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Deriving Generalized Temperature-Dependent Material Models for Masonry Through Fire Tests and Machine Learning

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DERIVING GENERALIZED TEMPERATURE-DEPENDENT MATERIAL MODELS FOR MASONRY THROUGH FIRE TESTS AND MACHINE LEARNING

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ABSTRACT

Masonry is one of the oldest and commonly used building materials in the construction industry. Among a variety of benefits, masonry provides low-cost construction, fire, and weather protection as well as thermal and sound insulation. In addition, masonry has superior material properties at elevated temperatures which is reflected by its slow degradation of its mechanical and thermal properties. Literature shows that we do not have a uniform material model that describes the mechanical degradation of masonry under fire conditions. As such, this limits the use of masonry in fire-based performance design of masonry structures. To bridge this knowledge gap, this thesis reviews regionally adopted fire testing methods on masonry and then presents findings from a fire experimental program aimed to explore the influence of elevated temperatures on the mechanical performance of concrete masonry units (CMUs). Our tests include heating and post heating evaluation of the compressive strength of CMUs exposed to realistic fire conditions. Then, this thesis delivers a methodology to derive generalized temperature-dependent material models for CMUs using statistical and Bayesian methods, as well as machine learning (by means of artificial neural networks). Finally, this work articulates limitations and research needs to be tackled in the near future.

DEDICATION

To all the lives lost and all of us still reeling
through the COVID-19 pandemic.

AKNOWLEDGEMENTS

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INTRODUCTION

1.1 Motivation

Structural Engineering involves the analysis and design of the structures for different types of loads applied by manmade and natural hazards. The natural hazards mainly include Wind, Earthquake and Fire. Although, current standards include different design guidelines and specifications for Earthquake and Wind exposures, the fire design guidelines are very scarce.

To further showcase the problem of fire in USA, the NFPA (National Fire Protection Association) reported in 2019 that, local fire departments have encountered approximately 1.3 million fires. These fires have led to an estimated property loss of $14.8 billion as direct property damage. What is more concerning is that a total of 3704 civilian deaths and 16,600 civilian injuries were caused by these fires? Furthermore, fire departments in US responds to fire somewhere every 24 seconds in 2019 from which 1/3rd occurred in or on structures. For every 2 hour and 22 minutes a civilian is fatally injured by fire. From all fire incidents, 481,500 was structural fire (37%). Structural fire contributes to 80% of the total civilian deaths, 84% of total civilian injuries and 83% which is $12.3 billion in direct property damage.

Structural fire engineering has been a lively branch of Structural Engineering, especially in the past few decades. After 9/11 attacks on World Trade Centre in US, more focus in the study of the behavior of different construction materials under fire exposure has been carried out [1–4]. This has resulted into a very extensive research on the concrete and steel fire behavior. Only recently, this focus has been broadening to Masonry and Timber [5–9].

Under fire, the degradation of mechanical and thermal properties occurs mainly because of physio-chemical changes in constituent materials. In case of masonry, a wide variety of constituent materials like Clay, Lightweight concrete, Calcium Silicate Concrete, different size and shapes of the units and lack of knowledge of fire behavior, makes this more challenging [10,11]. These factors also cause issues in experimental and numerical studies aimed to understand the behavior of masonry under fire.

Although, standards and guidelines to design masonry for earthquake is readily available. But the data on design of masonry under fire is very scarce [12–15]. The Eurocodes and ASCE manuals on structures gives guidelines to design bearing and compartment masonry walls. However, these guidelines are mainly deduced from series of experimental research programs and analytical studies conducted by various researchers that span 1980s-1990s. These experimental research programs are based on fire testing procedures described for measuring strength degradation and deformation with respect to time under standard exposures (i.e., ASTM E119 [16], ISO834 [17]). These tests are conducted till violation of design criteria (Integrity, Insulation and Load bearing capacity). Nevertheless, these tests are very expensive, time consuming, require certain equipment with appropriate setup and high expertise which make these not feasible in every condition. Also, these studies are greatly dependent on parameters like residual material properties, temperature attained and block humidity, among others [13,18,19].

Many researchers have carried experimental testing of masonry and materials to investigate hot and residual mechanical and thermal properties which involves mainly full-scale masonry specimens (primarily on walls/roofs) or small scale wallettes under standard fire tests. To study the properties of masonry under elevated temperatures, small scale (material level) tests are usually adopted. The only available material model in standard format is that of the Eurocode 6 [20]. In series of experimental tests, Eurocode 6 also provides general guidance on degradation of mechanical properties of masonry as a function of temperature rise. It is worth noting that this model was derived from a result of specific testing program and has not been amended nor revised for over 20 years. Hence, new advancements into this domain are very necessary.

Derivation of new reliable material model offers a uniform approach for modern fire. Furthermore, these material models can allow us to design new masonry structure, and help analyzing the existing fire exposed structure (i.e., post fire inspection). Property models are also a basic and most important input for using advanced simulation and modeling methods (e.g., finite element (FE), finite difference (FD), artificial intelligence (AI) etc.) in assessing masonry structures under fire conditions [7,17–19,25,29,30]. A typical numerical model consists of a fire model, a heat transfer model, and a mechanical model. For these models, temperature dependent material properties are the input to correctly predict the changes in properties properly and accurately.

These models are integral part of the analysis to determine the thermal response, time-deflection response and stresses generated within the masonry. Hence, the accuracy and the predictability of results and simulations is integrally depending on models. Owing to these challenges, it is essential to have more reliable modern material model [23]. However, the current research and open literature lacks the standardize material testing procedure under elevated temperatures. This hamstring the use of masonry in structural applications and limits the use of masonry in new construction via perspective and performance-based design approaches [4,24,25].

In the available literature [12,26–29], there are few works available which indicates following common observations: 1) 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 observations are simplifications adopted by the fire community to bridge the gap of lack of design guidelines, incomplete knowledge about masonry fire behavior and absence of standardize material testing procedure. However, there is significant variability available in the existing data. Deriving new temperature dependent property model, there is a need to study and overcome this variability. This can be done using different statistical and Artificial intelligence methods.

The goal of this research is to collect existing data on fire testing of masonry, determine the reduction of compressive strength of concrete blocks heated at elevated temperatures and post heating conditions and use the existing and experimental study data to predict the generalize temperature dependent masonry material model using statistical, Bayesian and Artificial Neural Network (ANN) and verifying these outcomes by results obtained from the Statistical Method.

1.2 Objective of the research

This research involves the experimental study of mechanical properties of CMUs at elevated temperatures and derivation of generalize temperature dependent property model. The objectives are as follows:

1) Review of the different testing procedures adopted by various researchers and collection of the results obtained was carried out.
2) Carry out an experimental program to investigate the mechanical properties industry standard concrete blocks under temperature of 20ºC, 200ºC, 400ºC, 600ºC, 700ºC and 800ºC at Unstressed Hot state conditions.
3) Perform fire tests to investigate the mechanical properties industry standard concrete blocks under temperature of 20ºC, 200ºC, 400ºC, 600ºC, 700ºC and 800ºC at Unstressed Residual conditions.
4) Apply Statistical and Bayesian methods to analyze and reduce the variability of existing data points and data points obtained from experimental study.
5) Apply Artificial Neural Network was used to analyze and reduce the variability of all the existing data points and data points obtained. Use of ANN to predict the generalize temperature dependent property model for masonry.

1.3 Outlines

Chapter 1 presents the introduction to the research program executed for this thesis. This chapter explains the objective of the research and outlines the different chapters in this thesis.

Chapter 2 describes a review of relevant research published and available in the open literature. Specially, this chapter reviews the variety of different self-established testing procedures used, different types of constituent materials used, and types of sizes used for masonry block specimen. This chapter also includes summary of all the results reported by all the researchers.

Chapter 3 presents a description of the experimental plan, testing procedures, and specifications of the equipment used.

