. The study emphasized a critical temperature range (400–600 °C) causing pH reduction due to carbonization and calcium hydroxide decomposition, shortening mortar lifespan. The thermal conductivity decreased at higher temperatures, which correlated with the density ratio. The findings suggest an optimal FA percentage for improved mortar properties heat exposure.

Horszczaruk et al. (2017) investigated the impact of nanosilica on cement mortars containing quartz, magnetite, and barite aggregates exposed to high temperatures (200 °C to 800 °C). The mortars were modified with nanosilica in various proportions. The findings revealed that an optimal nanosilica content enhances thermal resistance and prevents crack extension, particularly in mortars with quartz and magnetite aggregates. However, mortars containing barite aggregates tend to crack and exhibit spalling owing to the lower thermal resistance of the aggregate. Pan et al. (2017) examined the high-temperature performance of cementitious materials containing fine glass powder (GP) as a partial replacement for ordinary Portland cement. Various mixtures were prepared using different proportions of GP. Compressive strength tests were conducted at temperatures ranging from 20 °C to 800 °C, alongside X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermal strain tests on corresponding pastes. The results indicate two distinct temperature ranges for the effects of GP on the mortar strength. Below 500 °C, mortars with 20% GP showed superior performance because of reduced calcium hydroxide content. Between 500 °C and 800 °C, GP mortars exhibited higher strength loss, attributed to greater thermal incompatibility arising from paste shrinkage and sand particle expansion.

Pachta et al. (2018) and Bamonte et al. (2021) referred that the chemical composition and hydration products, carbonation and thermal stability, microstructural porosity and permeability, thermal expansion and ductility factors collectively explain why high-performance concrete (HLM) retains residual mechanical properties even at 700 °C, whereas cementitious mortars undergo rapid deterioration beyond 400 °C. İsafça et al. (2022) investigated the effect of elevated temperature on polypropylene fiber reinforced Khorasan mortar. Aruntaş et al. (2021) investigated lime usage in cement paste and mortar with different proportion of lime at room temperature.

Although studies have been conducted on the fire resistance or post-fire mechanical properties of cement-based mortars or mortars reinforced with other materials as a result of literature research, studies on HLMs are quite scarce and insufficient. Therefore, in this study, the effects of fire exposure at different levels on the mechanical strength of HLMs were investigated. As part of the investigation, the HLM was formulated following restoration standards, and prism-shaped specimens were prepared with HLMs. Subsequently, the specimens were exposed to elevated temperatures ranging from 200 °C to 700 °C. This was followed by a series of bending and compression tests. It is believed that the conducted research and experimental studies will fill this gap in the literature and present an original study.

2. Materials and Method

In this study, the fire resistance of HLMs is investigated. Within the scope of this research, these mortars were prepared according to restoration standards, and prism samples were created with HLMs. These samples were then subjected to bending and compression tests at temperatures ranging from 200 °C to 700 °C after being exposure to high temperatures. A total of 27 samples were included in the high-temperature tests, with three experimental samples, one temperature-monitoring sample, and three reference samples for each temperature. The reference samples were tested at room temperature, whereas the other samples were held at room temperature after completing the fire test and then tested under the same conditions as the reference samples. No tests were conducted on the temperature-monitoring samples; they were only used to monitor the internal temperatures of the samples using the embedded thermocouples that differs from past studies. In this study, all steps were performed according to the flowchart (Fig. 1).

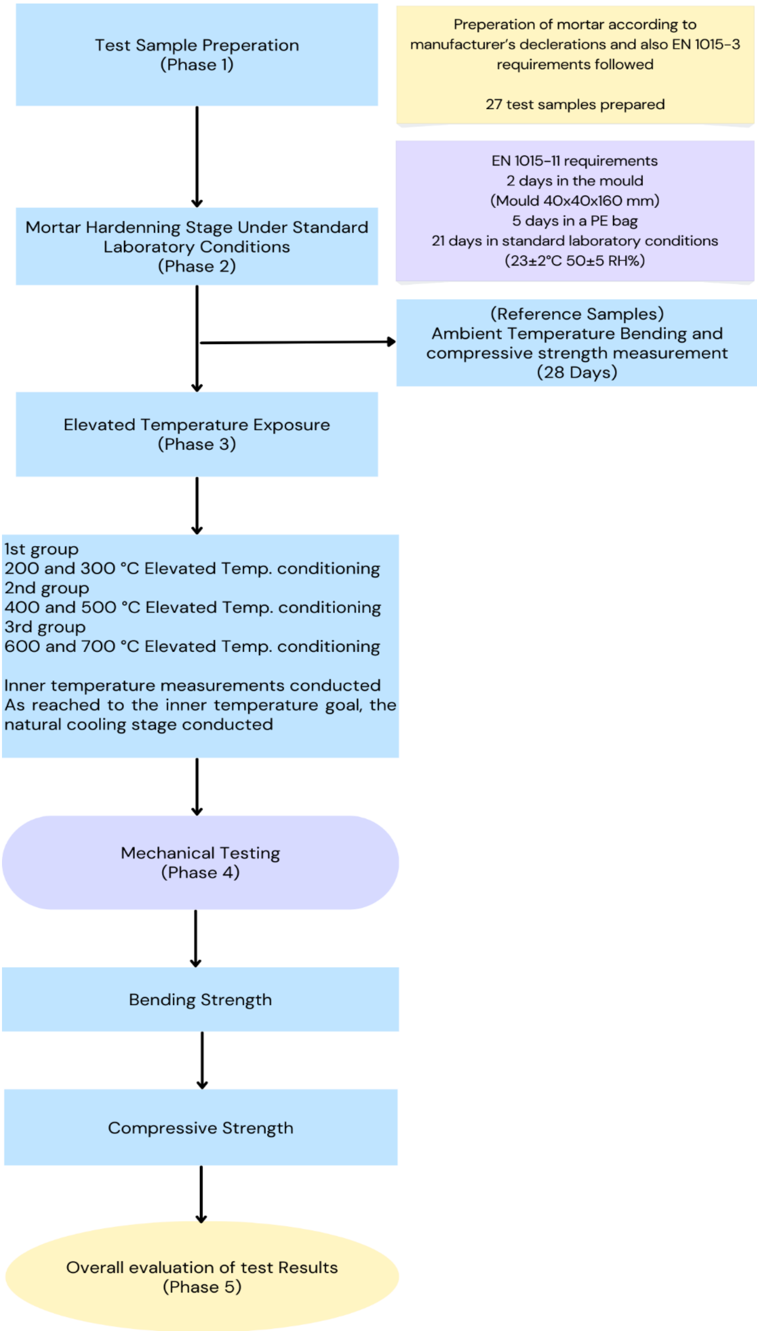

Fig. 1. Flowchart for the study.

2.1. Hydraulic lime-based mortar

Mortar serves as an adhesive substance that binds stones or bricks and plays a crucial role in masonry construction. It functions to fill the spaces between building blocks (mortar joints), thereby enhancing structural integrity. Additionally, mortar provides resistance to air and water infiltration, which bolsters the durability of masonry structures. The key properties of mortars include their workability, cohesiveness, resistance to external forces, and ease of spreading. The strength and durability of masonry structures are significantly influenced by the physical properties of the mortar. The bond strength and binding characteristics of mortar play a crucial role in determining the overall performance of a building. A well-formulated mortar with a strong bond strength enhances the structural integrity of the masonry, ensuring stability and resilience against various external forces and environmental factors. Consequently, understanding and optimizing these mortar properties are essential for ensuring the longevity and effectiveness of masonry structures. Cakir (2011) investigated the required volume of mortar varies based on the type of masonry, typically ranging from 0 to 20 percent of the total volume. Despite its relatively small volume, mortar plays a crucial role in masonry structures. The initial state of the mortar was plastic, but it rapidly commenced a hardening process. Mortar is typically produced by blending sand, lime, cement, and water. Previously, traditional mortar was composed of mud, clay, and lime. Lime mortars, among the earliest variants, trace back to Babylonian origins, although Egyptians advanced mortar technology by incorporating lime and gypsum to construct pyramids. Historical masonry structures commonly use HLM. However, Sánchez (2007) described Romans revolutionized mortar production by introducing cement, which subsequently became the predominant material for mortar applications.

HLMs are most commonly used to repair and restore historical masonry structures, and are special mortars prepared for historical structures without cement. It provides breathability and high water vapor permeability. It is compatible with historical structures and allows the production of mortars with different properties. Natural hydraulic lime (NHL) acquires its characteristics by calcining argillaceous or siliceous limestones, followed by pulverization via slaking with or without grinding. HLMs solidify via a dual process involving hydration, which forms a calcium-silicate-hydrate structure, and carbonation, which occurs as calcium hydroxide reacts with carbon dioxide in the air. Bompa and Elghazouli (2020) investigated commercial binders are categorized based on their hydraulicity levels, which correlate with the strength development. Natural hydraulic limes are categorized based on their compressive strengths. For example, the compressive strengths of the NHL2, NHL3.5, and NHL5 mortars were 2.0, 3.5, and 5.0 MPa, respectively.

In the scope of this study, a Teknorep 520 mortar (TEKNO Construction Chemical, Turkey), specially developed for historical buildings in accordance with the TS EN 998-2:2011 “Specification for mortar for masonry - Part 2: Masonry mortar” standard, was used utilizing NHL5 class natural hydraulic lime. The technical data for Teknorep 520 are listed in Table 1.

