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Fire Performance of Masonry under Various Testing Methods

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Abstract

Masonry, as a construction material, is known to perform well under elevated temperatures, which makes it an attractive choice for structural applications. This superior performance is a reflection of its inert thermal characteristics, good stability, and slow degradation of mechanical properties. Still, and similar to other construction materials, masonry undergoes a series of temperature-dependent physio-chemical and phase changes once exposed to high temperatures. Such changes are determined through temperature-dependent material models often obtained by means of physical tests on representative masonry specimens. A deep dive into the open literature shows that not only we lack standardized procedures for testing masonry under fire conditions, but existing researcher-derived methods vary significantly. As a result, available temperature-dependent material models also vary given their sensitivity to testing parameters (i.e., set-ups, heating history etc.). It is primarily due to the aforenoted observations that we continue to lack a holistic understanding of the fire behavior of masonry which also extends to limiting advancements in performance-based design of masonry structures. In order to bridge this knowledge gap, this paper reviews commonly adopted fire testing methods on masonry and the wide scatter of corresponding temperature-dependent material models to provide researchers and practitioners with much-needed knowledge that is currently missing in this domain. Findings from this review can then be used to develop modern and up-to-date temperature-dependent material models to

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facilitate the design of new masonry constructions or analysis of existing ones (including historical buildings).

Keywords: Masonry; Fire; Testing methods; Mechanical properties; Thermal properties.

1. Introduction

Masonry has been historically adopted as a primary building material of choice due to its cost-effectiveness, ease of fabrication, availability of raw materials, and thermal and sound insulation properties [1–3]. Masonry has also been heavily used in historical structures, many of which continue to stand despite undergoing natural and manmade hazards [4,5]. While advancements in construction materials and structural engineering continue to advance, as apparent by the ever continually updated standard testing procedures and building code provisions (i.e., with regard to ambient service conditions, earthquake, wind etc.) [6–10], little has been conducted in the area of fire engineering [11–14].

Of the available works in this domain, the majority of the conducted experimental campaigns were comprised of full-scale masonry specimens (primarily on walls/roofs) or small scale wallettes under standard fire tests [12,15–19]. These tests were aimed to examine the thermal and structural performance of masonry walls once exposed to standard fires (i.e., ASTM E119 [20], ISO834 [21]). Standard fire tests are largely concerned of evaluating three criteria: Integrity, Insulation, and Load bearing capacity of tested components [22,23]. For example, Allen and Harmathy [24] carried out an experimental campaign by conducting 71 fire tests on full-scale walls. In such tests, these researchers varied 44 different types of masonry blocks with different block geometry, moisture content, and aggregate type, which then were tested under ASTM E119 conditions. The same researchers used findings from the aforenoted tests to develop an empirical method to evaluate the fire endurance of masonry walls by accounting for the thickness of wall and type of aggregate. Another campaign was carried out by Ayala [25], who conducted steady state elevated temperatures testing on wallettes (up to 800°C) made of concrete masonry blocks. It is worth noting that standard fire tests are not only expensive, time consuming, require the availability of specialized equipment and qualified personnel, but also give little to minimal regard to the performance of masonry as a construction material [26–28].

In an effort to investigate the properties of masonry under elevated temperatures, small scale (material level) tests are often undertaken. In one study, Andreini et al. [28] tested 200 masonry specimens with distinct aggregate properties and mix design under temperature range of 20°C to 700°C to obtain mechanical properties at targeted temperatures (i.e., 25, 100, 200°C …). In each test, moisture content, compressive strength, and young's modulus were reported. In a similar effort, Khaliq and Bashir [29] reported mechanical properties of burnt masonry units tested in "hot state" at elevated temperatures (20 to 800°C) and derived a temperature-dependent material model. In lieu of experimental tests, Eurocode 6 [30] also provides general guidance on the degradation of mechanical properties of masonry as a function of temperature rise. It is worth noting that this model was developed as a result of a specific testing program and has not been updated nor revised for over 15 years. Hence, a modern look into this domain is warranted.

Arriving at a proper material model that captures the variation in thermal and mechanical properties of masonry is not only essential from a material science point of view but also as a mean to enable the design of new masonry structures and the analysis of existing ones (i.e., post-fire incidents) [31]. In addition, the same is also true to allow fully utilizing advanced simulation and modeling methods (e.g., finite element (FE), finite difference (FD), artificial intelligence (AI) etc.) in assessing masonry structures under fire conditions [28,32–34]. For example, a typical FE model consists of a fire model, a heat transfer model, and a mechanical model [35]. For these models to be properly developed and applied, a designer/user is required to supply temperature-dependent material models to describe the fire-induced changes to properties of masonry associated with the rise in temperatures.

Since these models are essential to evaluate thermal response, deflection history, and generated stresses within masonry components, the choice of the material model becomes elemental to the accuracy and predictability of the conducted analysis or simulation [36]. For this, it becomes essential to have a modern and well-established (or perhaps general) material model. Such a model is to be best obtained from a standard testing procedure that is vetted and reliable. However, there are virtually no standardized testing methods available in the open literature for masonry. This does not only further limits the use of masonry in structural and load bearing applications, but limits attempts aimed to utilize masonry in new constructions, whether via perspective or performance-based approaches [29,37,38]. On a more positive note, the open literature does identify a few works that modeled masonry structures under elevated temperatures with varying levels of success [11,35,39–41].

A few common observations the authors of this review have noted include: 1) there is an implied agreement that the properties of masonry would follow a similar trend to that of concrete material, and 2) regardless of the origin and composition of masonry, it is also common to assume that temperature-degradations in masonry are expected to follow that of the Eurocode 6 model. These noted observations are mere simplifications (or assumptions) that our community has adopted to overcome the lack of design guidelines, incomplete knowledge about masonry's behavior under elevated temperatures, and inexistence of proper testing procedures. In order to bridge this knowledge gap and overcome those challenges, this paper first reviews different testing methods performed on masonry from a material and structural behavior perspective, and then dives to review properties of masonry and associated materials models commonly adopted in the literature.

This review starts by describing commonly used fire testing methods on masonry elements and materials, as noted by notable works. Then, this review goes on to generally classify testing methods into "material level", "small scale testing", and "large-scale testing". Trends of how temperature dependent mechanical and thermal properties of masonry materials degrade under elevated temperatures are then discussed in a dedicated section. Finally, the absence of design guidelines, standard testing procedures, knowledge gaps and warranted areas of research, together with main challenges and future works required to overcome such challenges, are articulated.

2. Tests on Masonry under Elevated Temperatures

2.1 Material Level/Small Scale Testing

The mechanical and thermal properties of masonry (especially masonry blocks) have a significant effect on the overall behavior of masonry in fire. These properties are a function of mix design constituents (type of aggregate, binder type, water content etc.). As noted earlier, there are few experimental studies available on such properties [25,26,28,29,42–48]. As will be seen herein, a good number of researchers have adopted fire testing on small-sized specimens/prisms and blocks to assess these properties.

Overall, two types of tests are often used: 1) steady state test, and 2) transient state test. In the first set-up, a specimen is first heated without the application of a mechanical load and the load is then applied once a predetermined temperature is reached. In the second type of testing, the specimen is loaded to a predefined load level prior to heating and then heated until failure [25,33]. The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (RILEM, from the name in French *Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages*) also refers to testing conditions with the application of load and exposure to heating as hot stressed (specimen is loaded prior to heating and then tested), hot unstressed (testing specimen under heating without preload) and residual unstressed conditions (heating specimen to specified temperature and testing after cooling) [49,50].

In a notable study conducted in 1960s, Harmathy [46] fire-tested 47 hollow and solid block specimens of size 0.02 m^2 made up of concrete (17.5% hydrated Portland cement and 82.5% expanded shale), brown clay brick, and insulating fire brick. The main aim of this testing was to examine the effect of moisture content on fire performance of masonry materials. In these tests, Harmathy [46] used an electric furnace of a square cross section (0.76 m × 0.76 m) to conduct the aforenoted tests – see Fig. 1. All specimens were dried for 6 hrs in a furnace heated to 105°C. Before each fire test, oven dry specimens were exposed to hot steam for predetermined amount of time to reach a desired level of moisture content which varied between 0-0.21 percent by volume. Thirty-five specimens were tested once, and the remaining twelve were subjected to repeated fire exposure. This testing program have noted three key findings: 1) tested specimens yielded 6 to

19% increase in fire endurance during the first fire test than in the repeated tests, 2) *"there were undoubtedly more than negligible differences in the properties of specimens of supposedly identical materials"* [46], and 3) moisture content increases with increasing permeability of masonry and decreases with increasing fire endurance. The appendix lists a collection of reported measurements taken from this particular study.

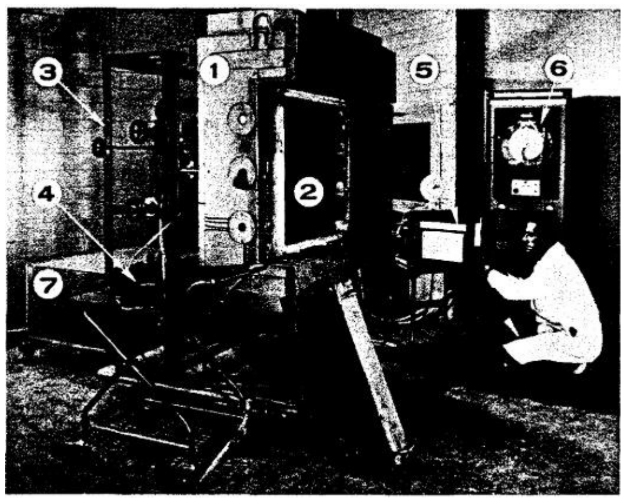


Fig. 1 Fire test assembly used in [46] (notes: 1. electric furnace, 2. Inconel plate, 3. air supply control equipment, 4. oxygen analyzer, 5. multipoint temperature recorder, 6. temperature controller recorder, and 7. saturable core reactor) – low quality figure was provided in the original cited work [46] (Credit line: Springer Nature, Fire Technology, Experimental study on moisture and fire endurance, T. Z. Harmathy, Dec 31, 1969, License Number: 4954600677915.)