Chapter 4 outlines the results from the experimental studies on blocks subjected to ambient and elevated temperatures at hot state and residual tests. This chapters also reports experimental findings in terms of reduction in compressive strengths.

Chapter 5 focuses on the analysis of the test data and existing data using Statistical, Bayesian and Artificial intelligence methods to predict the temperature dependent material model.

Chapter 6 represents experimental limitations and future scope of this work. It also states all the important inferences with the final temperature dependent property model.

2. LITERATURE REVIEW

This chapter reviews commonly used fire testing methods on masonry elements and materials, as used by notable works. Then, this chapter 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.

2.1 Material Level/ Small Scale Testing

The mechanical and thermal properties of masonry have significant effect on the overall behavior of the masonry when exposed to fire. These are properties are generally dependent on mix design constituents viz., types of aggregate, binder type, water content, etc. As mentioned in Introduction section, earlier done experimental studies on masonry with results are [10,25,30–38]. Following subsection describes the small sized specimen, block prism and single block testing and obtained properties.

Generally, two types of fire test are adopted [23,37]:

a) Steady State test: In this set-up, a specimen to be tested is heated first without application of any mechanical load. The load is applied when the predetermined temperature is reached.
b) Transient State test: In this testing, the specimen is applied with load of predetermined level prior to heating and then it is heated till failure occurs.

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) [39,40].

In a notable study executed in 1960s, Harmathy [34] 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 under fire exposure. Effect of moisture content on fire performance of masonry was evaluated. Harmathy used an electric furnace of a square cross section of 0.76m×0.76m to conduct mention testing – see Fig. 1. Prior to testing all the specimens were dried in over for 6 hr under 105^{o}C. Before the fire test, the oven dry specimens were exposed to steam for predetermine amount of time to get desired moisture content values which varied between 0-0.21 percent by volume. 12 of the specimens were subjected to repetitive fire exposure and 35 specimens were tested once. This testing program have concluded 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"* [34], 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.

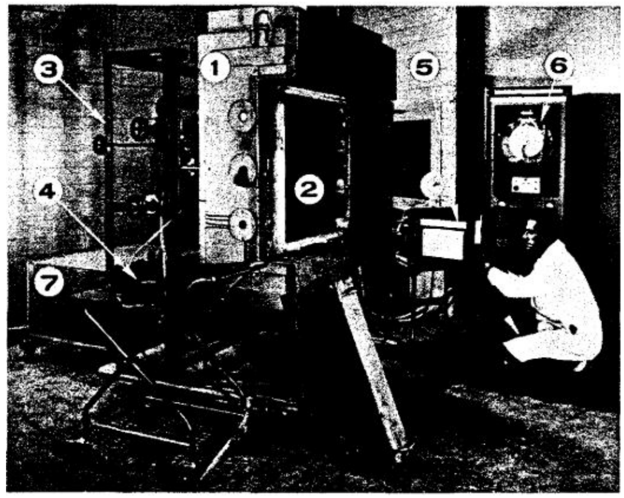

Figure 1 Fire test assembly used in Harmathy.

(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 [34]

In the series of extensive experimental studies, Andreini et al. [41] investigated the mechanical properties of masonry material by testing 200 cylindrical specimens with diameter 100 mm and height 200mm. 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 of 20ºC to 700ºC. Thermal properties of tested specimens at elevated temperatures were determined by Thermal Characterization of Transitional Phase (TCTP) procedure. Post TCTP, the mechanical properties were determined by Hot Mechanics Characterization Method (HMCM) consisting of a compression testing post fire 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) [30,36] – see Fig. 2. The trend of compression strength, ultimate strain, and modulus of elasticity as function of exposure time were reported. Based on stress-strain curves obtained, these authors derived a material model for masonry which are mentioned in sections below [41]. The appendix lists some of measurements taken by Andreini et al. experimental study [41].

Figure 2 Steps of HMCM testing procedure by Andreini

(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) [36].

Ayala and Bailey [22] tested lightweight concrete masonry blocks of dimensions 440×215 ×100mm under targeted temperatures of 200ºC, 400ºC, 600ºC, 700ºC and 800ºC under steady state set-up. Mortar capped concrete blocks were tested for residual compressive strength under steady state thermal conditions with heating rate of 600ºC/hr. Total 5 blocks for each targeted temperature was heated and cooled to determine residual compressive strength. The mean loads during compressive strength test shown abnormal behavior between temperature of 200ºC to 600ºC which was attributed to increase in loads at temperature increases. Compressive strength of tested blocks was reduced by 28% from 200ºC to 400ºC. The degradation observed at 600ºC and 800ºC was 18% and 65% respectively[22]. Ayala and Bailey [22] also reported the comparison of performance of similar block of dense concrete, concluding better performance of lightweight concrete blocks. This study further investigates the fire performance of 18 masonry wallettes (Medium scale) of 685 mm height, 670 mm width and 100 mm thick made up of light weight 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.

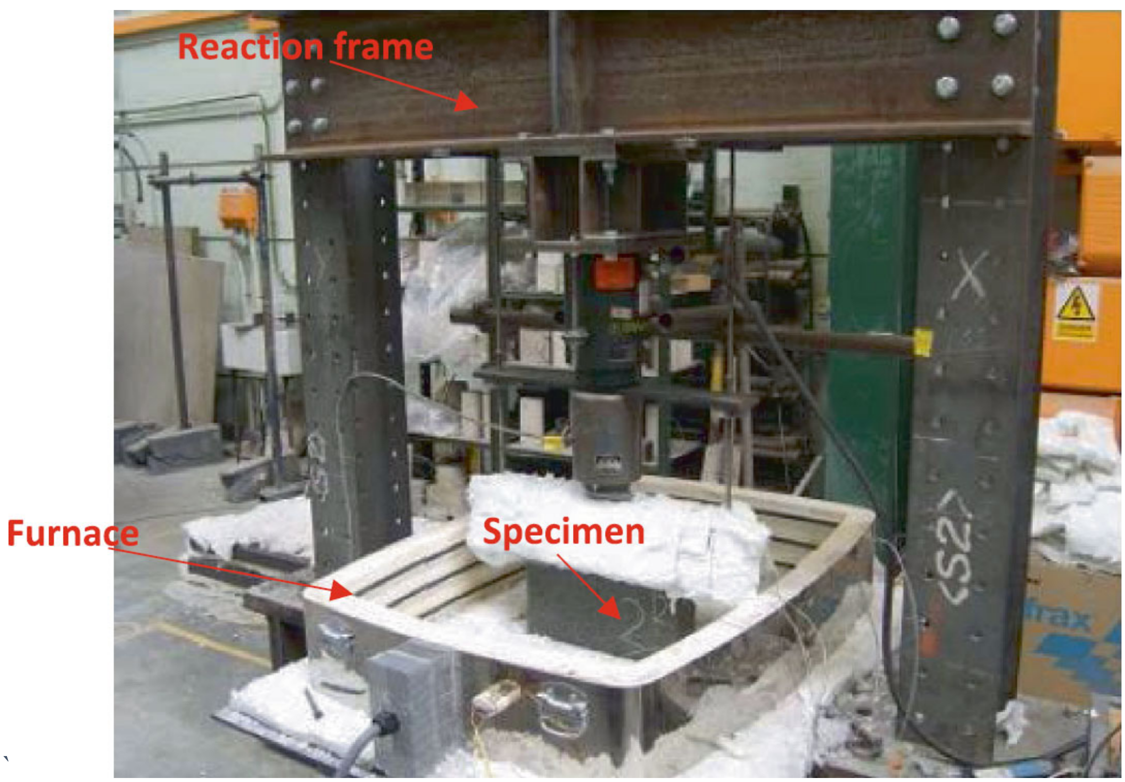

Figure 3 Testing arrangement used by Ayala and Bailey.