Table 1. Technical data of Teknorep 520.

General Information	
Material structure	Special blend with natural hydraulic lime based and adjusted gradients
Cement content	0%
Appearance	Off-white and white coffee
Shell life	12 months in dry place in unopened packaging
Package	20 kg kraft bag
Application Information	
Implementation process	Min. 30 minutes
Application ground temperature	(+5 °C)–(+35 °C)
Grain size	< 2 mm
Application thickness	Each storey 1–5 cm
Performance Information	
Flexural strength	>2.0 N/mm^2
Compressive strength (EN 1015-11)	10–15 N/mm^2 (M10 Class)
Water vapor permeability (EN 1745)	μ < 35
Capillary water absorption (EN 1015-18)	0.2 kg m^{-2} h$^{-0,5}$
Bond strength	> 0.15 N/mm^2
Reaction to fire	A1

2.2. Preparation of hydraulic lime-based mortar specimens

To prepare the specimens, Teknorep520 was mixed at 20/6 water content ratio in the laboratory. Subsequently, the mixed mortar was poured into molds measuring 40 × 40 × 160 mm, according to the specifications outlined in EN 1015-11. These specimens were then enclosed in polyethylene bags to maintain a relative humidity of 95% ± 5, as to the guidelines provided in EN 1015-11 (Fig. 2). After a period of five days, the specimens were extracted from the molds and kept in polyethylene bags for an additional two days, for a 7-day duration. Subsequently this, the specimens were transferred to laboratory conditions of 65% ± 5% relative humidity and 20 °C for further testing.

Fig. 2. Test specimens.

3. Elevated Temperature Tests (ETTs)

In this study, the experimental studies took place at the Construction Materials, Fire and Acoustic Laboratory of the Turkish Standards Institution (TSE) in İstanbul, Türkiye. The specimens were subjected to a designated constant temperature using the ISO 834-1 temperature–time curve. A specialized furnace powered by natural gas burners was to achieve these temperatures. To adhere to the EN 1363-1 standard and prevent direct flame contact, the specimens were positioned 750 mm away from the furnace burner. Two-plate K-type thermocouples were deployed throughout the tests to regulate the furnace temperature and positioned 100 mm from the specimens, following the guidelines outlined in EN 1363-1. Additionally, a K-type Inconel thermocouple was utilized to accurately gauge the temperature of the specimens (Fig. 3). This controlled specimen, which is distinct from those used for mechanical property evaluation, served solely to monitor the temperature levels.

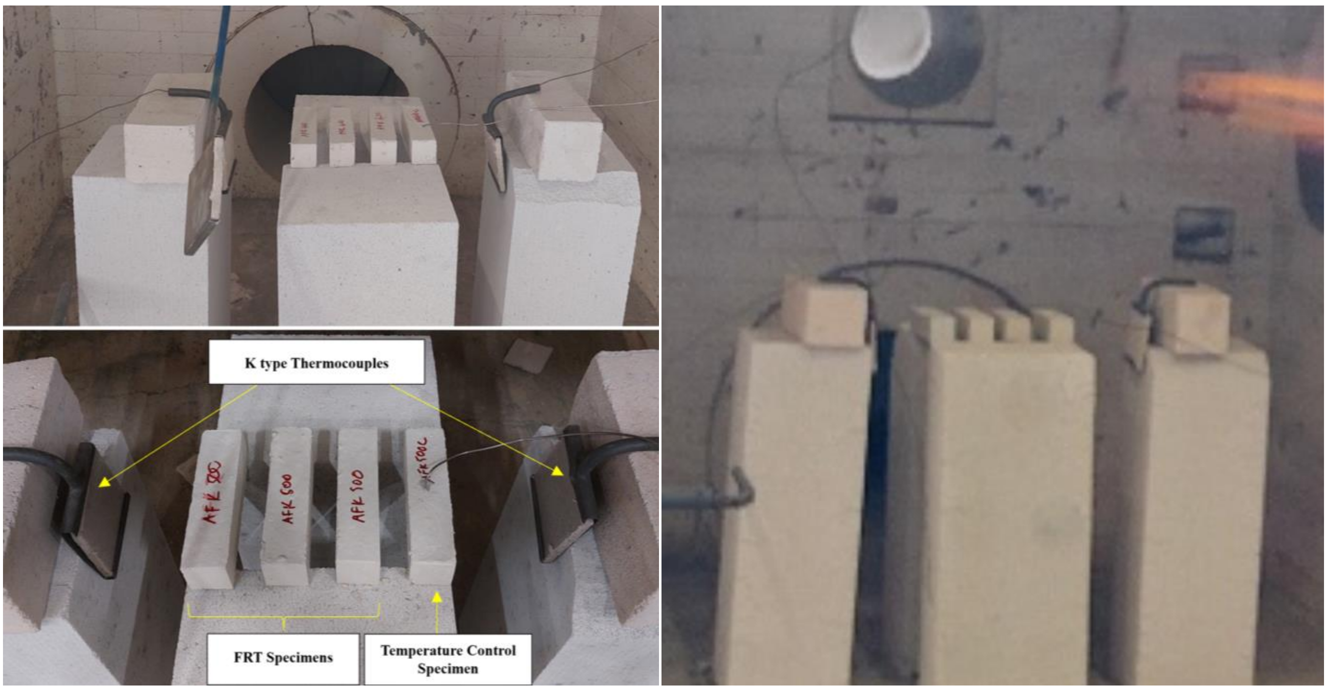

Fig. 3. ETT system.

This study conducted six ETTs spanning temperatures ranging from 200 °C to 700 °C in increments of 100 °C. For each test, four specimens were used, with one designated for measuring the mortar temperature and the remaining three for assessing the mechanical properties. Upon reaching the target temperature for each specimen, the furnace cover was removed, and both the furnace and specimen were allowed to cool until below 100 °C, with the cooling phases meticulously recorded. The standard temperature-time curve obtained from the thermocouples is shown in Fig. 4, and the temperature profiles for elevated conditions are depicted in Figs. 5–10.

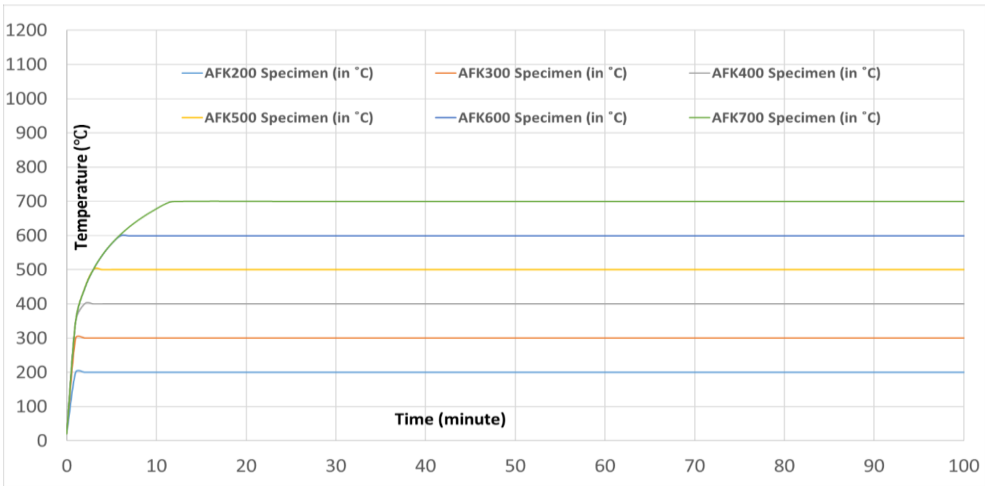

Fig. 4. Standard temperature-time curve (ISO 834).

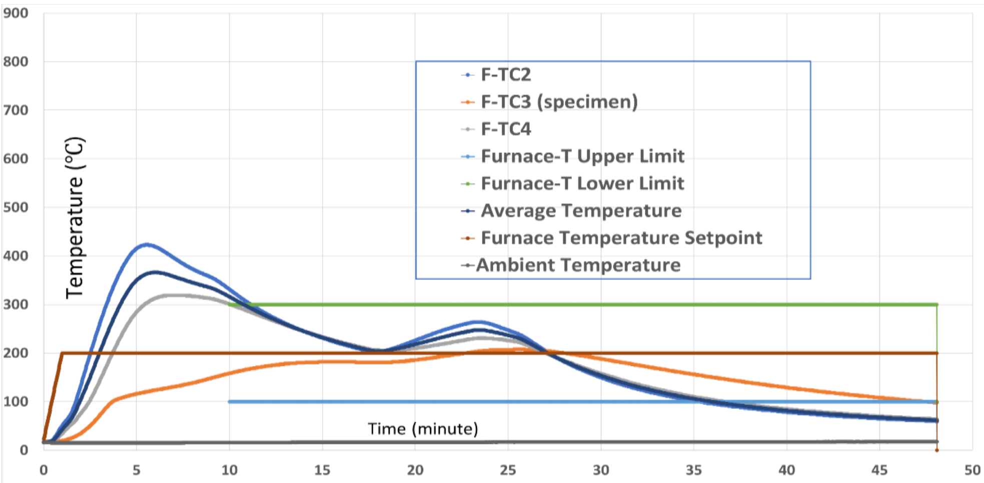

Fig. 5. Time-temperature exposure curve for 200 °C test specimen.