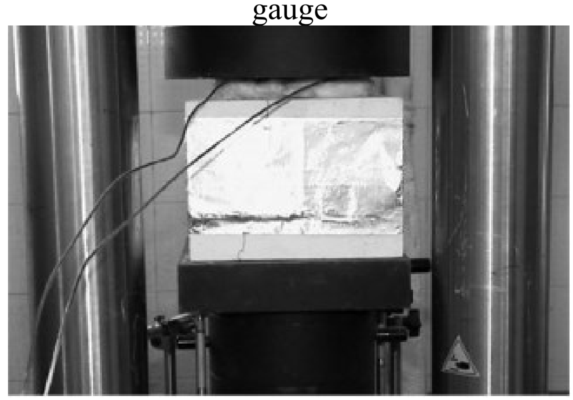
In a series of comprehensive testing, Andreini et al. [47] experimentally investigated the mechanical properties of masonry by testing 200 cylindrical specimens with a 100 mm diameter and a 200 mm height. Mineral wool coated cylinders made of clay, light weight concrete, façade lightweight concrete, light weight concrete with volcanic gravel, aerated autoclaved concrete and hydraulic lime mortar were subjected to temperature range of 20ºC to 700ºC. First, thermal properties of tested specimens at elevated temperatures were measured via Thermal

Characterization of Transitional Phase (TCTP) procedure. Then, the mechanical properties were determined by Hot Mechanics Characterization Method (HMCM) consisting of a compression testing post exposure to the following predefined heating history of 20-100ºC (0.5 hr) → 100ºC (2hrs) → 100ºC to target temperature (1.5 hrs) → hold at target temperature (2.5 hrs) [26,28] – see Fig. 2. The variation of compression strength, ultimate strain, and modulus of elasticity as function of exposure time were reported. Based on stress-strain readings, these authors derived a material model for masonry which is described in a later section [47]. The appendix also lists some of the reported measurements taken by Andreini et al. [47] study.

a) Taking out of furnace

b) Measurement of height with centesimal gauge

c) Placing of specimen in thermos



d) Specimen under compression testing

Fig. 2 Steps of HMCM testing procedure by Andreini et al. [28] (Credit line: John Wiley and Sons, Fire and Materials, Mechanical behavior of masonry materials at high temperatures, Mauro Sassu, Lamberto Mazziotti, Saverio La Mendola, et al., January 14, 2014, License Number:5022850839828)

Ayala and Bailey [25] tested lightweight concrete masonry blocks of dimensions 440 × 215 × 100 mm under targeted temperatures of 200ºC, 400ºC, 600ºC, 700ºC, and 800ºC in a steady state thermal set-up (see Fig. 3). A total 5 blocks for each target temperature were heated and cooled to determine losses in compressive strength in concrete masonry blocks. These researchers reported that the compressive strength of tested blocks was reduced (on average) by 28% from 200ºC to 400ºC. The same researchers also observed consistent degradation at 600ºC and 800ºC of 18% and 65%, respectively [25]. When Ayala and Bailey [25] compared the performance of lightweight concrete masonry blocks to similar sized blocks made of dense concrete, they noted a much improved performance in the case of masonry. In lieu of material level tests, Ayala and Bailey [25] also investigated fire performance of 18 masonry wallettes specimens of 685 mm height, 670 mm width, and 100 mm thick made up of lightweight solid concrete blocks. Masonry wallettes were tested for compressive strength according to EN 1052-1 and EN 1996-1-2 after fire exposure pertaining steady state conditions.

Fig. 3 Testing arrangement used by Ayala and Bailey (Original figure appears in Ayala's thesis [25])

Khaliq and Bashir [29] carried out unstressed tests on burnt masonry bricks temperature in the temperature range of 20ºC to 800ºC. For ambient temperature testing, ASTM C1006 and ASTM C1314-14 were used to determine tensile and compressive strength of burnt masonry bricks. On the other hand, Khaliq and Bashir [29] extended the commonly used ASTM and RILEM methods for concrete to masonry. In total, fifteen brick specimens of size 112.5 × 112.5 × 75 mm and 225 × 112.5 × 75 mm were tested to determine the compressive strength, modulus of elasticity, and stress-strain curves. In examining the mechanical properties at high temperatures, RILEM 129-MHT procedure was used with exposure of 20, 200, 400, 600, and 800ºC and a hold of 60 min. Specimens were tested immediately after heating and were wrapped in a thermal insulation blanket to minimize heat losses (see Fig. 4).

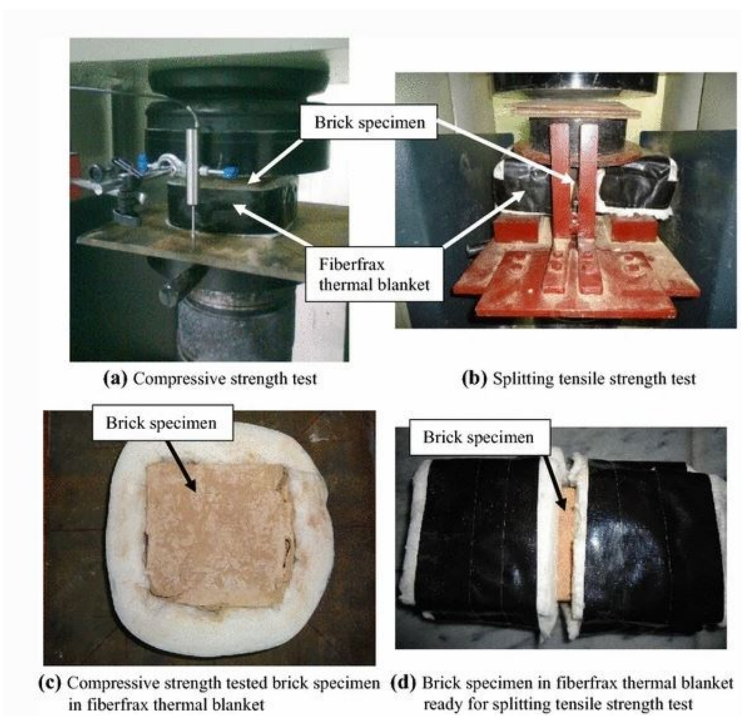


Fig. 4 Burnt masonry brick under compression and tensile strength tests [29] (Credit line: Springer Nature, Materials and Structures, High temperature mechanical and material properties of burnt masonry bricks, Wasim Khaliq et al., March 17, 2016, License Number: 4954611421326)

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Russo et al. [45] conducted an experimental investigation of mechanical properties under elevated temperatures for residual (post-heating) behavior of masonry units (see Fig. 5). The type of masonry bricks that were primarily used was clay brick. In this testing set-up, Russo et al. [45] built small wallettes of size 250 × 120 × 55 mm. These block specimens were exposed on one side to two heating histories, each expressing an exposure condition represented by the maximum temperature (300 or 600°C), with a similar heating rate (~19°C/min) and having a one hour holding duration. Compressive strength and elastic modulus of bricks were evaluated according to UNI EN 772-1 and UNI 9724 provisions, respectively. The appendix also lists reported measurements taken by Russo et al. [45].

Fig. 5 Residual (post-heating) testing of masonry units by Russo et al. [45]
(Credit line: Springer Nature, Experimental Mechanics, Experimental and Theoretical Investigation on Masonry after High Temperature Exposure, S. Russo et al., April 21, 2011, License Number: 4954640044417)

Xiao et al. [48] conducted fire tests on three series of masonry concrete blocks consisting of recycled concrete aggregates as coarse aggregate and sand as fine aggregates with varying percentages of 25%, 50%, 75%, and 100%. For series 1 and 2, the effect of using sand as a replacement of crushed clay brick (CBA) was studied. For series 3, the influence of utilizing crushed clay brick as coarse aggregate as replacement of recycled concrete aggregate by weight of 25%, 50%, 75%, and 100% was examined. In these tests, concrete blocks of size 200 × 100 × 60 mm, were tested after being exposed to 300°C, 500°C and 800°C for a duration of 4 hr to determine their compressive and flexural strength. It is interesting to note that irrespective of the proportion of replaced aggregates, all the blocks exhibited higher residual compressive strength at 300°C and 500°C than that of the initial strength (i.e., at 20°C) – thereby suggesting improved performance post moderate heating. However, the compressive strength values degraded to 52% at 800°C. On the contrary to the compressive strength, the residual tensile strength values decreased up to 54% at a temperature of 500°C, continuing to 800°C [48]. Some of the findings reported by Xiao et al. [48] are summarized in the appendix.

In a more recent work, Bosnjak et al. [42] experimentally investigated the residual performance of solid clay brick and calcium silicate bricks (see Fig. 6). The testing was carried out on 3 specimens of masonry unit type, mortar, and masonry prism according to DIN EN 772-1, DIN EN 1015-11, and DIN EN 1052-1, respectively, in the temperature range of 20°C to 1100°C with a holding duration of 2 hours. The compressive strength of calcium silicate brick was increased significantly till 300°C and dropped abruptly at 700°C, likely to be related to the volumetric change of siliceous sand, decomposition of the C-S-H phases, as well as to the cracking between C-S-H phases and sand particles. For calcium silicate brick prism, compressive strength decreases significantly after 700°C [51]. Bosnjak et al. [42] attributed such losses to the strong degradation of mortar, which also accelerated fire-induced losses in modulus of elasticity. Unlike calcium silicate bricks, the clay bricks exhibit low sensitivity to elevated temperatures with virtually minor degradation in compressive strength up to 500°C, which is then accompanied by an increase in strength due to the structure of the clay brick changing to clinker.

Fig. 6 Brick prisms under compression strength test (note: Left – calcium silicate brick prism, Right – clay brick prism) (Credit line: Elsevier, Construction and Building Materials, Experimental and numerical studies on masonry after exposure to elevated temperatures, Josipa Bošnjak, Serena Gambarelli, Akanshu Sharma, Amra Mešković, January 10, 2020, License Number: 4954620364144)

2.2 Large and Medium Scale Structural Testing

In lieu of small scale material testing, it is quite common to investigate the holistic structural performance of masonry components, and assemblies via large and medium scale testing as such tests may provide a better glimpse into the structural performance of masonry walls/floors (ASTM E119 2016; British Standards Institution 1987; BSI 2012; Sciarretta 2015). This section reviews some of such works in detail, and a more in-depth discussion on these studies can be found at their respective references.

2.2.1 Full Scale Testing

According to the ASTM E119, load bearing walls specimens should not be restrained on vertical edges, while non-load bearing walls should be restrained on all four sides. For such a fire test to be successful, the test specimen should withstand applied loads during fire, provided no passage of flame or gases (i.e., major cracks develop), pass hose stream test, and that temperature rise on the unexposed side remains below 139ºC. If, during hose stream test, openings develop, allowing water projection beyond the unexposed surface, the test is deemed unsuccessful [52].

In one of the earliest recorded test series on masonry, which were performed between 1907-1909, Humphrey [56] conducted thirty fire tests on 1.8 × 2.7 m full scale wall panels in Underwriters' Laboratories, Chicago, IL. These panels were made of a variety of masonry blocks made with river and slag sand, common hydraulic pressed and sand lime brick, gravel cinder, limestone, and granite. Each wall panel varied material blocks with different moisture content. These panels were tested for 2 hr of fire exposure with a targeted temperature of 926ºC (see Fig. 7). Humphrey [56] primarily recorded temperature measurements at the exposed and unexposed face of each panel and that of the furnace as well. These fire tests were also followed by hose stream test (e.g., quenching test). In the event that a wall specimen failed, masonry blocks were dismantled to be individually tested under compression. It is worth noting that Humphrey [56] faced a series of challenges during this early campaign which can be summarized by inexperienced operators, freezing conditions during fire testing in winter, etc. On a more positive note, Humphrey [56] thoroughly documented his findings on all tests, some of which can be found in the appendix.