Khaliq and Bashir [26], undertaken an unstressed test program on Burnt masonry bricks temperature of 20ºC to 800ºC. Total of fifteen brick specimens of size 112.5×112.5×75mm and 225×112.5×75mm were used for determining compressive strength, modulus of elasticity and stress strain curves. For testing of specimen at ambient temperate, ASTM C1006 and ASTM C1314-14 were used to determine tensile and compressive strength. For mechanical properties at high temperatures, RILEM 129-MHT procedure was used with exposure of 20ºC, 200ºC, 400ºC, 600ºC and 800ºC for hold of 60 min. Specimens were tested immediately after taking out of furnace wrapped in thermal insulation blanket with average temperature loss of 10ºC.

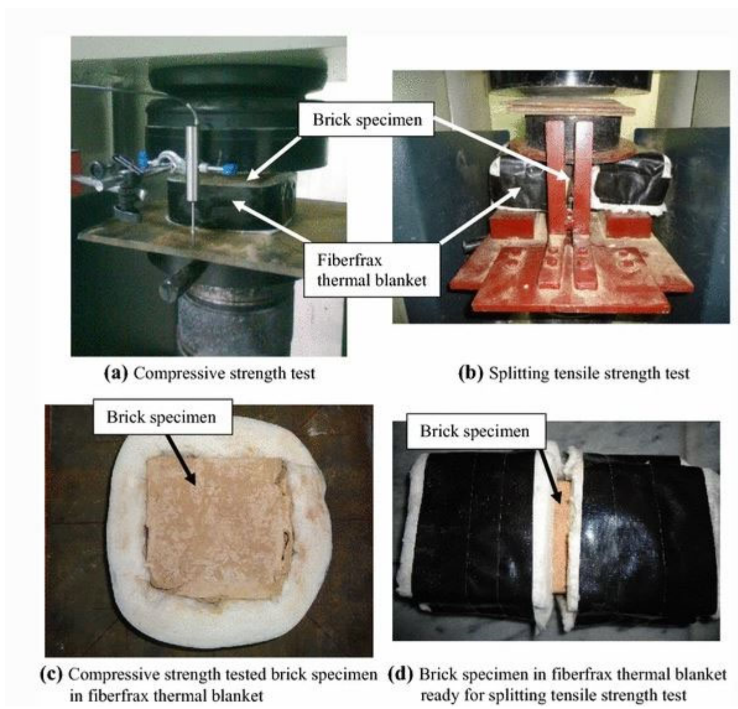

Figure 4 Burnt masonry brick under compression and tensile strength tests.

(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: 5104300503519) [26]

Russo [33] conducted an experimental investigation of mechanical properties under elevated temperature. The calcium silicate brick was used for residual behavior of masonry unit (see Fig. 5). For testing, Russo used small wallettes of size 250×120×55 mm. The one side exposure for two heating histories with 300 or 600ºC of maximum temperature with same cooling rate (~19°C/min) and one hour of retention time was used. Compressive strength and elastic modulus were examined according to UNI EN 772-1 and UNI 9724 provisions, respectively. List of reported results are given in the appendix.

Figure 5 Residual (post-heating) testing of masonry units by Russo

(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: 5104300293715) [33]

Xiao [42], conducted fire tests on three series of masonry concrete blocks consisting recycled concrete aggregates as coarse aggregate and sand as fine aggregates at percentage of 25%, 50%, 75% and 100%. For series 1 and 2, effect of using sand as replacement of crushed clay brick (CBA) was studied. For series 3, impact of using crushed clay brick as coarse aggregate was examined for replacement of recycled concrete aggregate by weight of 25%, 50%, 75% and 100%. Concrete block fabricated in the mould of size 200 X 100 X 60mm, were tested cooled after exposure of 300ºC, 500ºC and 800ºC for 4 hr to determine compressive and flexural strength. Objective of tests was to determine the residual density, loss in mass, flexural and compressive strengths. Irrespective of proportion of aggregates, all the blocks exhibited residual compressive strength values at 300ºC and 500ºC higher than value at 20ºC. On the other hand, at 800ºC compressive strength values degrade up to 52%. On contrary to compressive strengths, residual tensile strength values decreased up to 54% at temperature of 500ºC continuing at 800ºC. Some of the findings reported by Xiao et al. are summarized in the appendix.

Recently, Bosnjak [43], experimentally investigated residual performance of solid Clay brick and Calcium silicate brick (see Fig. 6). The testing was carried out on 3 specimens each of individual masonry unit, mortar, and masonry prism according to DIN EN 772-1, DIN EN 1015-11 and DIN EN 1052-1 respectively, for temperature range of 20ºC to 1100ºC for 2 hour and cooling. The compressive strength of calcium silicate brick was increased significantly till 300ºC and dropped abruptly at 700ºC. This is most likely to be related to the formation of cracks between sand particles and C-S-H phases. For calcium silicate brick prism, compressive strength decreases significantly after 700ºC. These losses were credited to the degradation of mortar accelerating the fire induced losses in the modulus of elasticity. Clay bricks exhibited low sensitivity, on contrary to calcium silicate bricks, to elevated temperatures with very less degradation in compressive strength up to

500ºC. After 500ºC, strength of the clay bricks was observed to be increased as the structure of clay changed to clinker.

Figure 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: 5104300655545)[10]

2.2 Large and Medium Scale Structural Testing

Instead of small-scale material testing, it is quite common to investigate the structural fire performance of masonry components and assemblies via large and medium scale testing. These types of tests are primarily adopted to examine the structural performance of masonry walls/ floor floors (ASTM E119 2016; British Standards Institution 1987; BSI 2012; Sciarretta 2015). Following sections outlines through such experimental studies done in detail and more in-depth discussion can be read from references[42].

2.2.1 Full Scale Testing

According to ASTM E119, for load bearing walls, specimen should not be restrained on vertical edges. However, non-load bearing walls should be restrained on all four sides. For test to be said successful the test specimens should withstand applied loads during test provide no passage of flame or gases, fire, and hose stream test, rise of temperature on unexposed side less than 139ºC. If, during hose stream test, opening develops allowing water projection beyond unexposed surface, test should be considered as unsuccessful [42].

In the series of experiments performed between 1907-09, Humphrey [46] conducted thirty fire tests on full scale wall panels. These wall panels of dimensions 1.8×2.7 m was tested in Underwriters' Laboratories, Chicago, IL. The blocks used for the assembly of the wall panels were 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. Masonry was given 2 hr of fire exposure with targeted temperature of 926ºC (1700ºF). Temperature measurements of exposed and unexposed face of panel and furnace were observed. There fire tests also involved hose stream test (e.g., quenching test). In case the wall specimen failed, masonry blocks were dismantled from the wall and tested under compression. It is worth mentioning that Humphrey faced a series of obstacles during the fire testing due to inexperienced operator, freezing conditions in winter, etc. Humphrey has documented all the findings and detailed observations, which can be found in Appendix.

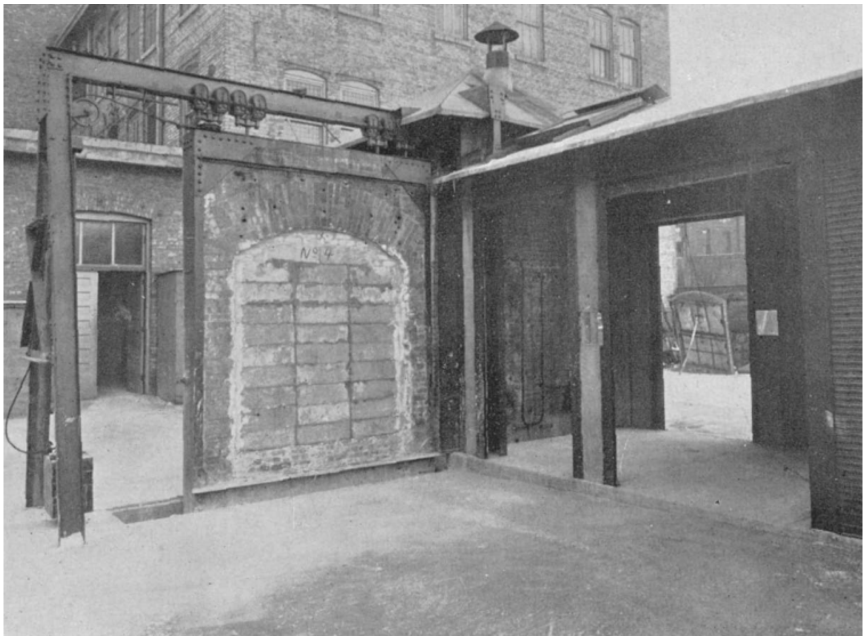

Figure 7 Fire test set-up by Humphrey

(Republished courtesy of the United States Geological Survey.)[46]

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 [47] (i.e. Report 117) and by Foster et al. [18] (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.