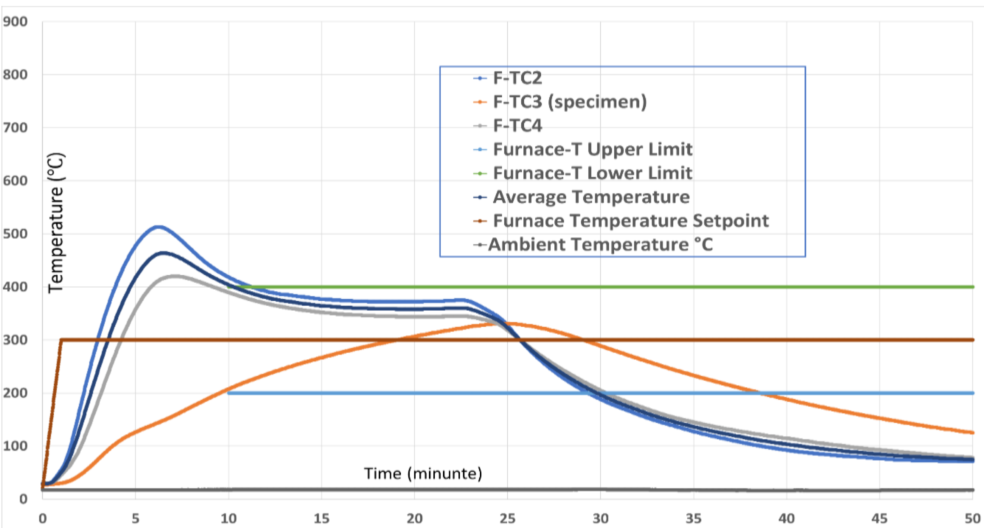

Fig. 6. Time-temperature exposure curve for 300 °C test specimen.

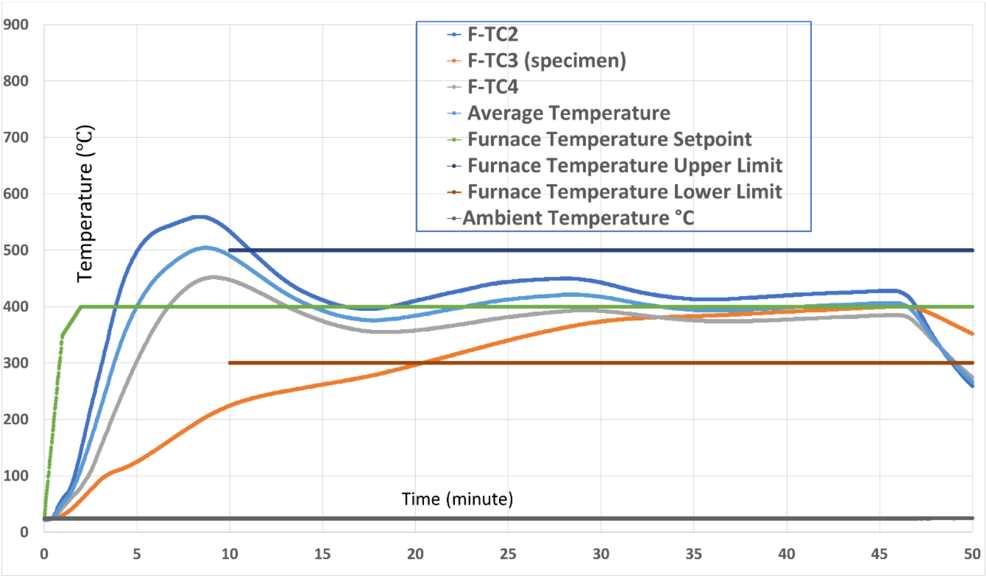

Fig. 7. Time-temperature exposure curve for 400 °C test specimen.

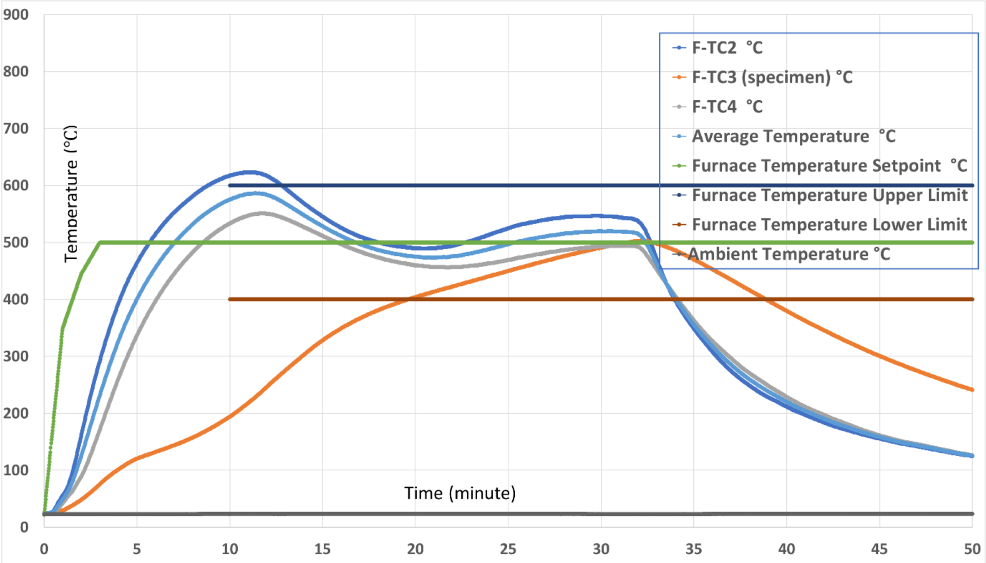

Fig. 8. Time-temperature exposure curve for 500 °C test specimen.

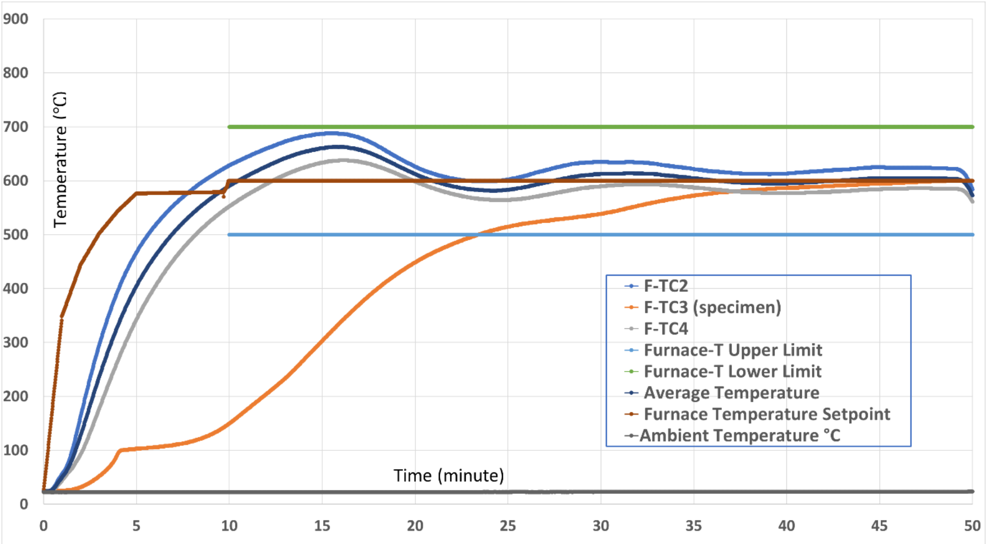

Fig. 9. Time-temperature exposure curve for 600 °C test specimen.

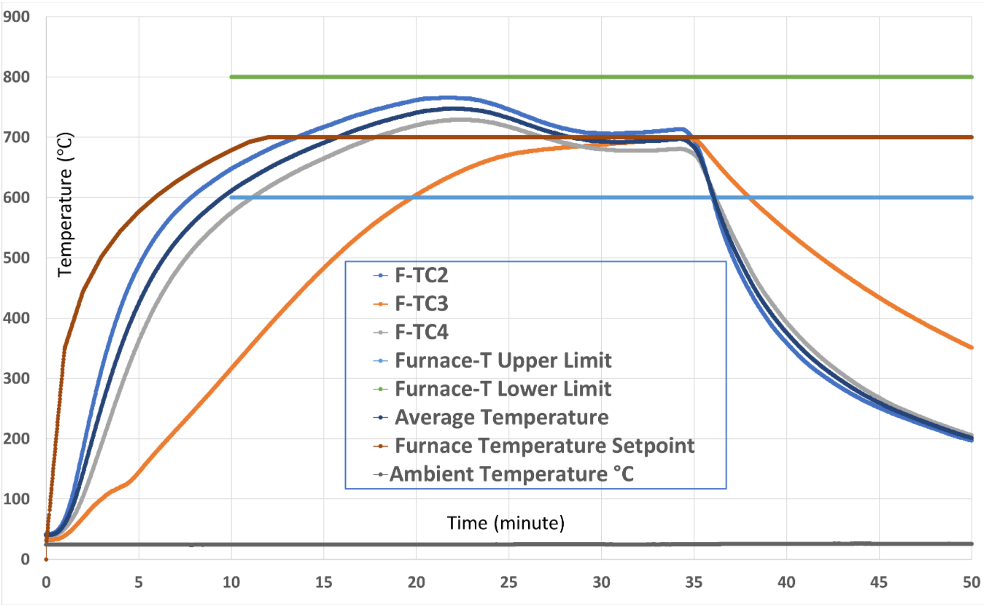

Fig. 10. Time-temperature exposure curve for 700 °C test specimen.