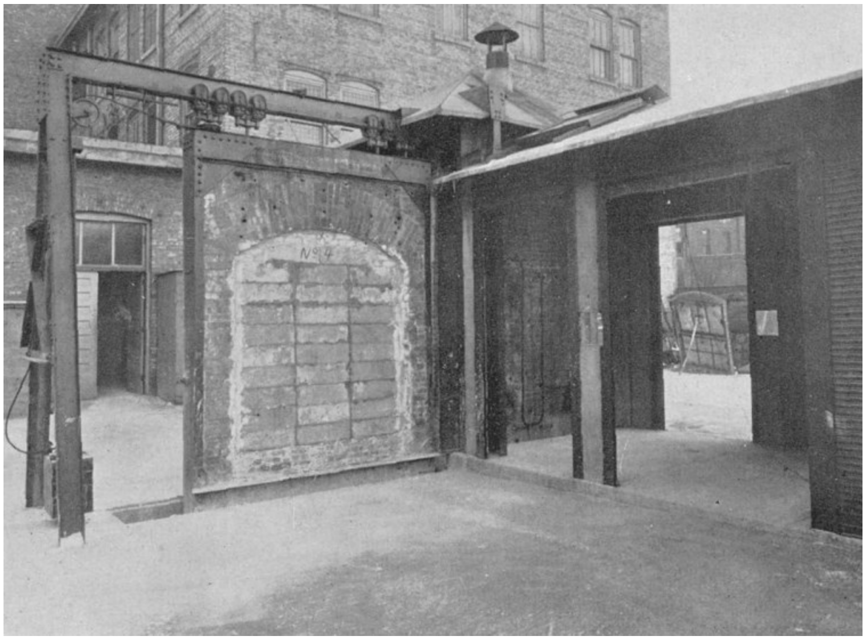

Fig. 7 Fire test set-up by Humphrey [56] (Republished courtesy of the United States Geological Survey.)

In 1950-60s, the National Bureau of Standards (currently; National Institute of Standards and Technology (NIST)) carried out experimental campaigns in which full scale masonry walls were tested under fire. Two notable campaigns are described herein, those tested by Ingberg [57] (i.e., Report 117) and by Foster et al. [15] (Report 120). Report 117 covered masonry walls built from units made with cinder, pumice, expanded slag, or expanded shale aggregates; while Report 120 covered masonry walls built of units made with calcareous or siliceous gravel aggregates. Both campaigns were conducted using the fire testing facility shown in Fig. 8.

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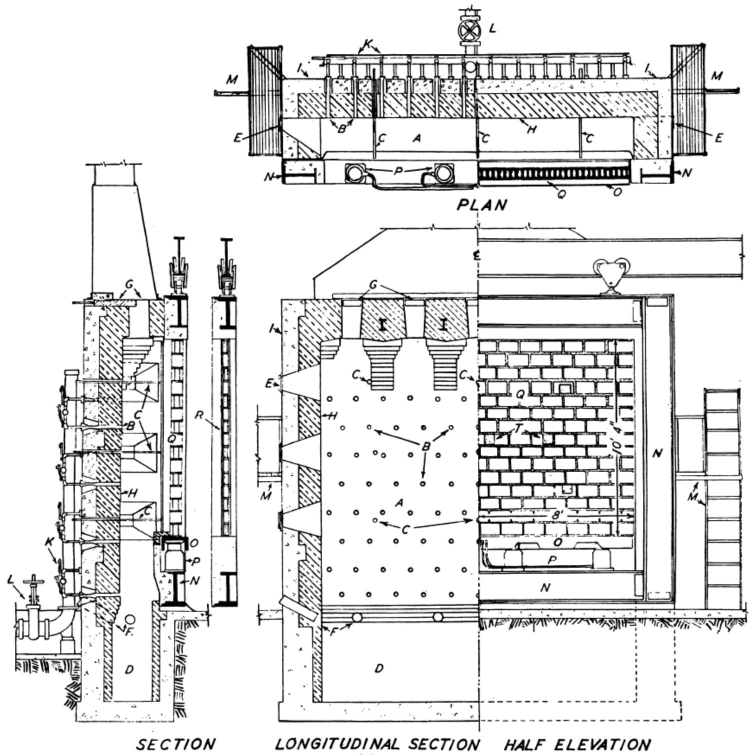

Fig. 8 Fire testing furnace by Ingberg [57] and Foster et al. [15] (note: A- Furnace chamber, B- Burners, C- Thermocouple Protection tubes, D- pit for debris, E- mica-glazed observation window, F- Auxiliary air inlets, G- Flue outlets and dampers, H- Fire brick furnace lining, I- Reinforced concrete furnace shell, K- gas cocks, L- Gas control valve, M- ladders and platforms to upper observation windows, N- movable fireproofed test frame, O- Loading beams, P- Hydraulic loading jacks, Q- Load bearing test wall, R- Non-load bearing test partition, T- asbestos pads covering thermocouples on unexposed surfaces of test wall.) [58] (Republished courtesy of the National Institute of Standards and Technology.)

Ingberg [57] carried out full scale standard fire tests and hose stream tests on 4.8 × 3.3 m fifty four solid and 19 hollow brick walls during 1921-1954. In this program, solid, rolok, rolok bak, rolok faced design, and cavity design walls frame made up of solid concrete, sand lime, clay, and shale were tested. Fire endurance of walls of different thicknesses (100-228 mm) under working load conditions was measured. In addition, wall temperature, furnace temperature, and deflection measurements were also recorded throughout the fire tests. Time-temperature curves and wall deflection curves with respect to exposure time were maintained [57]. In the same testing campaign, 16 lightweight aggregate concrete masonry unit walls (load bearing and non-load bearing) were tested under fire conditions. These units contained cinder, expanded shale, pumice or expanded slag. These tests noted fire resistance of tested walls in the range of 69 min to about 7 depending upon thickness, moisture content, type of aggregate, and load bearing properties [59]. In another series of experiments, 12 walls with different thicknesses containing concrete masonry units of calcareous and siliceous aggregates were also tested and 3 walls were tested using hose stream test. The fire resistance of un-plastered wall made up of calcareous aggregate was limited to 1 hour or total collapse or failure under load for non-loadbearing. Fire resistance values for identical load bearing and non-load bearing walls with plaster were found to be 1 hr 51 min to 3 hr 57 min. Load bearing wall failure was determined by temperature rise on the unexposed side [58]. See appendix for a preview of Ingberg [57] full scale standard fire tests.

Foster et al. [15] tested twelve walls of gravel aggregate concrete masonry units under standard fires, and three of these walls were also tested via hose-stream test. Five walls were made of calcareous aggregates (i.e., natural aggregates less susceptible to damage by fire), and the remaining seven walls were made with siliceous aggregates. Overall, non-load bearing 101 mm thick, and load bearing 203 mm and 305 mm walls were tested. Non-load bearing walls made of siliceous aggregates and thinner walls made (203 mm and 305 mm thick) of calcareous aggregates failed in 60 min or less under fire exposure. On the other hand, load-bearing walls with calcareous aggregates and of 203 mm and 305 mm thick achieved good fire resistance (exceeding 180 min), and those of 305 mm thick achieved 5 hr or more of fire resistance and were limited by the temperature rise on the unexposed surface. Foster et al. [60] also presented a parallel fire testing program on similar walls but made from lightweight aggregate concrete masonry units. These walls varied in thickness from 75 mm to 254 mm (with fire resistance ranging between 76 min to 420 min). All walls in the aforenoted tests were 4.8 m long and 2.4-3.3 m high.

In the 1970-1980s, Byrne [61] conducted fourteen fire tests on load-bearing masonry walls made from clay brick units. These walls had nominal dimensions of 90 mm thickness by 3 m width, and varying heights 2.1 m, 2.4 m, 2.7 m, and 3.0 m. The tested walls were loading with permissible loads levels (17.4%-125%) and subjected to standard fire conditions as per the AS 1530 provisions. Byrne [61] noted that walls having a slenderness ratio of 20 or less achieved a 60 min fire resistance rating. Byrne [61] also pointed out the importance of applied loading levels on fire resistance of masonry walls.

Between 1974 and 1986, Lawrence and Gnanakrishnan [62] also conducted a comprehensive test campaign on 146 full scale load-bearing walls and another 30 on nonloadbearing walls, with masonry units of different material types and thicknesses. The tested specimens were made of clay, concrete, and calcium-silicate masonry and had thicknesses that varied between 90 mm to 273 mm (with various levels of imposed loading from 0 to 125% of working load). Lawrence and Gnanakrishnan [62] noted that the relatively low thermal conductivity of masonry has led to developing high thermal gradient, which also generated differential expansion of the hot and cold faces of the tested walls. Overall, these researchers pointed out the discrepancy in fire response between identical specimens and acknowledged the need to evaluate the repeatability of fire

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resistance tests. Similar findings to that of Byrne [61] were also documented with regard to the negative impact of slenderness ratio on the fire resistance of masonry walls.

In 2006, Al Nahhas et al. [63] experimentally investigated the thermo-mechanical behavior of large-sized masonry walls. Walls of square cross-section measured at 2.82 × 2.82 m and 20 mm thick were tested for 6 hr under the ISO 834 standard fire. These walls were made up of hollow blocks and were loaded under the vertical load of 13 ton/m with fire exposure of 20ºC to 1200ºC (see Fig. 9). The used blocks resembled those adopted by the French industry and had a compressive strength of 4 MPa. The thermal behavior of masonry, found repetitious, was defined by Plateaus at 100ºC because of moisture evaporation. Lateral displacements variations as linear from 0 to 25 min and quasi-constant till 45 min were derived from observations during the fire tests. Thermal expansion causing vertical displacement followed a linear path from 0 to 30 min until 90 min following similar behavior as plateaus increasing the displacement after that [63].

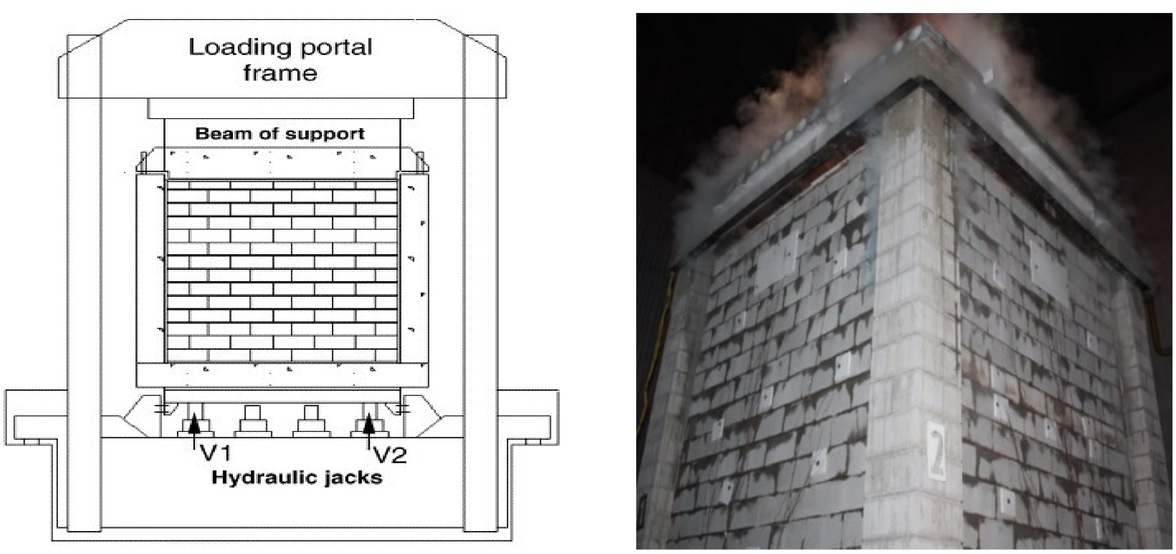

Fig. 9 Testing setup used by Al Nahhas et al. [63] (Left), Keelson [64], and Pope and Zalok [65] (Right) (Credit line: Elsevier, Applied Thermal Engineering, Resistance to fire of walls constituted by

hollow blocks: Experiments and thermal modeling, F. Al Nahhas, R. Ami Saada,G. Bonnet, P. Delmotte, January 1, 2007, License Number: 4954640866660)

Keelson [64] evaluated the parameters governing fire performance of concrete masonry with test setup involving 4 masonry walls of 2.8 m in width and 3.2 m height with three varying thicknesses of 100 mm, 150 mm, and 200 mm (see Fig. 9). Walls were subjected to standard fire exposure according to CAN/UCL S-101. Results of these tests noted the occurrence of large thermal bowing effects followed by thermal cracks and spalling. It is worth noting that Keelson [64] extended that of Pope and Zalok [65] within the same research group.