Ingberg [47] 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 thickness (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 [47]. In same testing campaign, 16 lightweight aggregate concrete masonry unit walls (load bearing and non-load bearing) were tested under fire conditions. These unit contained cinder, expanded shale, pumice, or expanded slag. These tests noted fire resistance of tested walls in range of 69 min to about 7 depending upon thickness, moisture content, type of aggregate and load bearing properties [48]. In another series of experiments, 12 walls with different thickness 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 unexposed side [49]. See appendix for a preview of Ingberg [47] full scale standard fire tests.

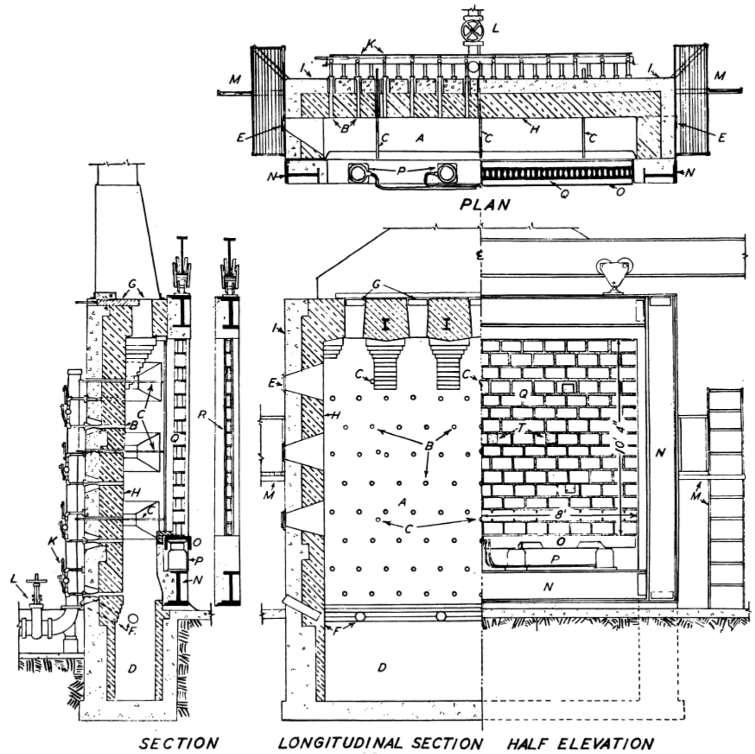

Figure 8 Fire testing furnace by Ingberg [47] and Foster et al. [18]

(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.) (Republished courtesy of the National Institute of Standards and Technology.)

Foster [18] tested twelve walls of gravel aggregate concrete units under standard fire exposure and hose stream test for three of these walls. Five of total walls were consist of calcareous aggregates (viz., natural aggregates less susceptible to damage by fire) and the rest seven walls were made with siliceous aggregates. Non-load bearing wall with thickness of 101 mm and load bearing walls of 203mm and 205 mm were involved in test. Non load bearing walls of siliceous aggregate and thinner walls of calcareous aggregates were collapsed in 60 min or less after exposing to fire. On the other hand, load-bearing walls with calcareous aggregates and of 203 mm and 305 mm thick showed good fire resistance (exceeding 180 min) and those of 305 mm thick showed 5 hr or more of fire resistance and were limited by the temperature rise on the unexposed surface. Foster [55] also presented a parallel fire testing program on similar walls but made from lightweight aggregate CMUs. 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 [50] 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 [50] noted that walls having a slenderness ratio of 20 or less achieved a 60 min fire resistance rating. Byrne [50] also pointed out the importance of applied loading levels on fire resistance of masonry walls.

Between 1974 and 1986, Lawrence and Gnanakrishnan [51] 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 [51] 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 discrepancy in fire response between identical specimens and acknowledged the need to evaluate the repeatability of fire resistance tests. Similar findings to that of Byrne [50] were also documented with regard to the negative impact of slenderness ratio on the fire resistance of masonry walls.

In 2006, Nahhas [52] experimentally investigated thermo-mechanical behavior of full size masonry walls. Walls of size 2.82m height and width with thickness 20mm was tested for temperature measurements inside walls with horizontal and vertical displacements during 6 hr exposure to ISO 834 standard fire. These walls were made up of hollow blocks under vertical load of 13 ton/m with fire exposure of 20ºC to 1200ºC. Blocks used in these tested were industry standard blocks from France with compressive strength of 4MPa. Lateral displacements variations as linear from 0 to 25 min and quasi-constant till 45 min were derived from observation with respect to fire exposure. Thermal expansion causing vertical displacement increased linearly from 0 to 30 min until 90 min obeying identical behavior as plateaus increasing the displacement after that.

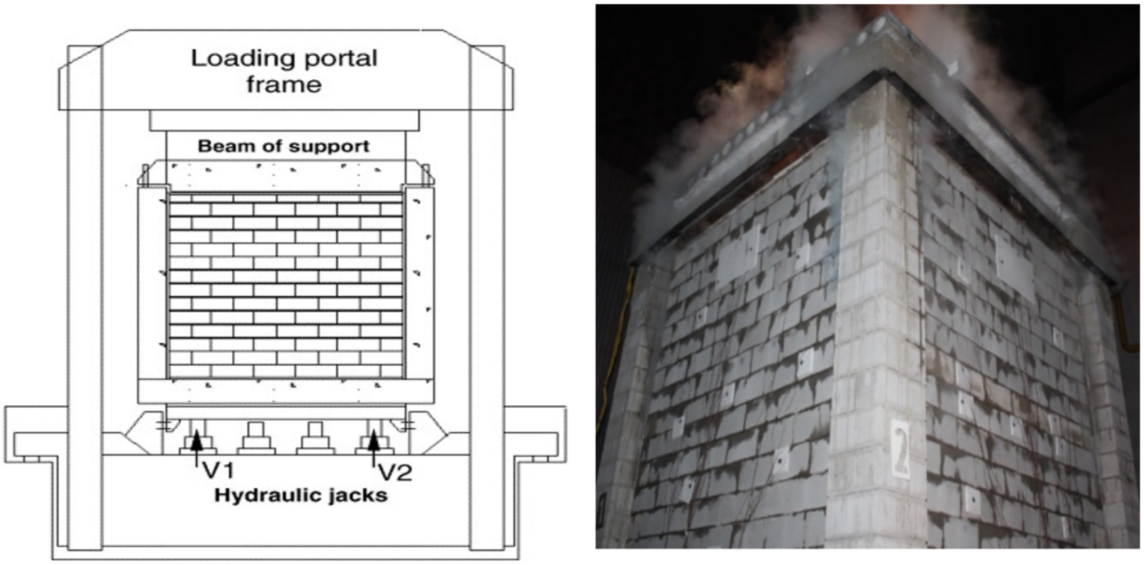

Figure 9 Testing setup used by Al Nahhas et al. [52] (Left), Keelson [53], and Pope and Zalok [54] (Right)

Keelson [53] 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 [53] extended that of Pope and Zalok [54] 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 [12] experimentally tested 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 two thick load bearing walls tested under different loads and insulation configurations under standard exposure according to ISO 834, as well as EN 1363 and EN 1365 provisions (see Fig. 10). This study states two phases of heat transfer which were primarily governed by the thickness of wall and time required to evaporate moisture within masonry blocks as: transmission phase and plateau phase. Conclusively, fire resistance of 60 to 240 min were noted based upon the properties of walls. The thicker walls seem to perform better under fire conditions despite undergoing spalling [12].