4. Mechanical Tests After ETTs

After the ETTs were completed, subsequent mechanical assessments were conducted to evaluate the structural integrity of the specimens under varying temperature conditions. Both bending and compression tests were performed to comprehensively analyze the mechanical properties following EN 1015-11. For each temperature increment tested during the ETTs, the specimens underwent three-point bending tests (Fig. 11) to assess their flexural strength and stiffness. The specimens were subjected to controlled loading until failure or until a predefined displacement limit was reached. Bending tests provide crucial insights into the ability of a material to withstand bending forces, which are essential for assessing its performance in real-world applications.

In addition to the bending tests, compression tests were conducted on separate specimens exposed to each temperature level during ETTs (Fig. 12). The specimen mechanical tests were performed 1-day after ETTs in order to be sure cooled to room temperature. Compression tests involve the application of axial loads to specimens to determine their compressive strength and deformation behavior. These tests help to understand how the material responds to compressive forces, which is vital for evaluating its structural stability and load-bearing capacity.

5. Results and Discussion

In this section, the findings of the study are presented and engaged in a comprehensive discussion to interpret the results. Additionally, the findings are contextualized within relevant literature and theoretical frameworks, fostering a perspective that enriches the discourse surrounding the findings.

5.1. Flexural strength

The flexural strength exhibited a distinct pattern with an increase in temperature. At 200 °C, the flexural strength decreased to approximately 70% of the ambient level, followed by a gradual decline of approximately 10% per 100 °C until reaching 700 °C. Ultimately, the flexural strength to a mere 20% of the ambient level at the highest temperature point. This gradual decrease underscores the susceptibility of the material to thermal degradation over prolonged exposure to elevated temperatures (Figs. 13–19).

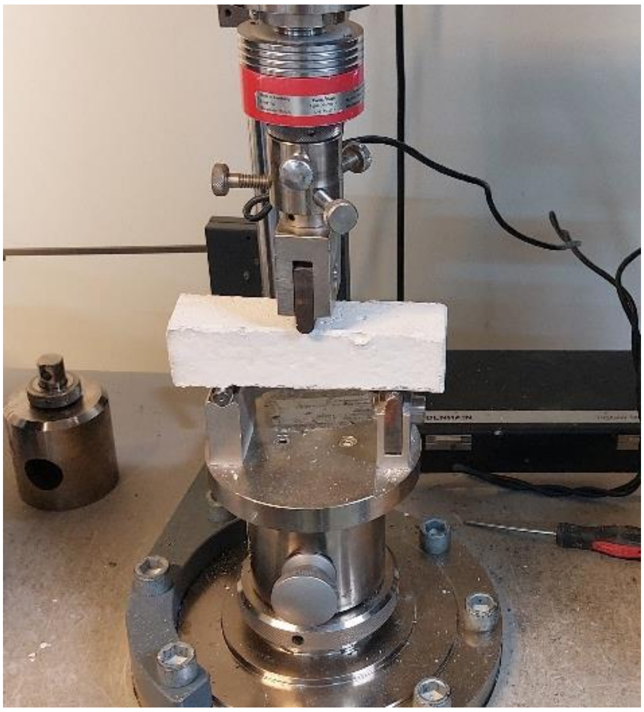

Fig. 11. Three-point bending test on the specimens.

Fig. 12. Compression test on the specimens.

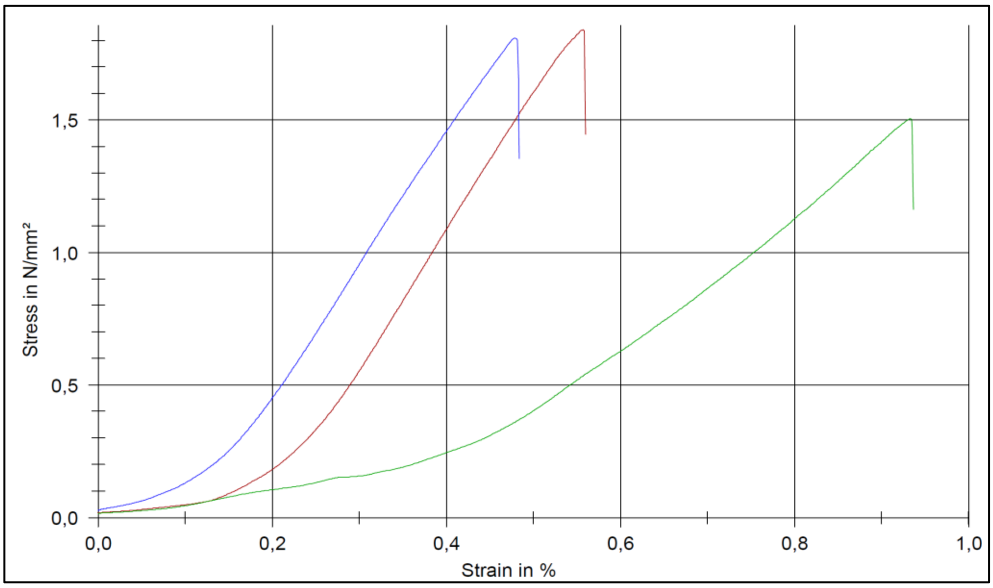

Fig. 13. The flexural strength at 20 °C.

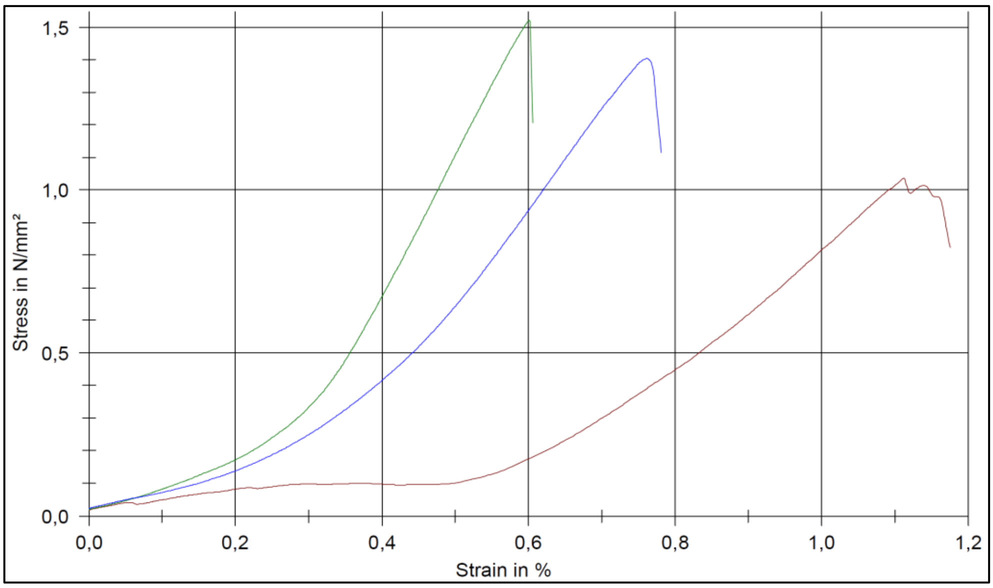

Fig. 14. The flexural strength at 200 °C.

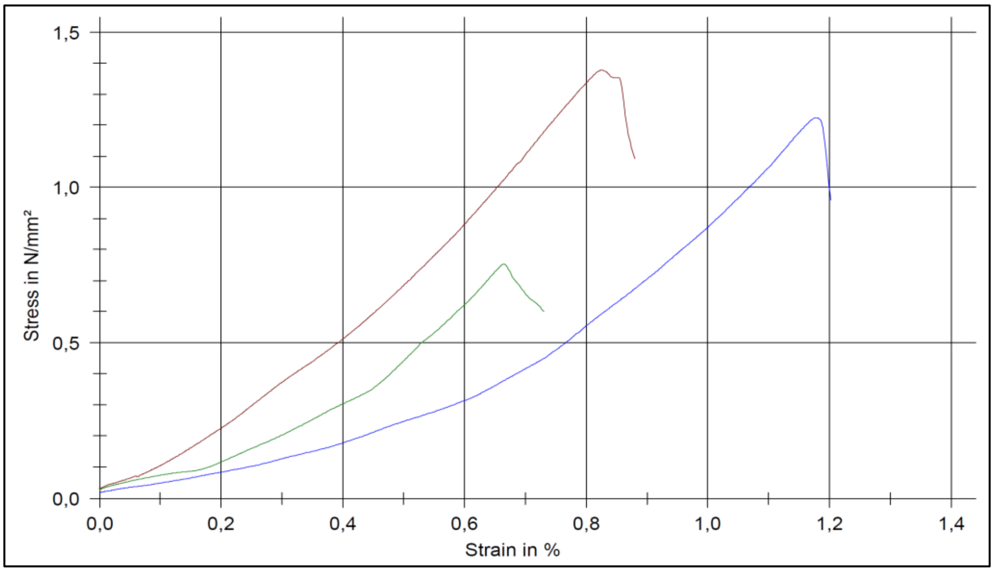

Fig. 15. The flexural strength at 300 °C.