2.2.2 Medium (Half) Scale Testing (Wallettes)

The standard fire test methods state the methodology for evaluating fire resistance i.e., time at which specimen fails under standard fire conditions. Such full-scale tests are very expensive and may not be attainable in many cases since access to testing equipment and facilities can be limited. As such, a number of researchers have adopted modified testing methods that involve masonry walls of medium scale. These walls are often called *wallettes*.

In one study, Nguyen and Meftah [11] conducted experiments on 4 walls of varying masonry block thickness, block orientations, joint type, applied loads, and protection layers. These walls comprised of: one non-load bearing wall, one thick non-load bearing wall and 2 thick load bearing walls tested under different loads and insulation configurations and standard exposure according to ISO 834, as well as EN 1363 and EN 1365 provisions (see Fig. 10). This study noted two phases of heat transfer which were primarily governed by the thickness of wall and time required to evaporate moisture within masonry blocks as: the transmission phase and plateau phase. Overall,

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fire resistance of 60 to 240 min was observed depending upon the properties of walls in which thicker walls seem to perform better under fire conditions despite undergoing spalling [11].

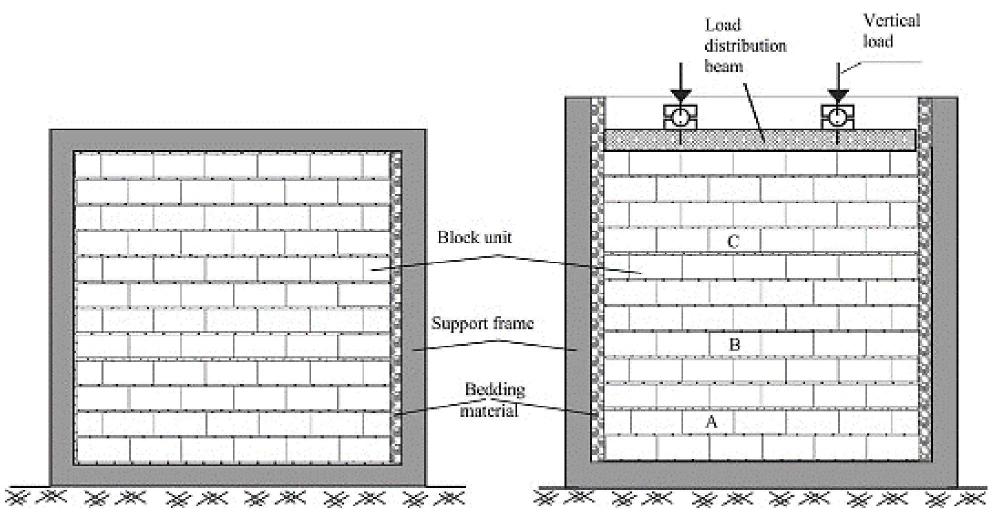

Fig. 10 Test setup: Non-load bearing wall (Left), Load bearing wall (Right) as undertaken by Nguyen and Meftah [11] (Credit line: Elsevier, Fire Safety Journal, Behavior of clay hollow-brick masonry walls during fire. Part 1: Experimental analysis, Thê-Duong Nguyen, Fekri Meftah, August 1, 2012, License Number: 4954620752967)

In an experimental research program at the University of Venice [45], the mechanical properties of clay brick masonry were measured by testing ten square specimens of 250 mm width and height under compression and elevated temperatures. These specimens were wallettes replicates of separating and non-separating walls as per RILEM specifications i.e., load bearing 25 mm thick separating wall, load bearing 38 mm thick separating wall, load bearing 25 mm thick non-separating wall and load bearing 38 mm thick non-separating wall (see Fig. 11). Those specimens were exposed to two temperature exposures with the same heating rate but with two different maximum temperatures of 300°C and 600°C attained at 1hr. The specimens subjected to 300°C were shown to be undamaged, and those exposed to 600°C underwent interfacial cracks and micro

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cracks. In general, +4% and -13% change in compressive strength with +10% and -7% change in stiffness of wallettes was observed for exposure temperatures of 300ºC and 600ºC, respectively.

Fig. 11 Wallettes specimens to be put to fire tests as per [45] (Credit line: Springer Nature, Experimental Mechanics, Experimental and Theoretical Investigation on Masonry after High Temperature Exposure, S. Russo et al., April 21, 2011, License Number: 4954640044417)

Lopes et al. [66,67] presented findings from an experimental investigation on masonry specimens consisting of three cell concrete blocks identical to those used in US and European constructions. This experimental program consists of six load bearing masonry specimens of 1 m height, 100 mm thick, and 1.4 m width built according to EN 1365-1 [68] and EN 1363-1 [69] (see Fig. 12). All specimens were tested under ISO 834 standard fire exposure until thermal or mechanical failure. Lopes et al. [66] documented temperature vertical displacement measurements as a function of fire exposure and reported that fire endurance of the tested masonry specimens at 1 hr (which seems to agree with some of the tabulated data obtained from Eurocode 6 and Australian code (AS 3700) for wall thickness of 70 to 100 mm [66]). Lopes et al. [66,67] also reported that the current values of Eurocode 6 can overestimate the insulation capacity and the loadbearing capacity of some of the tested walls.

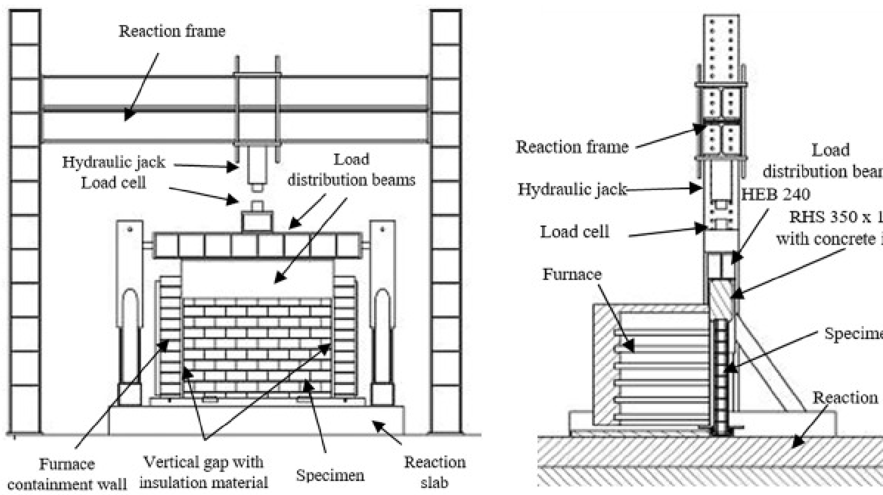

Fig. 12 Wallettes testing set-up by Lopes et al. [66,67] (Credit line: Elsevier, Engineering Structures, Experimental and numerical analysis on the structural fire behaviour of three-cell hollowed concrete masonry walls, Rafael G. Oliveira, João Paulo C. Rodrigues, João Miguel Pereira, Paulo B. Lourenço, Rúben F.R. Lopes, February 1, 2021, License Number: 5022851471141)

Al-Sibahy and Edwards [70] carried out fire tests on two different types of masonry wallettes (total dimensions of 670 × 685 × 100 mm) at moderately high temperatures ranging from 20°C to 400°C (see Fig. 13). The tested wallettes were produced using lightweight concrete blocks that incorporate expanded clay or recycled waste glass and metakaolin. These researchers noted a minimal reduction in the loadbearing capacity of both types of masonry wallettes under elevated high temperatures, estimated at 80-90% for the modified wallettes, same capacity for the reference specimens. However, the same researchers also noted that unloaded reference specimens tested at 400°C failed due to spalling, whereas the modified wallettes seemed to perform well.

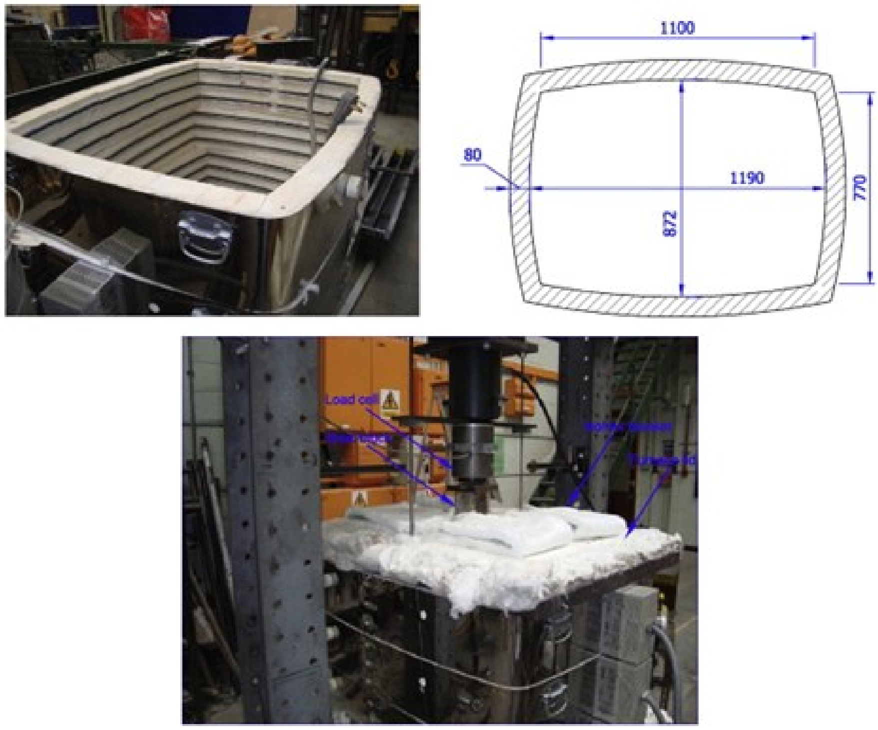

Fig. 13 Wallettes testing set-up by Al-Sibahy and Edwards [70] (Credit line: Elsevier, Engineering Structures, Behaviour of masonry wallettes made from a new concrete formulation under combination of axial compression load and heat exposure: Experimental approach, Adnan Al-Sibahy, Rodger Edwards, March 1, 2013, License Number: 5022841389494)

Bai et al. [43] studied thermal properties of hollow shale blocks by carrying out testing on square wallettes that were 1650 mm high and 365 mm wide. Hollow shale blocks with void ratio of 54% and compressive strength up to 10 MPa was used in the tested wallettes. Thermal properties were evaluated in a steady state manner using the guarding heat-box method according to Chinese codes (see Fig. 14). The heat transfer coefficient of used masonry blocks, observed from test, was 0.726 $W/m^2.K$ which was then compared with the values of different masonry materials tested by same test method. The capacity of the tested walls to preserve induced heat were shown to be 3.16 times that of traditional clay brick, 3.11 times of concrete block walls and 1.69 times of recycled concrete blocks [43].