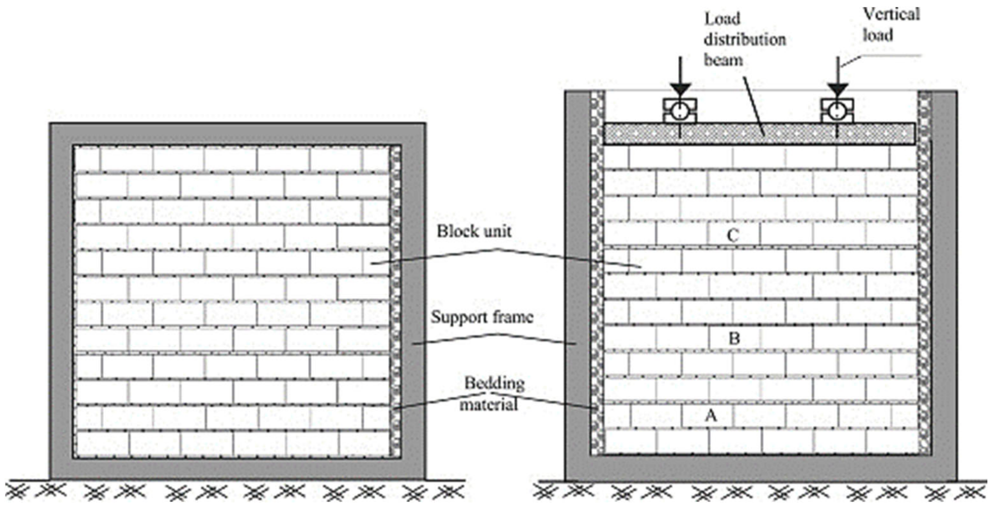

Figure 10 Test setup: Non-load bearing wall (Left), Load bearing wall (Right) as undertaken by Nguyen and Meftah [12]

(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: 5104301087606)

In an experimental research program at the University of Venice [33], the mechanical properties of clay brick masonry under compression at elevated temperatures were measured by testing ten square specimens of 250 mm width and height. These specimens were wallettes (Medium size specimen) replicates of separating and non-separating walls (non-load bearing and load bearing) 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 300ºC and 600ºC attained at 1hr. The specimens subjected to 300ºC were shown to be undamaged and those exposed to 600ºC underwent interfacial cracks and micro 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.

Figure 11 Wallettes specimens to be put to fire tests as per [33]

(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: 5104300293715)

Lopes et al. [55,56] experimentally investigated masonry specimens consisting of three cell concrete blocks identical to that used in US and European constructions. In 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 [57] and EN 1363-1 [58] (see Fig. 12). All specimens were tested under ISO 834 standard fire exposure until thermal or mechanical failure. Lopes et al. [55] 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 [55]).

Lopes et al. [55,56] also presented that the current values of Eurocode 6 can overestimate the insulation capacity and the loadbearing capacity of some of the tested walls.

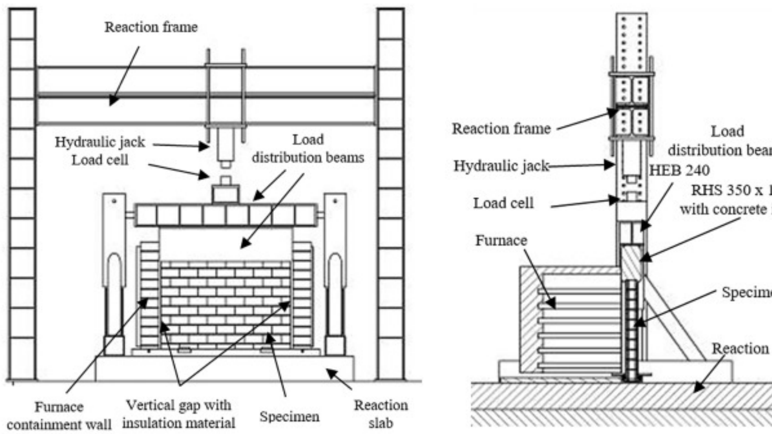

Figure 12 Wallettes testing set-up by Lopes et al. [55,56]

(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: 5104301301565)

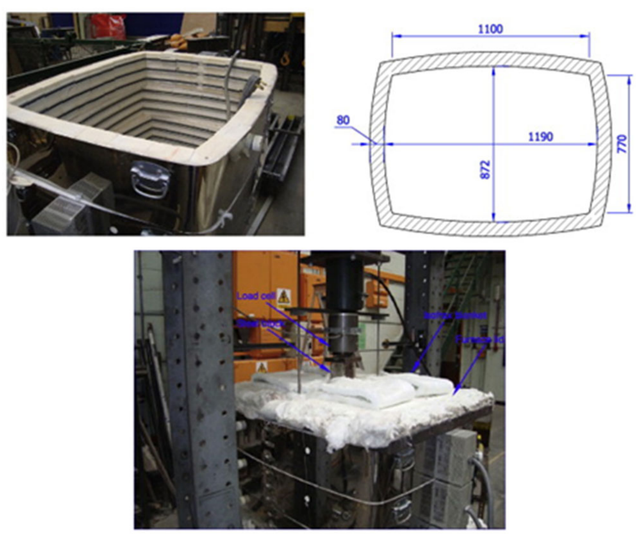

Figure 13 Wallettes testing set-up by Al-Sibahy and Edwards [59]

(Credit line: Elsevier, Engineering Structures, Behavior 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: 5104301405114)

Bai et al. [31] tested thermal properties of hollow shale blocks by carrying out experimental study on square wallettes that were 1650 mm heigh 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 by steady state procedure 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 [31].

In identical testing, an extensive experimental study carried out by Madrid et al. [32], in which three walls made up of sawdust and lime-mud CMUs' of 1190 mm in height, 1000 mm in height and 190 mm thick were tested to investigate their thermal properties. The aim of 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% [32]. 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).

(a) Bai et al. [31] (b) Madrid et al. [32]

Figure 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 CMUs, Maggi Madrid, Aimar Orbe, Hélène Carré, Yokasta García, April 30, 2018, License Number: 5104301495807)

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2.3 Properties of Masonry at Elevated Temperatures

To extend our previously noted motivation behind this work, there continues to be very limited works in this area. As such, this section includes temperature-dependent material models for common masonry materials with a special 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.

2.3.1 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 lack of standard testing procedures, a variety of testing methods and specimen sizes were used by various researchers (as shown in an earlier section – also see [10,25,30–38]).

For example, Fig. 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 raw 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) the degradation of masonry is much slower than concrete.