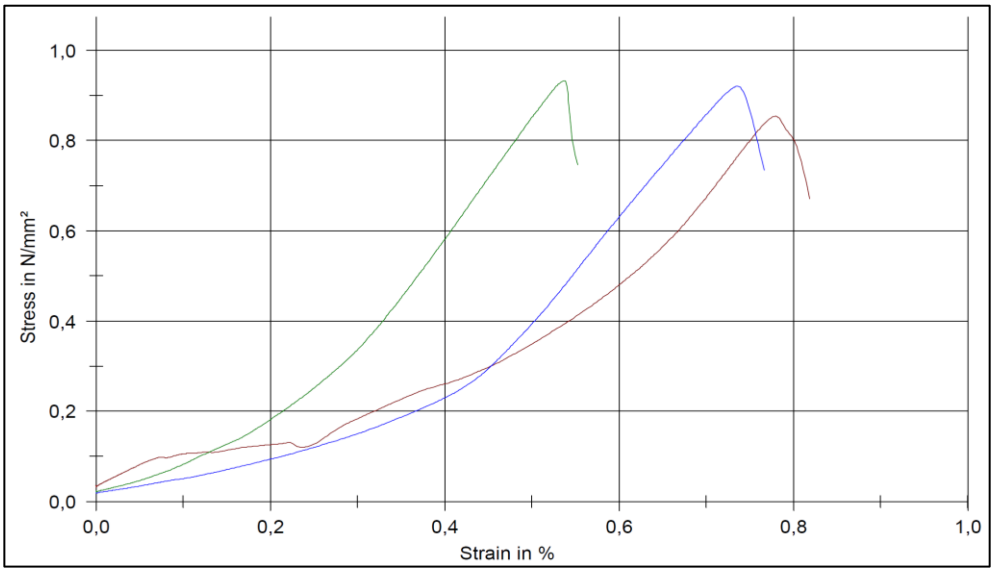

Fig. 16. The flexural strength at 400 °C.

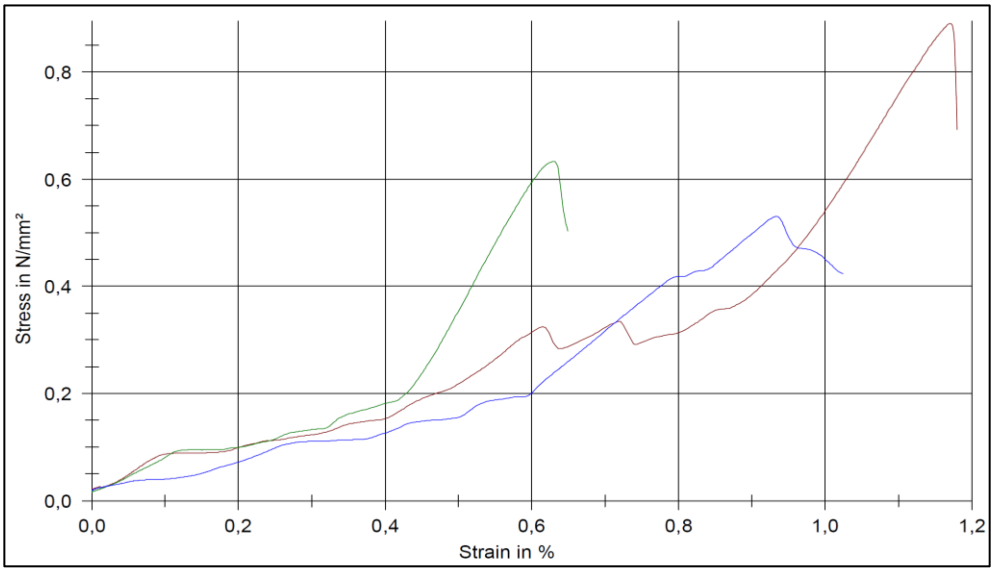

Fig. 17. The flexural strength at 500 °C.

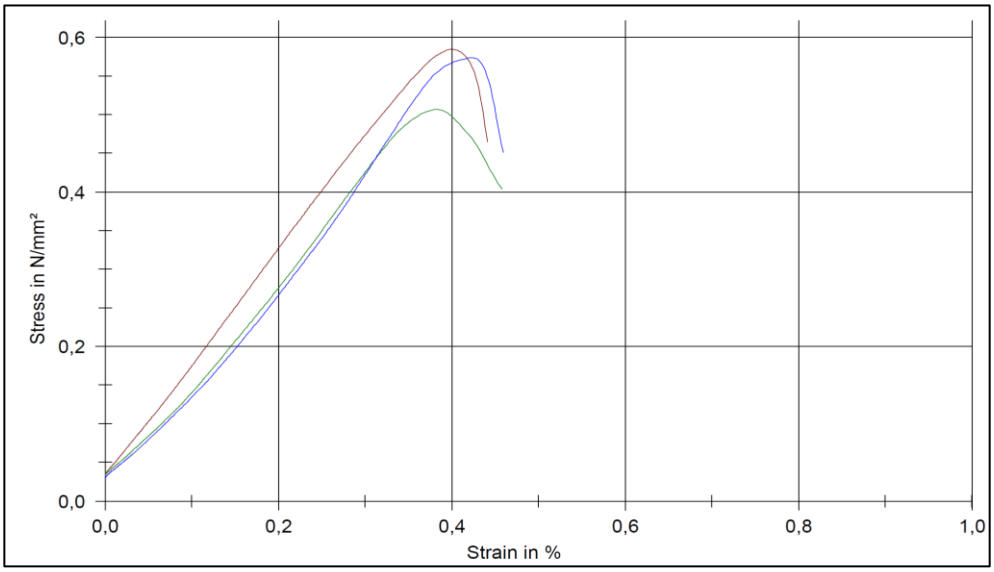

Fig. 18. The flexural strength at 600 °C.

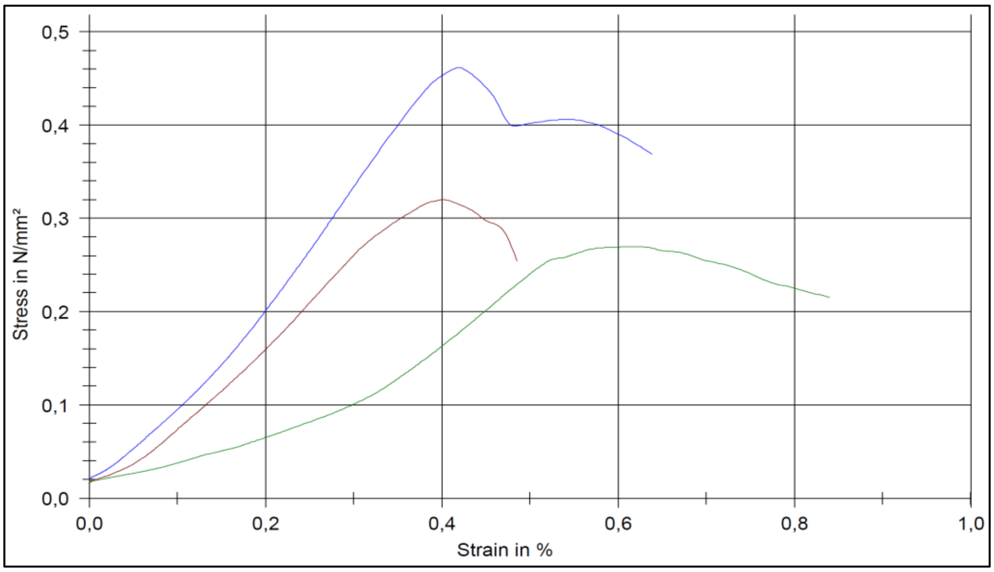

Fig. 19. The flexural strength at 700 °C.

Table 2 presents the results of the flexural tests conducted on HLM specimens subjected to varying temperatures. As observed from the data, there was a clear trend in the flexural strength of the mortar as the temperature increased. At lower temperatures (20 °C), the control specimens exhibited the highest flexural strength, gradually decreased with increasing temperature rises. This decline became more pronounced at higher temperatures, with a significant reduction observed at 400 °C and above. The average flexural strength across all the specimens followed a similar pattern, indicating a consistent response of the mortar to thermal exposure. These findings suggest that the HLMs experienced a decline in flexural strength as they underwent thermal stress, which has implications for their suitability for applications subjected to elevated temperatures (Table 2 and Fig. 20). In a similar manner, Pachta et al. (2018) concluded that the flexural strength of the lime-based mortars gradually decreases up to 800 °C, and at 1000 °C, it is minimized. Pachta and Stefanidou (2021) observed the flexural strengths of the lime- and cement-based mortars were reduced around 85–90% at 1000 °C.

Table 3 presents the energy absorption values obtained from the flexural tests conducted on HLM specimens exposed to varying temperatures. Flexural tests were performed to assess their ability to dissipate energy under different thermal conditions, providing insights into their structural integrity and performance. At temperatures ranging from 20 °C to 700 °C, the specimens exhibited varying levels of energy absorption, indicating a response to thermal stress of the material. Notably, as the temperature increased, discernible fluctuations were observed in the energy absorption values across the specimens. This decline in energy absorption could be attributed to the thermal degradation of HLMs, resulting in alterations to their microstructure and mechanical properties. Such changes might lead to compromised structural performance and durability, particularly under elevated-temperature conditions.

Table 2. Data obtained from flexural test results in N/mm² (MPa).