(a) Bai et al. [43] (b) Madrid et al. [44]

Fig. 14 Variation of hot box method to evaluate thermal conductivity testing of wallettes
(Credit line: Elsevier, Construction and Building Materials, Thermal performance of sawdust and lime-mud concrete masonry units, Maggi Madrid, Aimar Orbe, Hélène Carré, Yokasta García, April 30, 2018, License Number: 4977531489322)

In a similar work, an extensive experimental study carried out by Madrid et al. [44], in which three walls made up of sawdust and lime-mud concrete masonry units' of 1190 mm in height, 1000 mm in height, and 190 mm thick were tested to investigate their thermal properties. The aim of the study was to determine the thermal conductivity and the thermal resistance of sawdust and lime-mud concrete masonry. The tests were conducted using a guarded hot box device (see Fig. 14), containing two remote chambers with hot and cold conditions on either side of each tested specimen to regulate the real-life conditions. The outcomes showed that 5% sawdust enhances the thermal resistance value by 18%, moreover, 5% sawdust and 15% lime mud improved the resistance by 11.1% [44]. In general, the authors would like to note that the body of available works dedicated to evaluating thermal properties of masonry is scarce (for both ambient and fire conditions).

3. Properties of Masonry at Elevated Temperatures

To echo our previously noted motivation behind this work, there continues to be very limited works in this area. As such, this section compiles temperature-dependent material models for common masonry materials with a particular emphasis on mechanical (compressive strength, tensile strength, and modulus) and thermal properties (thermal conductivity, and specific heart) *under elevated temperatures*. Please note that some tests conducted *residual* property testing, and these were described in more details in an earlier section (see Table 1).

Table List of reviewed tests together with their testing conditions

Test	Testing regime (Residual/ Hot Conditions)	Properties examined*
Ayala and Bailey [25]	Hot conditions	f_c
Khaliq and Bashir [29]	Hot conditions	f_c, f_t
Russo and Sciarretta [27]	Hot conditions	f_c
Andreini et al. [47]	Hot conditions	f_c
Eurocode 1996 [30]	Hot conditions	f_c, k, c
Russo et al. [45]	Hot conditions	f_c
Bosnjak et al. 2019 [42]	Residual Condition	f_c
Eurocode 2 [71]	Hot conditions	f_c
Xiao et al. [48]	Residual Condition	f_t
Nadjai et al. [35]	Residual Condition	f_t
Kodur and Sultan [72]	Hot conditions	k, c

* f_c: Compressive Strength, f_t: Tensile Strength, k: Thermal Conductivity, c: Specific Heat

Overall, thermal and mechanical properties of masonry degrade in response to physio-chemical changes triggered by the rise in temperature. It is due to this rise in temperature that cementitious materials undergo hydration reactions, thus, affecting the thermal and physical microstructure of masonry. Much of the discussion in literature notes the similarity between concrete and masonry [38]. For example, when the temperature increases beyond 100°C, moisture starts to evaporate. Then, between 100-110°C, Calcium Silicate Hydrate (CSH gel) experiences an endothermic reaction debonding the water molecules [73]. Above 300ºC, an exothermic reaction takes place, which introduces micro-cracks as effect of gas release [73,74]. At 530ºC, other endothermic reactions take place resulting in separation of Calcium Hydroxide ($Ca(OH)_2$) [75]. Above 600ºC, CSH gel decomposes further, and at 800ºC, a substantial loss in strength takes place [76]. In-depth discussion on the above can be found at the following references [24,29,38].

3.1 Compressive Strength (f_c)

The compressive strength for load bearing masonry components is a key property to trace at elevated temperatures since it governs the load bearing capacity of fire-exposed components. This property is generally determined by testing small-sized specimens via small scale tests and is then converted into a reduction factor. Reduction factors ($f_{c,200°C}/f_{c,25°C}$) reflect the change in this property at a target temperature (i.e., $f_{c,200°C}$) to that at ambient temperature ($f_{c,25°C}$). Owing to the lack of standard testing procedures, a variety of testing methods and specimen sizes were used by various researchers (as shown in an earlier section). Figure 15 presents a compilation of available trends depicting temperature-induced degradation in compressive strength reduction factors. The presented data shows a large scatter which can be attributed to the above two observations in addition to variations in raws used in fabrication, types of aggregates, heating history, moisture content etc. Still, one can also see three common trends in which: 1) the compressive strength continues to degrade with rising temperatures, 2) this degradation rapidly sets at temperatures higher than 600ºC, and 3) this degradation is slower in masonry than concrete.

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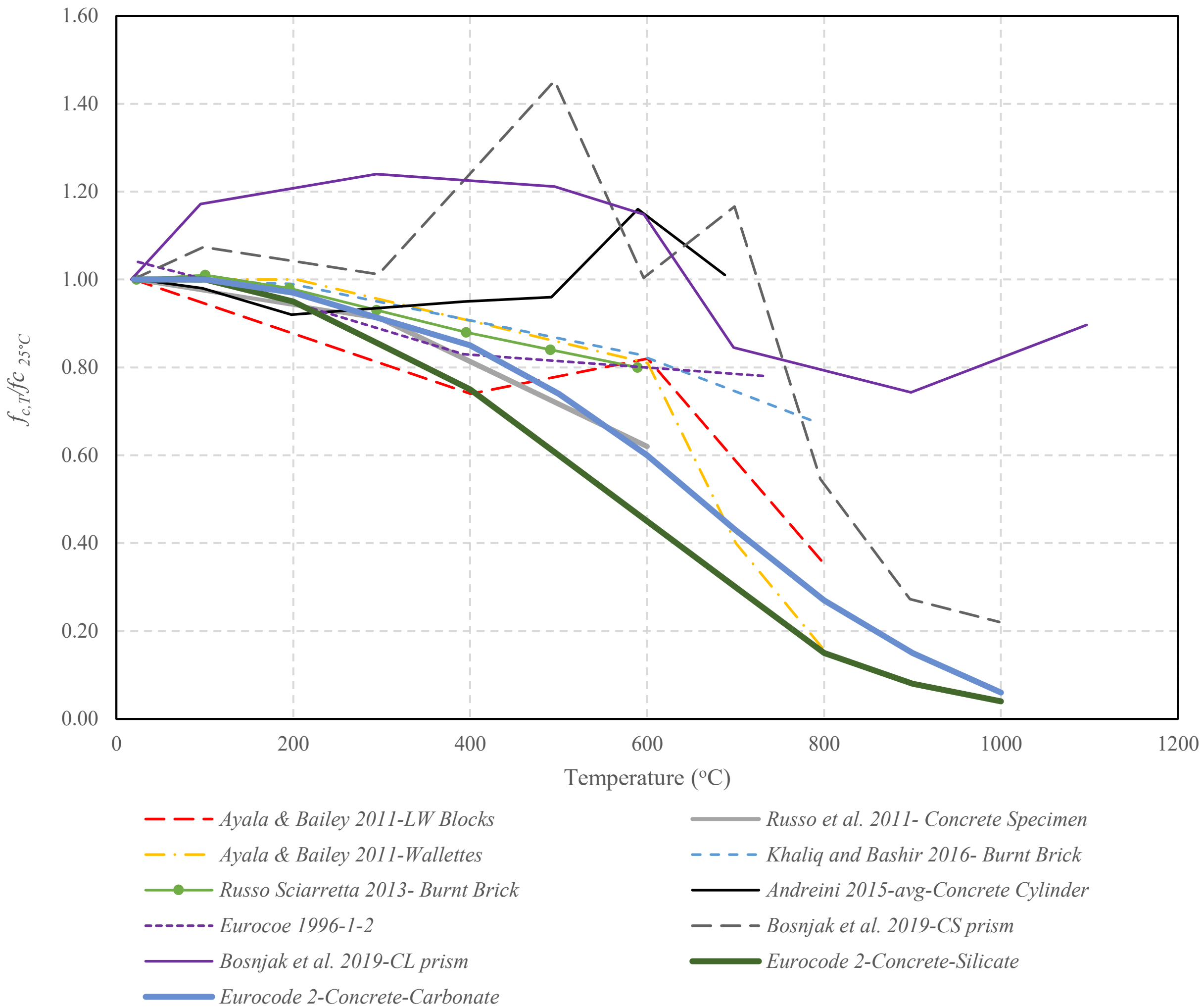

Fig. 15 Degradation in compressive strength of masonry under elevated temperatures (note: tests by Bosnjak et al. [42] were under residual conditions)

Khaliq and Bashir [29] reported how the compressive strength of burnt bricks reduces as temperature rises from 20°C to 800°C. This reduction was attributed to ongoing physical and chemical changes in microstructure of bricks as a result of mineralogical transformations and the formation of mechanical cracks due to thermal deformations with the rise in temperatures. With continuing mineralogical transformations and the development of mechanical cracks, the

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degradation in compressive strength also increases from 600°C to 800°C [29]. The reported decrease in compressive strength from 0-600°C was 20% to 27% at 800°C. Stress-strain curve and elastic modulus at every temperature were also derived [29]. Similarly, Russo and Sciarretta [27] findings agree with that reported by tests from Khaliq and Bashir [29]. The trend observed was accounted to the high number of silicates present in concrete used. Russo et al. [45] also tested clay brick wallettes and reported degradation in compressive strength. Their report shows a reduction in compressive strength at 300°C and 600°C was 9% and 38%, as a result of relatively chemical reactions triggered by the high content of silicate in clay bricks.

On the other hand, outcome of Andreini et al. [28] clearly shows a significant difference in trend in mechanical property degradation wherein degradation in this property remains stable up to 400°C. Beyond 400 °C, the compressive strength seems to recover and increase at 600°C. This difference in trend can be ascribed to the use of cylindrical specimens and a variety of ingredients (clay, aerated autoclaved concrete, lightweight concrete, hydraulic lime mortar etc.) involved in casting of specimens. Ayala et al. [25] proposed compressive strength reduction factors by testing wallettes made from lightweight concrete blocks. These specimens did not exhibit a significant reduction in compressive strength at 200°C (3%) and only 9% reduction was observed at 400°C. On the other hand, compressive strength decreases to 60% till 700°C and reaches to 83% at 800°C. This degradation can be credited to the deterioration of block material resulting from the reported premature melting of used aggregates at the temperature range of 700-800°C. In this testing program, the proposed compressive strength reduction model for tested blocks showed 65%

reduction in initial strength at 800°C. This higher value of residual strength can be associated with the excellent performance of lightweight particle properties under elevated temperatures [25].