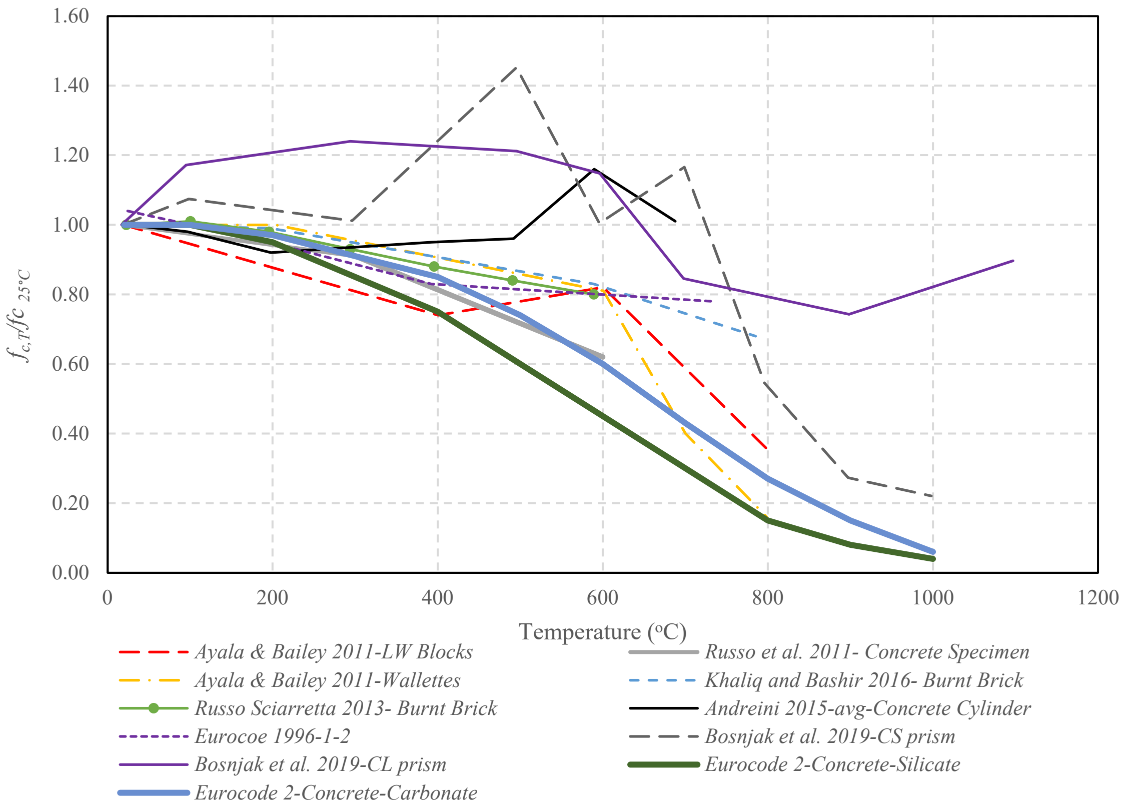


Figure 15 Degradation in compressive strength of masonry under elevated temperatures (note: tests by Bosnjak et al. [10] were under residual conditions) – please companion Table 1 for more insights.

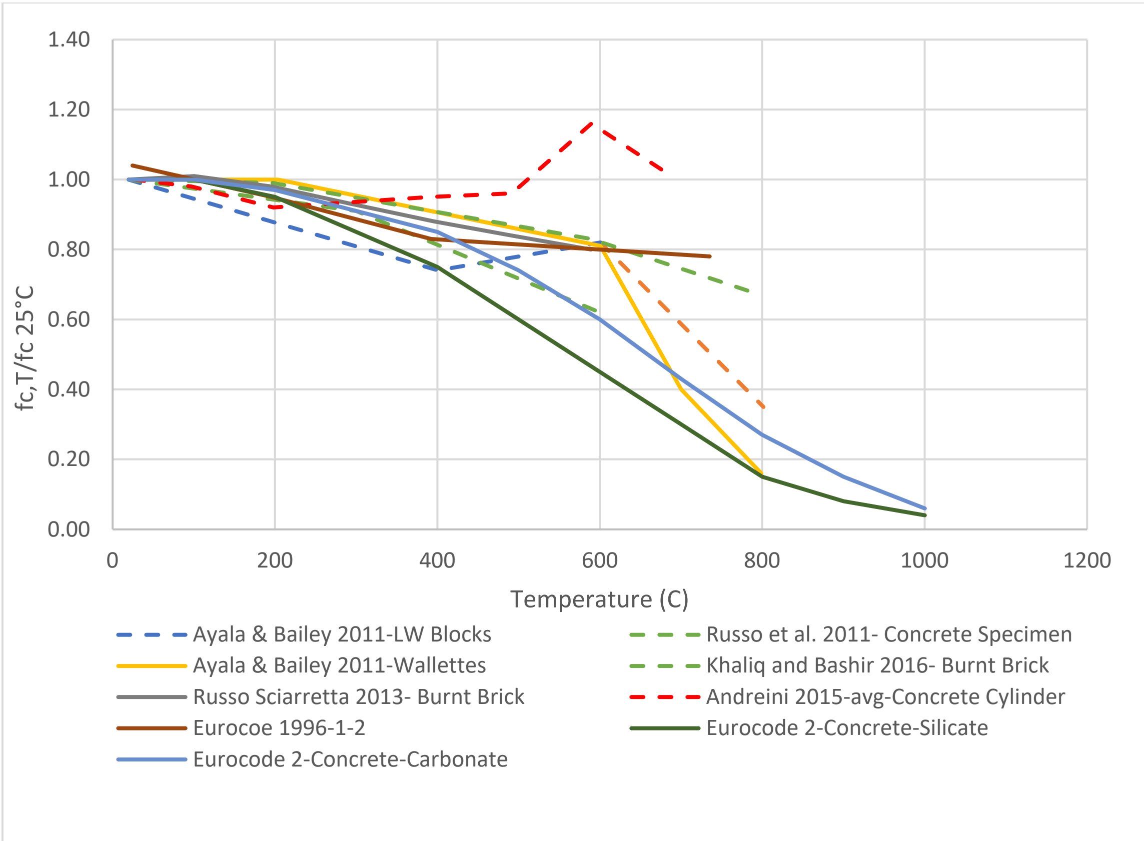


Figure 16 Degradation in compressive strength of masonry under elevated temperatures (Dashed line: Single specimen, Solid line: Wallettes) (Hot state only)

Sr. No.	Article	Testing under Residual/ Hot Conditions
1	Ayala & Bailey 2011-LW Blocks	Hot conditions
2	Ayala & Bailey 2011-Wallettes	Hot conditions
3	Khaliq and Bashir 2016- Burnt Brick	Hot conditions
4	Russo Sciarretta 2013- Burnt Brick	Hot conditions
5	Andreini 2015-avg-Concrete Cylinder	Hot conditions
6	Eurocoe 1996-1-2	Hot conditions
7	Russo et al. 2011- Concrete Specimen	Hot conditions
8	Bosnjak et al. 2019-CS prism	Residual Condition
9	Bosnjak et al. 2019-CL prism	Residual Condition
10	Eurocode 2-Concrete-Silicate	Hot conditions
11	Eurocode 2-Concrete-Carbonate	Hot conditions

Table 1 Testing by various authors and type of testing used.

Khaliq and Bashir [25] reported how the compressive strength of burnt bricks reduces as temperature rises from 20ºC to 800ºC. This reduction was attributed to ongoing physical and chemical changes in microstructure of bricks as a result of mineralogical transformations and formation of mechanical cracks due to thermal deformations with rise in temperatures. With continuing mineralogical transformations and development of mechanical cracks, the degradation in compressive strength also increases from 600ºC to 800ºC [25]. The reported decrease in compressive strength from 0-600ºC was 20% to 27% at 800ºC. Stress strain curve and elastic modulus at every temperature were also derived [25]. Similarly, Russo and Sciarretta [60] findings agree with that reported by tests from Khaliq and Bashir [25]. The trend observed was accounted to high number of silicates present in concrete used. Russo et al. [33] also tested clay brick wallettes and reported degradation in compressive strength. Their report shows reduction in compressive strength at 300ºC and 600ºC 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. [36] clearly shows a significant difference in trend in mechanical property degradation wherein degradation in this property remains stable up to 400ºC. Beyond 400ºC, the compressive strength seems to recover and increase at 600ºC. This difference in trend can be ascribed to use of cylindrical specimens and variety of ingredients (clay, aerated autoclaved concrete, lightweight concrete, hydraulic lime mortar etc.) involved in casting of specimens. Ayala et al. [37] proposed compressive strength reduction factors by testing wallettes made from lightweight concrete blocks. These specimens did not exhibit significant reduction in compressive strength at 200ºC

(3%) and only 9% reduction was observed at 400ºC. On the other hand, compressive strength decreases to 60% till 700ºC and reaches to 83% at 800ºC. This degradation can be credited to deterioration of block material resulting from the reported premature melting of used aggregates at temperature range of 700-800ºC. In this testing program, the proposed compressive strength reduction model for tested blocks showed 65% reduction in initial strength at 800ºC. This higher value of residual strength can be associated with excellent performance of lightweight particle properties under elevated temperatures [37].