Specimen	Control (20 °C)	200 °C	300 °C	400 °C	500 °C	600 °C	700 °C
1	1.840	1.040	1.380	0.850	0.890	0.580	0.320
2	1.810	1.520	0.750	0.930	0.630	0.510	0.270
3	1.740	1.400	1.220	0.920	0.530	0.570	0.460
Average	1.797	1.320	1.117	0.900	0.683	0.553	0.350

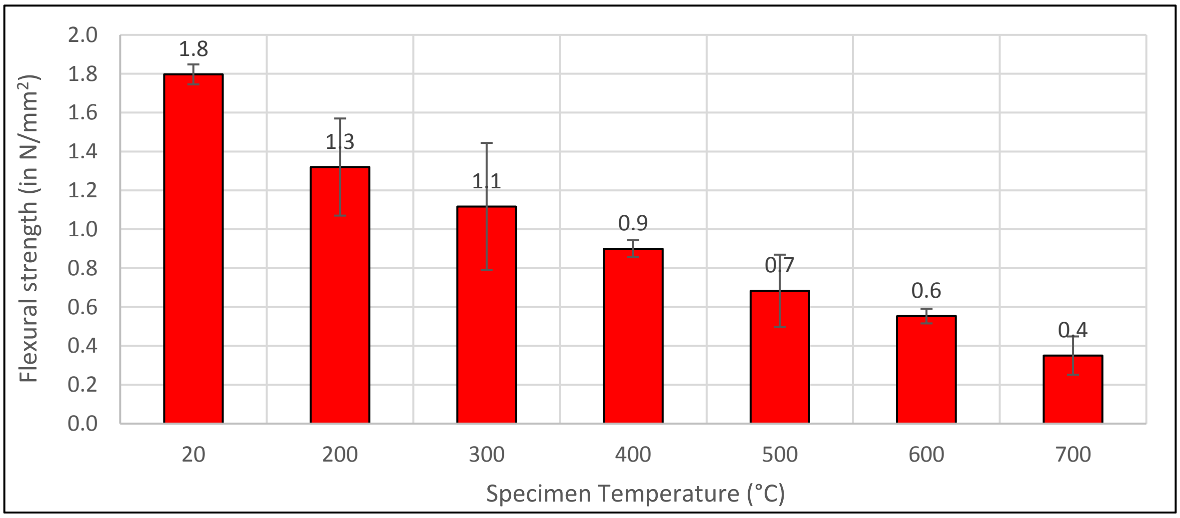

Fig. 20. Summary of flexural strength test results.

Table 3. Energy absorption of the specimens (Joule).

Specimen	Control (20 °C)	200 °C	300 °C	400 °C	500 °C	600 °C	700 °C
1	0.2406	0.3223	0.5590	0.2078	0.1467	0.1527	0.1835
2	0.4347	0.4154	0.2402	0.2564	0.3593	0.1458	0.0820
3	0.4865	0.4057	0.5290	0.2791	0.2291	0.1391	0.1353
Average	0.3873	0.3811	0.4427	0.2478	0.2450	0.1459	0.1336

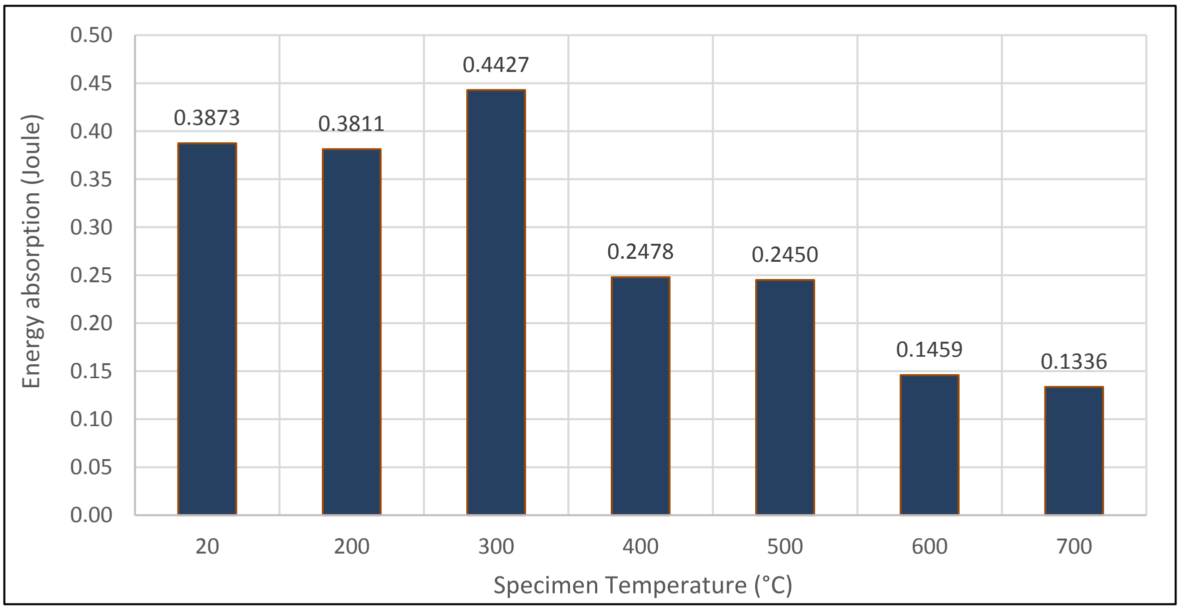

Fig. 21. Summary of energy absorption capacities.

5.2. Compression strength

Similarly, compression strength analysis revealed notable trends across various temperature ranges. Initially, up to 300 °C, the compressive strength remained relatively constant. However, a significant decrease was observed at 400 °C, where the strength decreased to 60% compared to ambient temperature conditions. This trend continued as temperature increased, with compression strength reaching a mere 30% of ambient levels at 700 °C. These findings suggest a critical temperature threshold, beyond which the structural integrity of the material is significantly compromised (Figs. 22–28).

In this study, the results showed that at lower temperatures (between 20 °C and 300 °C), the mortar generally exhibited higher compressive strength, indicating its structural integrity and stability under typical environmental conditions. However, as the temperature exceeded 300 °C, a significant reduction in compressive strength was observed in all specimens. This decline became particularly pronounced at temperatures exceeding 500 °C, indicating a critical threshold which the mechanical properties of the material were significantly compromised (Table 4 and Fig. 29). With an increase in temperature, a decrease in the mechanical properties and structural integrity of mortar and stones is supported in the literature. For example, Neto et al. (2022) reported that the deformability of masonry mortars increased significantly as the post-fire curing time and lime content of the mixture increased. Mortars with elevated lime content and extended post-fire curing periods displayed a more pliable nature. Karahan (2010) resulted that there is a significant decrease in compressive strength compared to the strength of the control reference mortar when temperature rise from 400 to 1000 °C. Bamonte et al. (2021) emphasized that for M15 class mortar, there is a slight increase in compressive strength at 200 °C with an increase. However, it is noted that as the temperature continued to increase, the compressive strength gradually decreased.

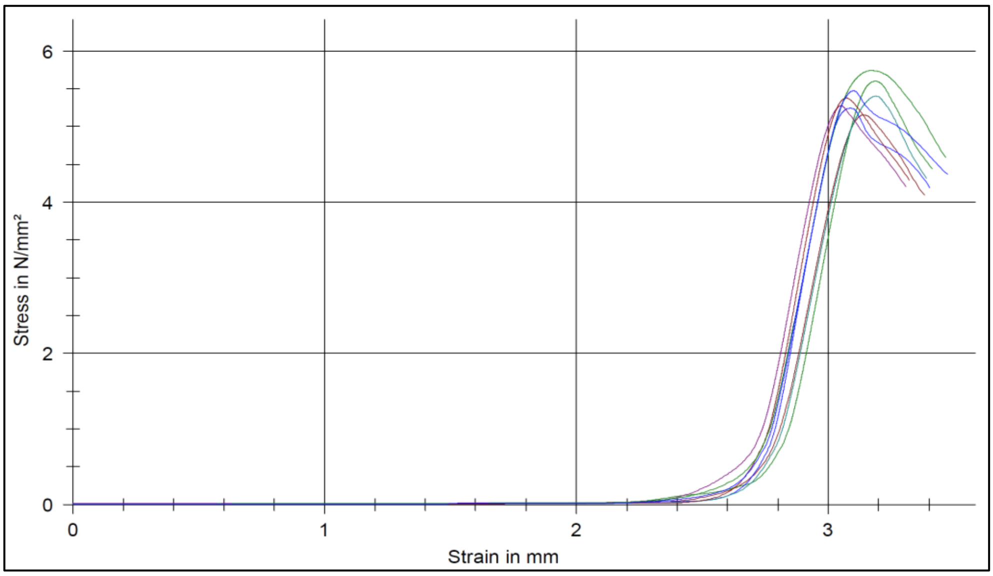

Fig. 22. The compressive strength at 20 °C.