Bosnjak et al. [42] derived the residual compressive strength values for calcium silicate (CS) and clay (CL) bricks. According to this study, calcium silicate strength significantly hikes from 300°C but abruptly drops to 30% after temperature crosses 700°C. This change can be in relation with the volumetric changes siliceous sand goes through, C-S-H gel decomposition, and development of cracks between C-S-H phases and sand particles. In the same study, testing on CS brick prisms showed an increase in compressive strength during 300-700°C and a significantly lower value (80% reduction) above this temperature krange. CL bricks prisms exhibited less reduction as compared to CS bricks at the residual conditions. Figure 15 also shows compressive strength reduction factors with respect to exposure time given by Eurocode 6 [77]. It is interesting to note that these factors do not rapidly degrade post 600°C.

3.2 Tensile Strength (f_t)

The tensile strength *(f_t)* property is often conservatively neglected in ambient temperature design due to its low magnitude. However, this property turns essential under fire conditions since it can govern the magnitude of spalling and thermally-induced cracks [65]. Unfortunately, very few researchers have reported testing this property under elevated temperatures. In a similar fashion to the compressive strength, the tensile strength of masonry material also generally degrades with the rise in temperature as credited to shrinkage, loss of moisture, formation, growth and merging of cracks at elevated temperatures [29].

In one study, Kahliq and Bashir [29] presented results of splitting tensile strength test on burnt masonry bricks. Figure 16 shows a general trend indicating that this tensile strength property remains virtually stable up to 200ºC, after which is starts to linearly degrade till reaching 800ºC. In a similar work, Xiao et al. [48] determined the tensile strength of recycled concrete aggregate blocksand noted only 2% loss observed at 300ºC. After this temperature, tensile strength decreases drastically, and only 50% of the tensile strength is retained at 500ºC, followed by 8% at 800ºC. Replacing sand by clay bricks was observed to have a positive effect on tensile strength property because of better binding properties of clay [48]. Nadjai et al.'s [35] outcomes of their tests seem to agree with that reported by Xiao et al. [48], showing a gradual decrease till 400ºC and an accelerated degradation at 800ºC [35].

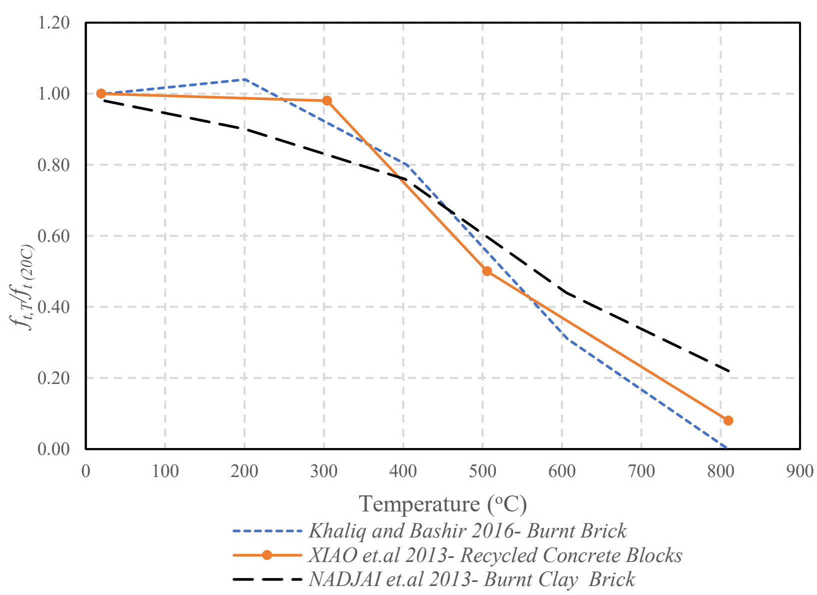

Fig. 16 Degradation in tensile strength of masonry under elevated temperatures

3.3 Modulus of Elasticity (E)

The modulus of elasticity (*E*) refers to the ability of a material to resist deformation. The degradation in modulus of elasticity reflects upon the temperature-induced damages arising in masonry, such as physio-chemical changes, micro-cracking, straining etc., as a function of rising temperatures. In general, the modulus of elasticity is evaluated as tangent modulus (or as a percentage 30% and 67% of compressive strength) obtained from compressive stress-strain curves at elevated temperatures. Figure 17 depicts data collected by various researchers, which shows a general trend of decrease with rise in temperature. The same figure also depicts the degradation of modulus of elasticity of concrete.

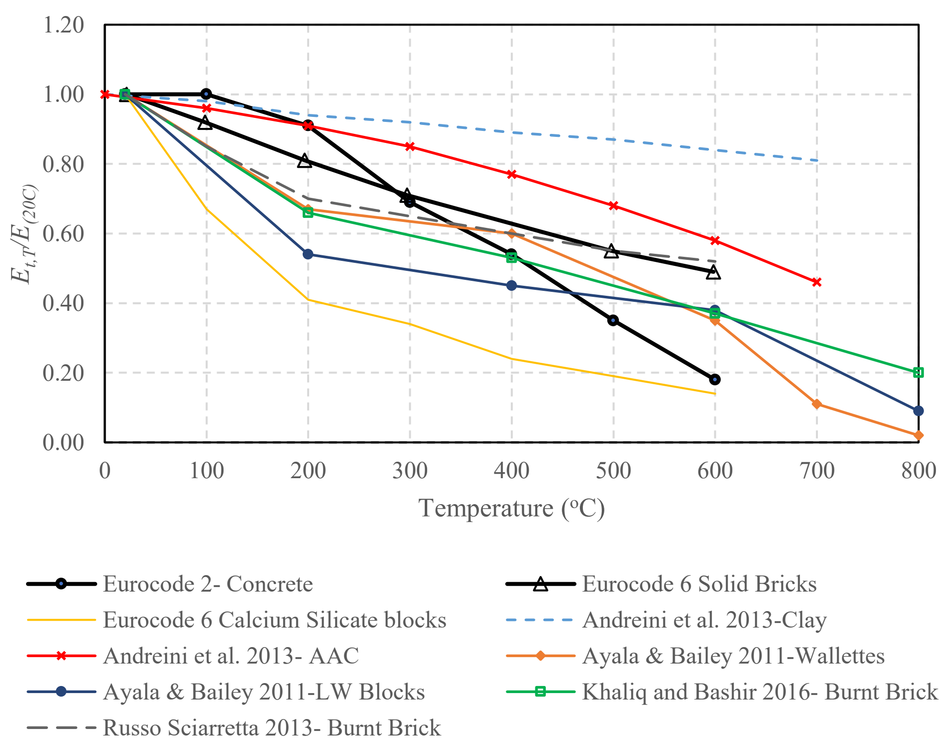

Fig. 17 Degradation in modulus of masonry under elevated temperatures

As per the results of tests conducted by Kahliq and Bashir [29] on burnt bricks under elevated temperatures, the elastic modulus significantly degrades from 20°C to 800°C but follows a slight gradual decrease till 200°C. At 400°C, this reduction reaches 50% and then linearly increases till 800°C [29]. Kahliq and Bashir [29] also noted that the overall trend of degradation of modulus of elasticity follows the same pattern as normal strength and high strength concretes. Test results obtained by Kahliq and Bashir [29] were on average 9.3% lower than that of listed by Eurocode 6 [77]. It is worth noting that the test results were 6.2% higher than results from Russo and Sciarretta [27], who noted reduction of 15% and 1% was observed at 300°C and 600°C, respectively. Andreini et al. [28] show a remarkably different and lesser trend in the degradation of modulus of elasticity (which could be attributed to their tests being conducted on cylindrical specimens and varying heating history) [28]. In Ayala et al. [28], the modulus property obtained were relatively smaller (i.e., lesser) when compared to those of normal weight concrete or that by other researchers. In general, the modulus of elasticity for both lightweight concrete blocks and wallettes diminished till 800°C, where reduction was 92% and 98%. This can be credited to higher volume of aggregates in wallettes which induce less stiffness as compared to normal concrete. The slightly better behavior of blocks can be attributed to the greater area exposed to temperature in case of wallettes [25].

3.4 Thermal Properties (k, c)

The thermal properties generally demonstrate the amount of energy required to heat a component and govern the distribution of temperature within a component. While the thermal conductivity (*k*) refers to the ability of a material to conduct heat, the specific heat (*c*) represents the amount of energy needed to raise the temperature by one unit amount. It is commonly accepted that masonry and concrete have comparable thermal properties due to the similarities between constituent materials [38,63] – especially since experimental data on thermal properties of masonry materials in particular is limited and scarce. Overall, the thermal behavior of masonry is primarily related to the presence of voids in micro-structure as well as to the thermal properties of aggregates, and raws used [33]. Figure 18 shows that the thermal conductivity decreases with a rise in temperature as a result of an increase in voids due to evaporation of moisture content and dehydration of cement paste [25]. The specific heat remains somewhat stable during elevated temperature and notably rises around 700^{o}C.

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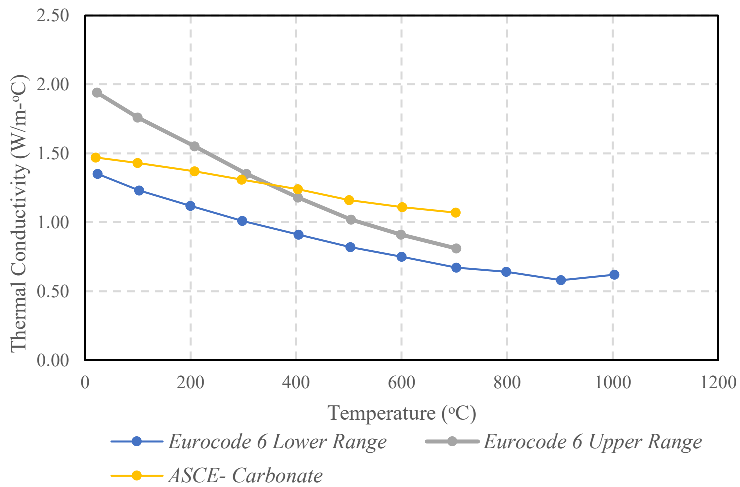
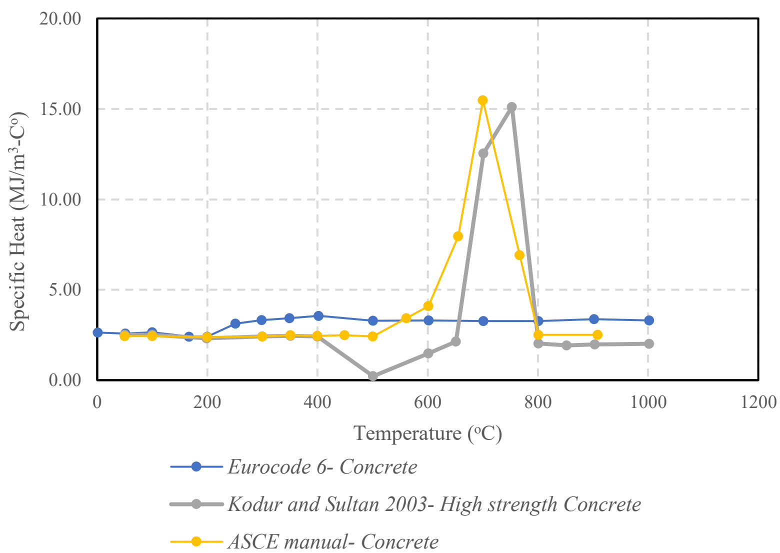


(a) Thermal conductivity



(b) Specific heat

Fig. 18 Variation in thermal properties of concrete under elevated temperatures

It is worth noting that a few works reported the thermal characteristics and properties of masonry and masonry-like materials but at ambient temperature [43,44,63]. For example, Bai et al. [43] stated that the experimental heat transfer coefficient of hollow shale block walls is 0.726 W/m^2K, which was said to meet the requirements of Chinese design codes. Madrid et al. [44] examined the effect of sawdust on traditional masonry and noted that the addition of 5% sawdust in block mixes improved their thermal resistance by 18.5%. Furthermore, 5% sawdust and 15% lime mud showed 11.1% increment in the same quantity. The improvement in thermal resistance was credited to the thermal conductivity of sawdust (approximately 0.13 W/m.K) which provides resistance to thermal flow within blocks [44]. Al Nahhas et al. [63] measured thermal properties of hollow blocks and reported specific heat and thermal conductivity of 900 J/Kg.K and 2 W/m^2, respectively. Zhu et al. [78] stated that the heat transfer coefficient of recycled concrete blocks has an average value of 0.93 W/m^2.K.