Bosnjak et al. [10] derived the residual compressive strength values for calcium silicate (CS) and clay (CL) bricks. According to this study, calcium silicate strength significantly hikes from 300ºC but abruptly drops to 30% after temperature crosses 700ºC. 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 increase in compressive strength during 300-700ºC and significantly lower value (80% reduction) above this temperature range. CL bricks prisms exhibited less reduction as compared to CS bricks at residual condition. Figure 15 also shows compressive strength reduction factors with respect to exposure time given by Eurocode 6 [61]. It is interesting to note that these factors do not rapidly degrade post 600ºC.

2.3.2 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 [54]. 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 rise in temperature as credited to shrinkage, loss of moisture, formation, growth and merging of cracks at elevated temperatures [25].

In one study, Kahliq and Bashir [25] 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. [38] determined the tensile strength of recycled concrete aggregate blocks and 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 [38]. Nadjai et al.'s [29] outcomes of their tests seem to agree with that reported by Xiao et al. [38] showing a gradual decrease till 400ºC and an accelerated degradation at 800ºC [29].

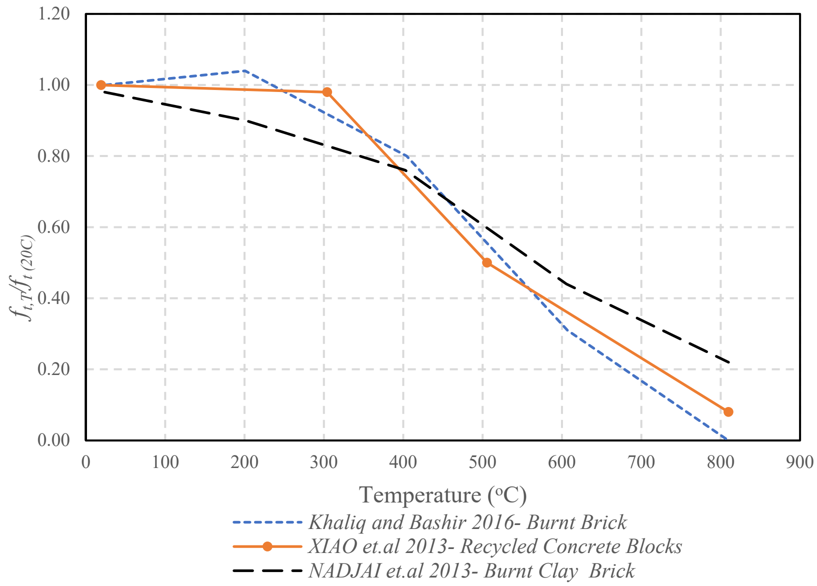


Figure 17 Degradation in tensile strength of masonry under elevated temperatures

2.3.3 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 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 increase in temperature. The same figure also depicts the degradation of modulus of elasticity of concrete.

As per the results of test conducted by Kahliq and Bashir [25] on burnt bricks under elevated temperatures, the elastic modulus significantly degrades from 20°C to 800°C but follows a slight gradual decrease till 200ºC. At 400ºC, this reduction reaches 50% and then linearly increases till 800ºC [25]. Kahliq and Bashir [25] 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 [25] were on average 9.3% lower than that of listed by Eurocode 6 [61]. It is worth noting that the test results were 6.2% higher than results from Russo and Sciarretta [60] who noted reduction of 15% and 1% was observed at 300°C and 600°C, respectively. Andreini et al. [36] shows a remarkably different and lesser trend in degradation of modulus of elasticity (which could be attributed to their tests being conducted on cylindrical specimens and varying heating history) [36]. In Ayala et al. [36], 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 800ºC, 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 [37].

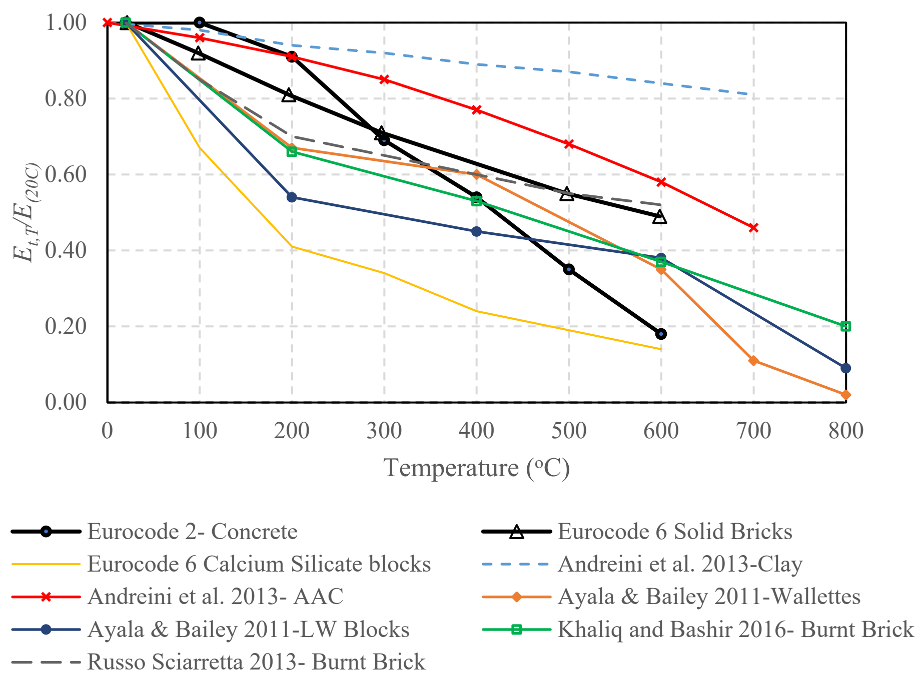


Figure 18 Degradation in modulus of masonry under elevated temperatures

2.3.4 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 [24,52] – 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 presence of voids in micro-structure as well as to the thermal properties of aggregates and raws used [23]. Figure 18 shows that the thermal conductivity decreases with rise in temperature as a result of increase in voids due to evaporation of moisture content and dehydration of cement paste [37]. The specific heat remains somewhat stable during elevated temperature and notably rises around 700^{o}C.

Specific heat of concrete is affected by the physiochemical changes in concrete material that occurs in cement paste and aggregates under elevated temperatures. The specific beat of carbonate aggregate concrete above this temperature is generally higher than that of siliceous aggregate concrete. Above 600°C, significant amount of heat is needed to increase the temperature of the carbonate aggregate concrete. This heat is approximately ten times the heat needed to produce the same temperature rise in siliceous aggregate concrete. Hence, sudden spike in Specific Heat can be attributed to this change in concrete.

It is worth noting that a few works reported the thermal characteristics and properties of masonry and masonry-like materials but at ambient temperature [31,32,52]. For example, Bai et al. [31] stated that the experimental heat transfer coefficient of hollow shale block walls is 0.726 W/m^{2}K, which was said to meet the requirements of Chinese design codes. Madrid et al. [32] examined the effect of sawdust to 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 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 [32]. Al Nahhas et al. [52] 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. [62]

stated that the heat transfer coefficient of recycled concrete blocks has an average value of 0.93 W/m^2.K.