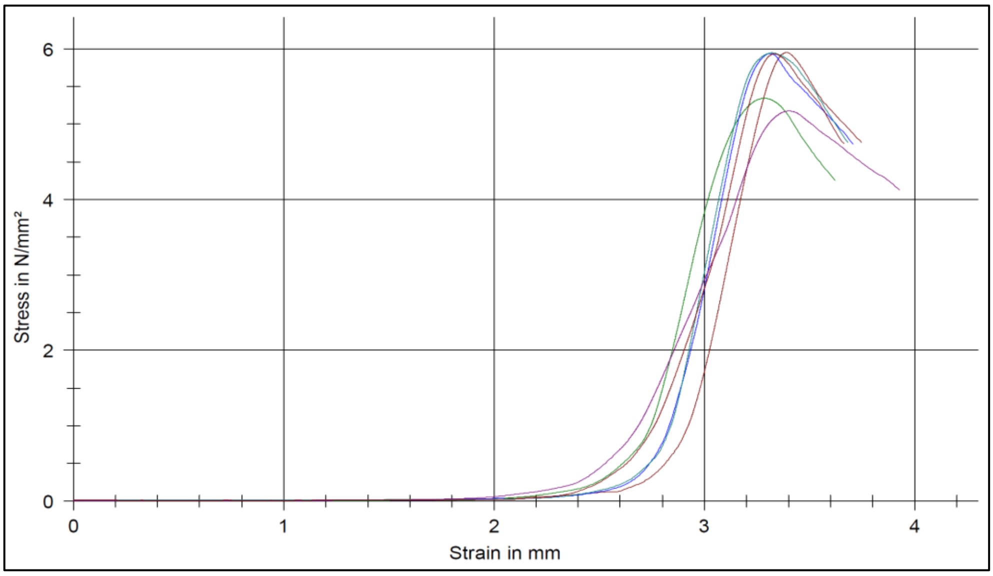

Fig. 23. The compressive strength at 200 °C.

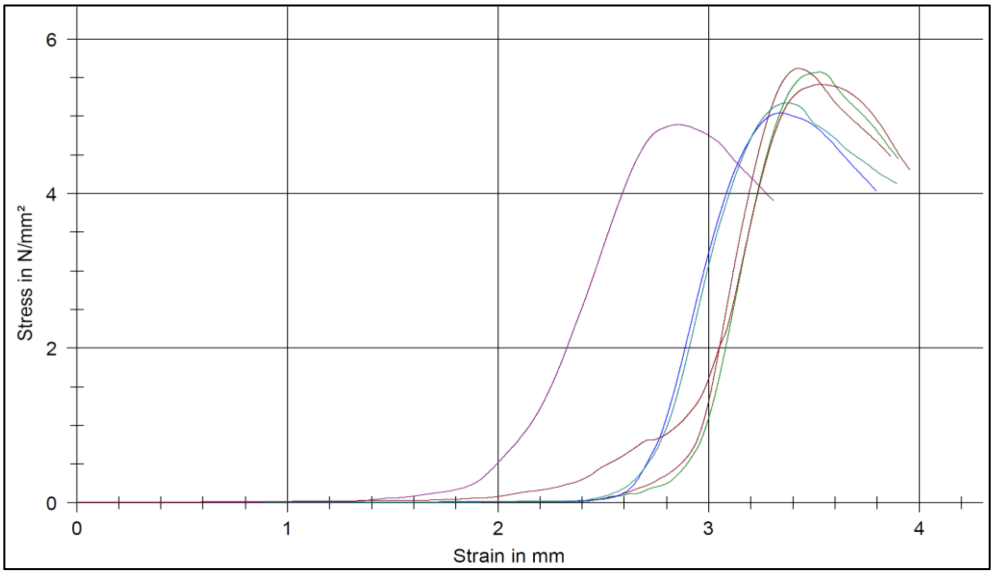

Fig. 24. The compressive strength at 300 °C.

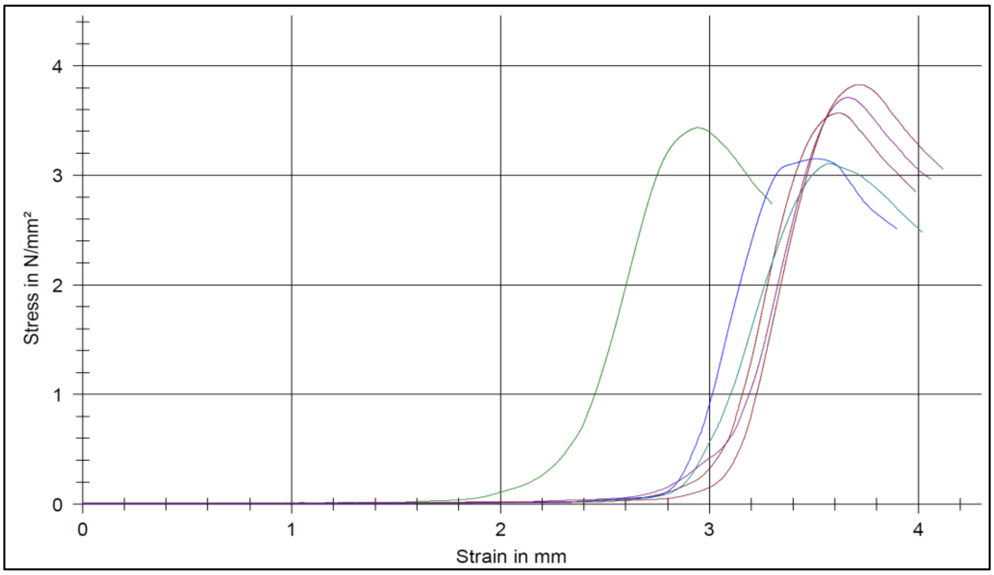

Fig. 25. The compressive strength at 400 °C.

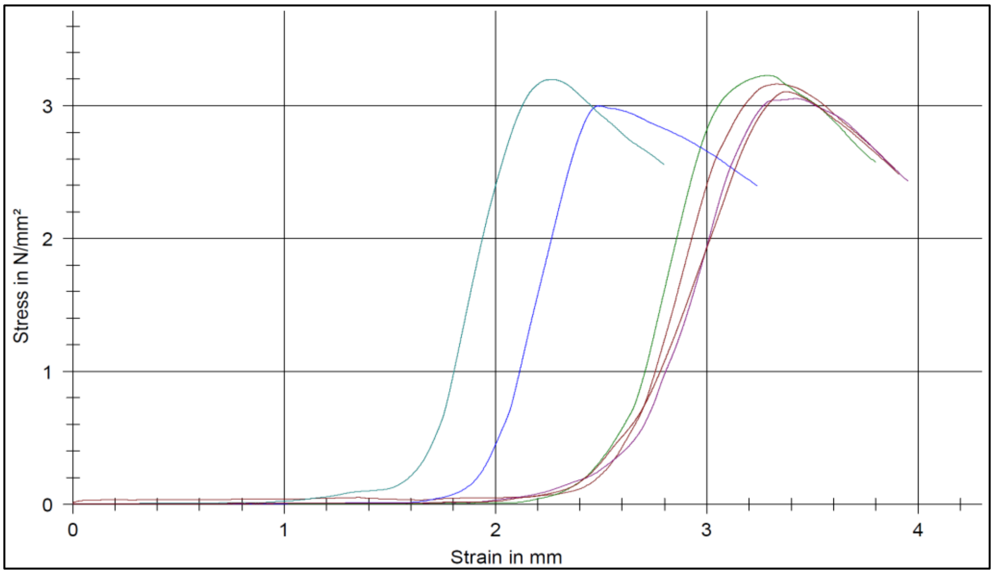

Fig. 26. The compressive strength at 500 °C.

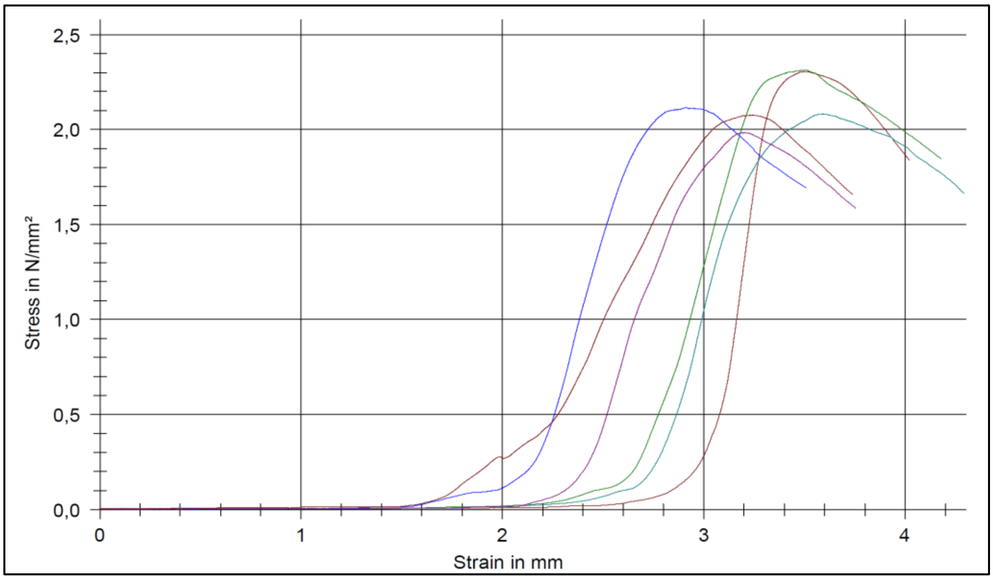

Fig. 27. The compressive strength at 600 °C.