4. Challenges and Future Works

The above review shows that the amount of works undertaken to investigate the properties of masonry under elevated temperatures is limited (from quantity and comprehensiveness points of view). The present review also highlights the lack of standardized testing procedures which have led researchers to design individualized testing methods that are naturally suited to the availability of equipment and testing facilities. In fact, currently available standard test methods, such as ASTM E119 in USA [52], ISO 834 in Europe [23,55], AS 1530.3 in Australia [79], only contain provisions for fire testing for full-scale masonry walls. At the time of this manuscript, the authors were not able to identify standard testing methods available for determining high temperature material level properties of masonry. Advancements in this domain are not only warranted but are also needed [27,33,80–83].

Currently, available standard testing methods for masonry illustrate procedures and specifications that are applicable for ambient temperature conditions. On one side, the behavior of masonry under elevated temperatures is highly sensitive to testing set-ups (e.g., heating equipment, rate of heating, rate of cooling, temperature range, and type of testing specimen, geometry and size etc.). These noted parameters are not influential to triggering chemical reactions and phase changes within masonry during testing but also govern the state of masonry post-heating conditions (i.e., in the aftermath of fire). This brings in an important notion of the need for evaluating the residual properties of masonry post heating conditions which can also be influenced by the cooling rate (fast vs slow), method of cooling (air vs. water) etc. [36,38,84,85]. Additional works are indeed required for examining the influence of elevated temperatures and testing regimes on the behavior of mortar materials [42,45].

While the presented review noted a lack of testing methods for masonry, on the opposite, there currently exist some methods for elevated temperature testing of cementitious materials, and these are only specified to use for concrete [86–88]. Whether these methods can be directly applicable to masonry or in need of tweaking is worth of examination. Despite of the proper extensibility of such tests to masonry, our review also raises another common observation duly noted in this domain. In this view, adopting different testing methods is likely to yield results that may not be easily compared and as such would complicate the outcomes of fire resistance analysis to a large extent [89–91]. This further complicates fire safety design, where engineers and practitioners aim to achieve a safe and optimal design.

Whether via traditional methods or advanced simulations, the lack of reliable material properties can result in unsafe and uneconomical design (especially since these material properties are used as input to numerical and software simulations to predict the fire response of masonry assemblies) [92,93]. Hence, the availability of standard testing methods for measuring properties can improve the quality of results and can help in developing more reliable design manuals for masonry. In addition to such methods, there is also a need for reliable equipment and instrumentation that can withstand severe and repeated elevated temperatures [93–96]. Along the same line, proper protocols for documentation and peer review results of tests. Furthermore, to increase the repeatability fire tests, duplicated specimens are advised to be conducted [97,98].

5. Conclusions

This paper reviews a collection of experimental methods conducted on masonry material and components over the past few decades to evaluate the high temperature mechanical and thermal properties of common masonry materials often used in construction applications. In addition, this review also covers generalized fire test procedures (full scale, half scale, and small scale) adopted by researchers according to examine the response of masonry elements (primarily walls under fire conditions. Overall, the lack of standard testing procedures (with regard to material properties of masonry) has led researchers to either; develop individual test procedures or extend test procedures used for concrete to masonry. The following list of inferences can also be drawn from this study:

- Available testing methods available in current standards lack guidance towards the testing of masonry materials at elevated temperatures. As such, there is an urgent need to develop standardized testing methods to evaluate the mechanical and thermal properties of masonry at elevated temperatures.
- The lack of standardized testing procedure and reliable testing equipment have led to the existence of a large scatter in reported properties and thermal/mechanical response of masonry components.

- There is significant variation in the data on thermal and mechanical properties of masonry as documented by the open literature. This can be attributed to the fact that researchers followed different testing procedures and methods.
- The variation in the available data could be overcome by adopting modern techniques and statistical and mathematical methods to develop more consistent temperature dependent property models. We invite interested researchers to explore this area.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix

Table A1: *Experimental Results reported by Harmathy* [46]

Run No.	Specimen	Nature of Run	Volumetric Moisture Content (cu.ft./cu.ft.)	Fire Endurance (hr)		Reference Unit	Fractional gain in fire endurance
				Containing moisture	Dry		
1	CS-3 5/8-100-1	FR	0.081	2.35	-	8	4.72
2	CS-3 5/8-100-1	RR	0	-	1.43	-	-
3	CS-3 5/8-100-1	RR	0.0603	2	-	2	6.61
4	CS-3 5/8-100-1	RR	0.0372	1.81	-	2	7.14
5	CS-3 5/8-100-1	RR	0.1156	2.49	-	2	6.41
6	CS-3 5/8-100-2	FR	0.0293	2.07	-	8	7.5
7	CS-3 5/8-100-2	RR	0	-	1.5	-	-
8	CS-3 5/8-100-3	FR	0	-	1.7	-	-
9	CS-3 5/8-100-4	FR	0.1054	2.86	-	8	6.47
10	CS-3 5/8-100-4	RR	0.123	2.53	-	7	5.58
11	CS-3 5/8-100-4	RR	0.065	2.15	-	7	6.66
12	CS-3 5/8-100-4	RR	0.208	3.05	-	7	4.97
13	CH-5 5/8-89.1-1	FR	0.0516	4.45	-	17	5.69
14	CH-5 5/8-89.1-1	RR	0	-	3.03	-	-
15	CH-5 5/8-89.1-1	RR	0.0943	4.83	-	14	6.3

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16	CH-5 5/8-89.1-2	FR	0.0185	3.73	-	17	4.56
17	CH-5 5/8-89.1-3	FR	0	-	3.44	-	-
18	CH-5 5/8-89.1-4	FR	0.142	5.44	-	17	4.09
19	CH-5 5/8-68.8-1	FR	0.0712	2.23	-	26	4.71
20	CH-5 5/8-68.8-1	RR	0	-	1.54	-	-
21	CH-5 5/8-68.8-1	RR	0.128	2.63	-	20	5.53
22	CH-5 5/8-68.8-1	RR	0.0543	1.98	-	20	5.26
23	CH-5 5/8-68.8-2	FR	0.0134	1.79	-	26	5.37
24	CH-5 5/8-68.8-2	RR	0.0034	1.53	-	25	-
25	CH-5 5/8-68.8-2	RR	0	-	1.58	-	-
26	CH-5 5/8-68.8-3	FR	0	-	1.67	-	-
27	CH-5 5/8-68.8-4	FR	0.1185	2.73	-	26	5.36
28	CH-5 5/8-68.8-4	RR	0.1044	2.38	-	25	4.85
29	CH-5 5/8-68.8-4	RR	0.048	2.07	-	25	6.46
30	BS-2 1/2-100-1	FR	0	-	0.64	-	-
31	BS-2 1/2-100-1	RR	0.168	1.03	-	30	3.63
32	BS-2 1/2-100-1	FR	0.0992	0.88	-	30	3.78
33	BS-2 1/2-100-1	RR	0.211	1.27	-	30	4.67
34	BS-4-100	FR	0	-	1.49	-	-
35	BS-4-100	RR	0.136	2.32	-	34	4.1

36	BS-4-100	RR	0.0582	1.78	-	34	3.34
37	BS-4-100	RR	0.209	2.65	-	34	3.72
38	BS-6-100	FR	0	-	2.78	-	-
39	BS-6-100	RR	0.1785	4.71	-	38	3.89
40	BS-6-100	RR	0.0396	3.26	-	38	4.36
41	BS-6-100	RR	0.0984	4.33	-	38	5.67
42	BS-6-100	RR	0.218	5.03	-	38	3.71
43	FH-8 1/4-46.7	FR	0	-	1.53	-	-
44	FH-8 1/4-46.7	RR	0.0183	1.73	-	43	7.14
45	FH-8 1/4-46.7	RR	0.0327	1.91	-	43	7.8
46	FH-8 1/4-46.7	RR	0.0547	2.08	-	43	6.57
47	FH-8 1/4-46.7	RR	0.1005	2.73	-	43	7.8

*C=concrete, 17.5% hydrated portland cement and 82.5% expanded shale; B=brown clay brick; F=insulating fire brick group 23; S = solid; H = hollow. The first number is the overall thickness of the wall, the second is percentage of specimen volume that is solid, and the third (if used) identifies specimens within a particular group.

*FR-First Run, RR- Repeat run

Table A2: Experimental Results from Russo et al. [45]

Compressive Tests on Bricks		
Sample	Dimensions (mm)	f_{bc} (N/mm^2)
B-NF-1	48×48×49	19.69
B-NF-2	45×45×45	18.58
B-NF-3	47×47×47	19.25
average NF	-	19.17
standard deviation NF	-	0.456
relative standard deviation NF	-	0.024
B-F3-1	53×52.5×52.5	16.73
B-F3-2	54×53×53	18.32
B-F3-3	54×54×53	18.44
B-F3-4	54×55×53	16.84
B-F3-5	54×55×52.5	16.64
average F3	-	17.39
standard deviation F3	-	0.8
relative standard deviation F3	-	0.046
B-F6-1	54×54×54.5	13.76
B-F6-2	54×55×55	12.48
B-F6-3	55×55×54.5	12.02
B-F6-4	56×54×56	11.87
B-F6-5	53×54×55	9.67
average F6	-	11.96
standard deviation F6	-	1.324
relative standard deviation F6	-	0.1107

*NF- ambient condition, F3- 300ºC exposure, F6-600ºC exposure

Table A3: Experimental Results derived by Xiao et al. [48]

Notation	Compressive Strength at different temperatures						
	20ºC	300ºC		500ºC		800ºC	
	MPa	MPa	C_{300}/C_{20} (%)	MPa	C_{500}/C_{20} (%)	MPa	C_{800}/C_{20} (%)
Series 1							
S1-0	19.3	29.9	55	26.3	36	9.3	-52
S1-25	23.9	41.4	73	31.5	32	11.8	-51
S1-50	21.9	40.4	85	31.4	44	12.8	-42
S1-75	17.7	35.4	100	25.9	47	11.8	-33
S1-100	16.9	33.9	101	25.1	49	12.3	-27
Series 2							
S2-0	16	25.9	62	22.5	41	9.9	-38
S2-25	17.6	31.6	80	25.1	43	11.6	-34
S2-50	19.2	33.5	75	30.6	60	13	-32
S2-75	18.9	33.8	79	32.3	71	12.8	-32
S2-100	14.9	28.8	93	24.9	67	11.1	-25
Series 3							
S3-0	29.8	35	17	31.4	5	14.4	-52
S3-25	21.9	40.4	85	31.4	44	12.8	-42
S3-50	19.2	33.5	75	30.6	60	13	-32
S3-75	17.3	36.9	113	32.5	88	15.4	-11
S3-100	16.3	35.9	121	31.3	92	14.8	-9

*Series 1 and 2 contains crushed clay brick for sand replacement at 0%, 25%, 50%, 75% and 100% representing 0, 25, 50, 50, 75 and 100 corresponding to specimen number. In case of Series 3, 0, 25, 50, 50, 75 and 100 indicated the percentage replacement coarse aggregate as crushed clay aggregate.

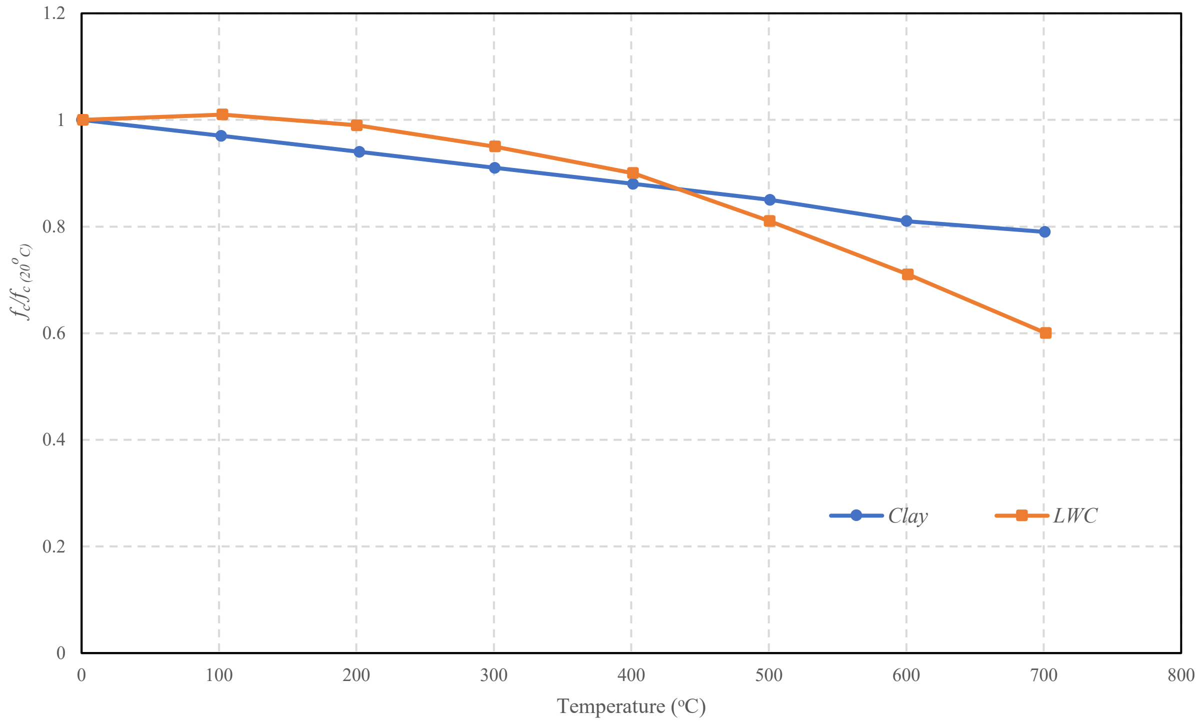

Figure A1: Reduction factors for Clay and Lightweight concrete (LWC) given by Andreini et al. [26,28]

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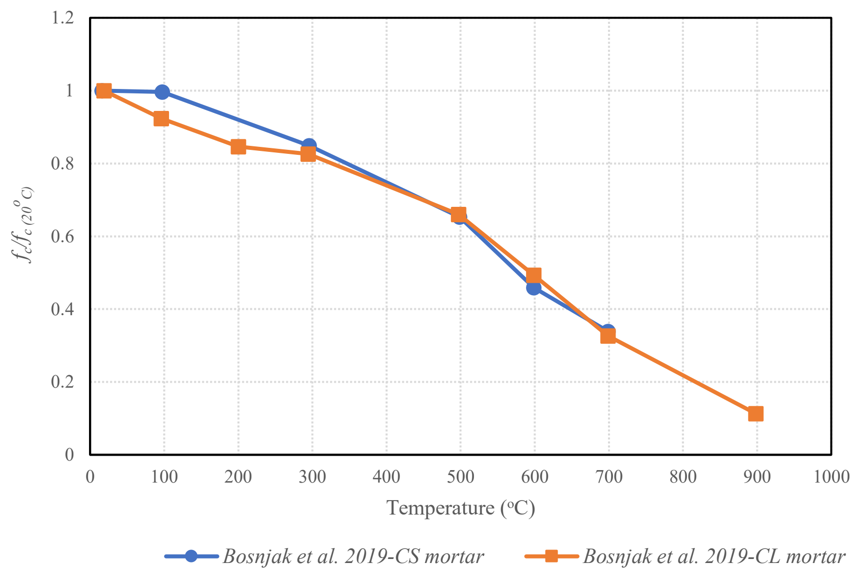

Compressive strength reduction factors of mortar with respect to temperature

Figure A2: Compressive strength reduction factors for mortar from Bosnjak et al. [42]

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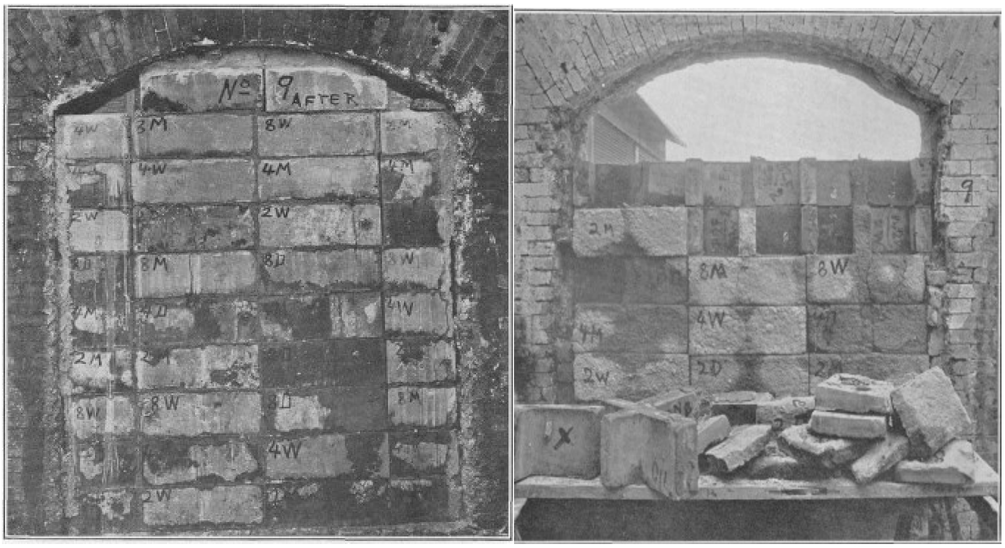
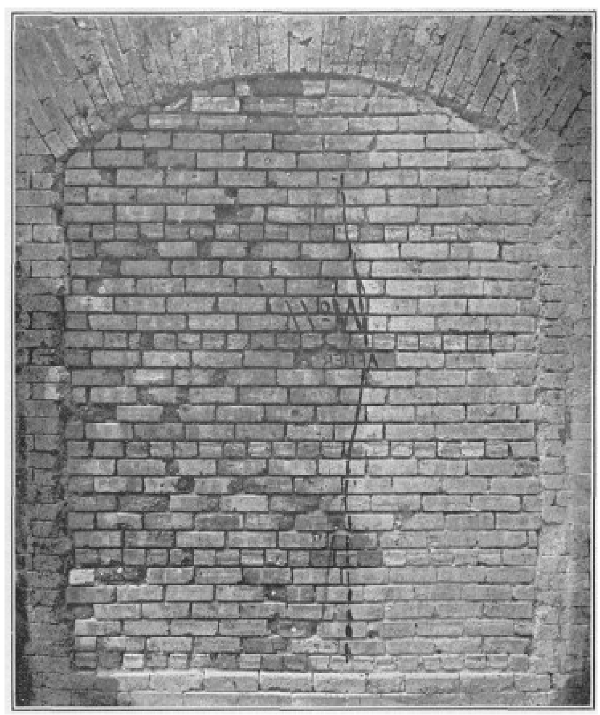
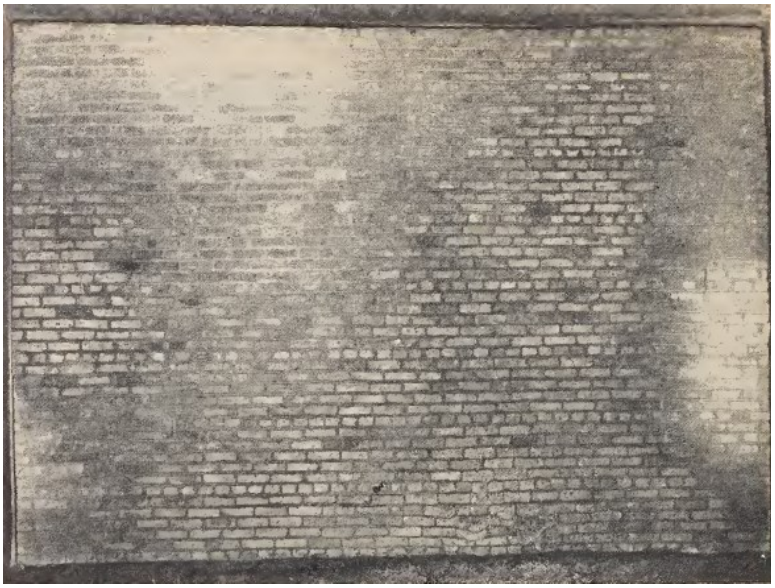


Face of Panel 9, Cement mortar building blocks after fire test, quenching (Left) and during dismantling (Right)



Face of Panel 11, Common bricks after fire test and quenching.

Figure A3: Experimental test photos of walls after fire exposure, quenching (Hose Stream) and during dismantling by Humphrey et al. [56] (Republished courtesy of the National Institute of Standards and Technology.)



Fire exposed face of 205 mm concrete brick wall after 6 hr fire test

Unexposed face of 305 mm thick clay brick wall after fire endurance test

Figure A4: Experimental test photos of walls after fire test by Ingberg et al. [57] (Republished courtesy of the National Institute of Standards and Technology.)