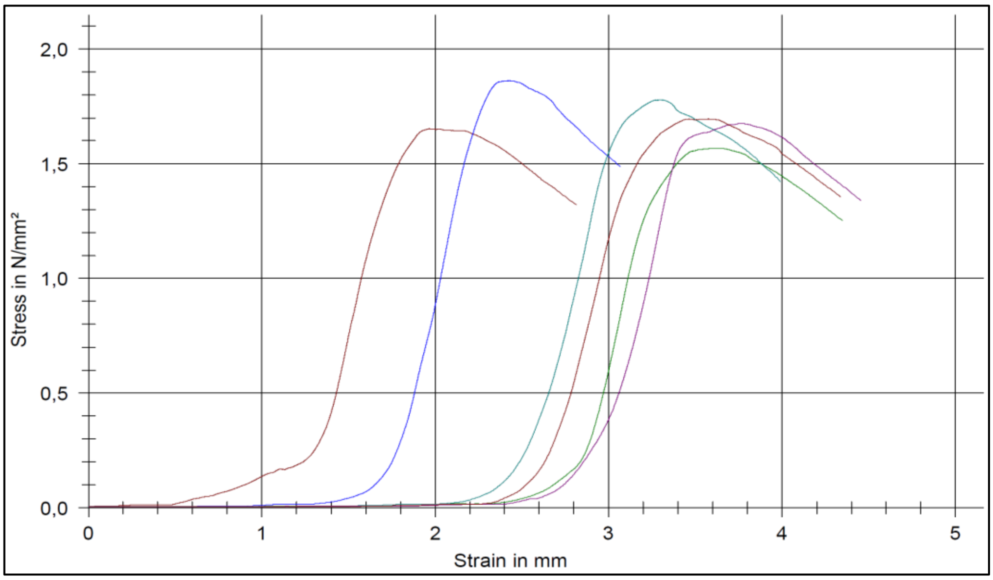

Fig. 28. The compressive strength at 700 °C.

Table 4. Data obtained from compression test results in N/mm^2 (MPa).

Specimen	Control (20 °C)	200 °C	300 °C	400 °C	500 °C	600 °C	700 °C
1	5,600	5,950	5,620	3,570	3,160	2,310	1,650
2	5,250	5,340	5,570	3,430	3,230	2,310	1,570
3	5,400	5,940	5,040	3,150	3,000	2,120	1,860
4	5,280	5,950	5,170	3,110	3,200	2,080	1,780
5	5,380	5,180	4,890	3,710	3,050	1,980	1,680
6	5,740	5,930	5,410	3,830	3,110	2,080	1,700
Average	5,442	5,715	5,283	3,467	3,125	2,147	1,707

The findings were compared with existing standards and codes, particularly Eurocode 6 and Turkish Seismic Code (TBDY-2018). It was observed that the Eurocode 6 assumption regarding the disappearance of strength values at 600 °C appeared conservative because the actual strength values at this temperature were higher than anticipated. Additionally, our results indicated alignment with class M1-2 as per TBDY-2018, highlighting the significance of considering the reduced material properties post-fire exposure for structural evaluation and safety.

In comparison to the assumption outlined in Eurocode 6, which suggests the disappearance of strength values at 600 °C, the actual compression strength at 600 °C diminishes to nearly 40% (2.1 MPa) of the ambient compression strength, whereas the flexural strength reduces to approximately 30% (0.6 MPa) of the flexural strength. This indicates that the Eurocode 6 assumption may have been overly conservative.

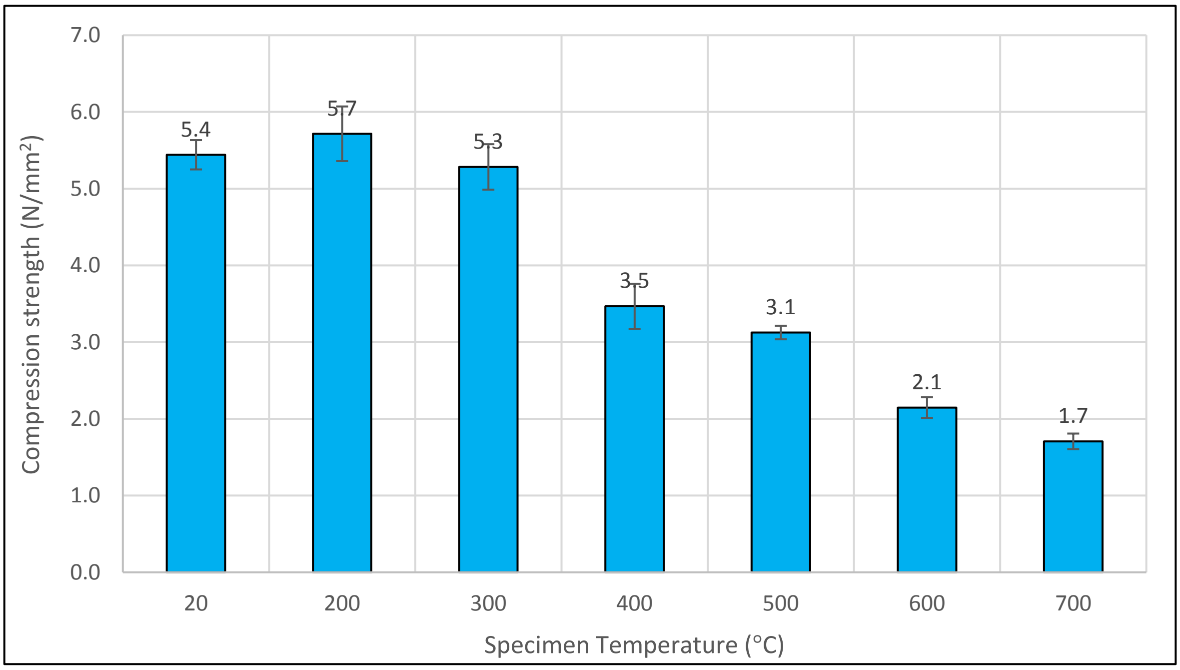

Fig. 29. Summary of compression strength test results.

6. Conclusions

From the moment historic masonry structures are erected, they face a myriad of challenges over time. These challenges inevitably result in damage, necessitating restoration and reinforcement endeavors. Among the materials employed in these efforts, HLMs stand out for their compatibility with the innate characteristics of historic construction. This research delves into assessing the fire resistance capabilities of HLMs.

In this study, HLMs were prepared in adherence to restoration standards followed by the crafting of prism specimens. These specimens were exposed to high temperatures ranging from 200 °C to 700 °C, after which bending and compression tests were carried out. A total of 27 specimens were meticulously prepared for ETTs, comprising three test specimens and one temperature-monitoring specimen for each temperature, along with three reference specimens. While the reference specimens were tested at room temperature, the remaining specimens were allowed to cool to room temperature post-fire exposure, following which they were tested under identical conditions to the reference specimens. In this study, the temperature monitoring specimens were solely utilized to track internal temperatures through embedded thermocouples; hence, no mechanical tests were conducted on them. The findings gleaned from these comprehensive experimental studies underscored that HLMs progressively lose their mechanical properties with escalating temperature. The flexural strength reduced to approximately 70% of the ambient value at 200 °C. Subsequently, from 200 °C onwards, there was a gradual decrease of approximately 10% until reaching 700 °C, resulting in a final flexural strength of approximately 20% of the ambient level. The compressive strength remains relatively stable at 300 °C. However, at 400 °C, it decreased to 60% of the compressive strength observed at ambient temperature. By the time it reached 700 °C, the compression strength had diminished to 1.7 N/mm^2, representing 30% of the strength recorded at ambient temperature. It is clearly seen that the compression strength experiences a slight decrease until reaching 300 °C. However, beyond this temperature, particularly after exposure to temperatures exceeding 300 °C, there was a significant decline in compressive strength, with values dropping by almost 30% compared to ambient conditions. Similarly, the flexural strength exhibits a gradually decreased up to 700 °C. However, even after exposure to temperatures as high as 700 °C, they still retained mechanical properties akin to those observed in lower-grade mortars. A compression value of 1.7 N/mm^2 at 700 °C exceeds the normal strength of masonry structures, suggesting that the Eurocode 6 assumption regarding strength loss at 600 °C is indeed conservative. Nevertheless, further evaluations, particularly those involving brick structural elements, are necessary to validate our conclusions. Despite the decline in strength, the compression strength at 700 °C (1.7 MPa) still retained considerable strength. Therefore, it can be inferred that it aligns with class M1-2, as per TBDY 2018.

Both energy absorption and compression strength of mortar declined significantly after 300 °C. Understanding how the mechanical strength of mortar varies with temperature is essential for designing structures that can effectively withstand thermal fluctuations. The results obtained can be utilized for the purpose of conducting a detailed micro-modelling of masonry structures. Furthermore, they can be employed as input data for the mortar part of the structural elements after fire exposure (thermal analysis) at related elevated temperature.

Further analysis and modeling based on these test results can provide valuable insights into the behavior of HLM under different environmental conditions, aiding in the development of more resilient and durable construction materials. In the event of collapse of historical structural elements following fire exposure, it is imperative to conduct further assessments considering the reduced material properties post-fire exposure. Further assessments will be performed for the structural analysis of masonry arch structures at elevated temperatures in actual fire cases.

Acknowledgements

The authors are sincerely grateful to Mr. İsmail Yıldırım and Mr. Osman Aydoğdu for their collaboration in conducting laboratory compression and flexural testing at the Turkish Standards Institution.

Funding

The authors received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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