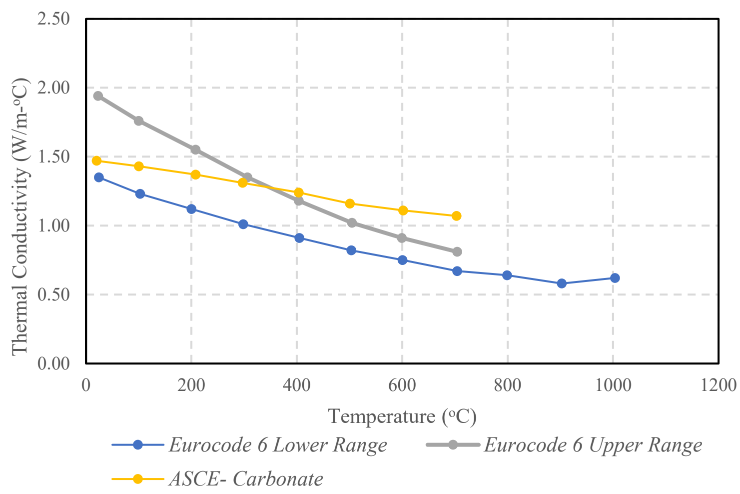


Figure 19 Variation in Thermal conductivity of concrete under elevated temperatures

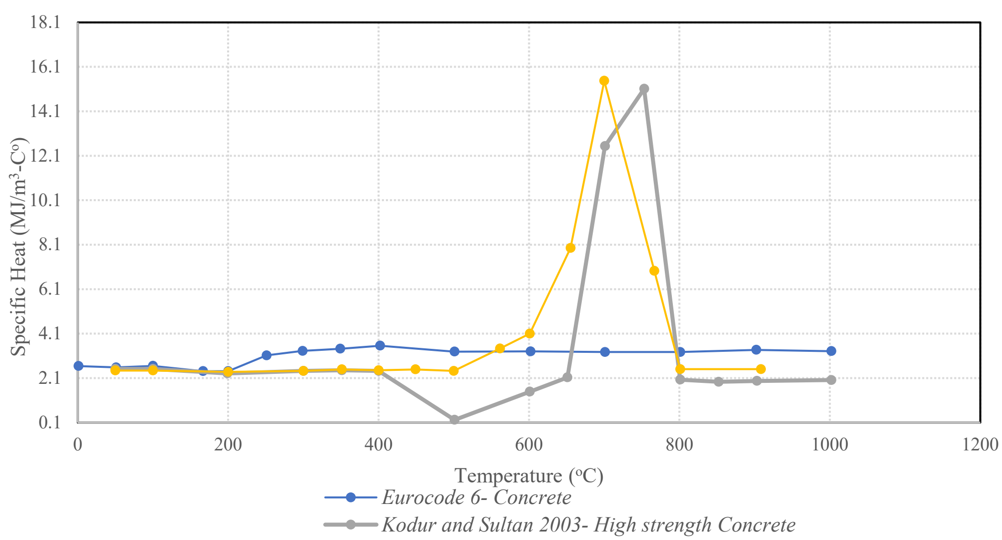


Figure 20 Variation of specific heat of concrete under elevated temperatures

3. EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter discussed the experimental program carried out for examining the compressive behavior of CMUs in fire as to develop temperature dependent material model. Experimental program on determination of compressive strength for industry standard concrete masonry unit under fire exposure is explained in this section. Detailed procedure for Hot state and Residual fire testing has also been presented. Furthermore, all the technical specification of the equipment used for the program are also mentioned below.

3.2 Experimental Program

The study was executed in following steps:

Step 1: This step includes the fire testing of the CMU specimens. Prior to actually fire testing, the selection of the heating rate, retention time and loading rate was selected based on the literature survey shown here [2]. For heating rate and retention time, Uniformity test was carried out.

Step 2: This step includes the investigation of mechanical properties of the specimens under unstressed residual testing conditions. The CMUs were heated to targeted temperatures 25ºC, 200ºC, 400ºC, 600ºC and 800ºC and allowed to cool down to ambient temperature. To avoid the discrepancy in results, every block was tested after 15 days after reaching to ambient temperature. The 3 CMUs were tested under compression to evaluate mechanical properties at each targeted temperature.

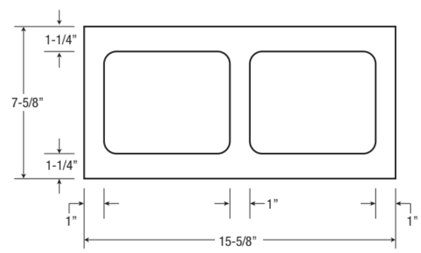
Step 3: This step includes the investigation of mechanical properties of the specimens under unstressed hot testing conditions. The CMUs were heated to targeted temperatures up to 800ºC and retained for 3 hrs after furnace temperature reached the targeted. The CMUs were tested under compression in hot state to get compressive strength and stress strain curves.

The following sections describes all the details of each step.

3.2.1 Test material and geometry

For this experimental program, US industry standard concrete masonry units were used. These blocks are the half-cut units from the conventional 8-inch hollow concrete blocks which are used as common construction material. The blocks were consisting of Lightweight aggregates. The concrete masonry specimen of half of dimensions are shown in Figure 20. The concrete blocks were donated from General Shale and then stored in ambient (24ºC) and dry atmosphere (40% Humidity). Compressive strength of concrete block was tested according to specifications stated in ASTM C140. Before performing actual experiments, few CMUs were tested under variety of conditions (see Figure 22-23). Approximately, 15 blocks were tested as a trial before finalizing the test setup for experimental program. Then, a total of another 27 specimen tests were carried out for this program to examine mechanical properties of blocks under elevated temperatures. Three specimens for each targeted temperature were tested under both hot state and residual state setup. The results at the specific temperature were observed.

Figure 21 Half size CMU



a) Top view

b) Side view

Figure 22 Dimensions of Standard 8-inch Concrete Masonry Unit (a: top view, b: side view)

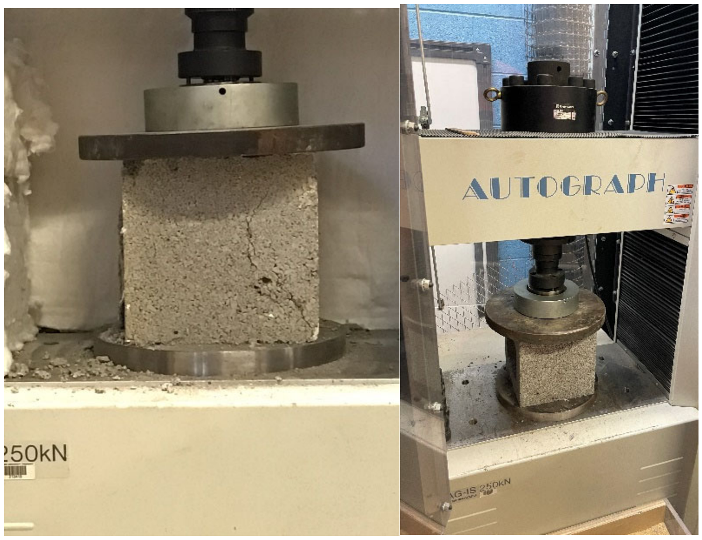


Figure 23 Trial Testing Setup -1

Figure 24 Trial Testing Setup -1

3.2.2 Testing Setup

a) Heating Equipment

For determining material properties of the concrete masonry specimens at elevated temperature, electric muffle furnace was used. This furnace was Global gilson 1537 in^3 Muffle furnace with heating capacity up to 1083ºC. Interior chamber walls have 2.5in (64mm) minimum thickness refractory firebrick, mounted heating elements, and interior dimensions of 13×13.5×8.8in (33×34.3×22.4cm) W×D×H. The exterior of the unit is a painted, heavy-gauge steel case (see Figure 24-25). Furnace was having capacity to input the targeted temperature with constant heating rate and retention time. Temperatures were recorded manually. All the temperature measurements were taken at 5 minutes intervals.

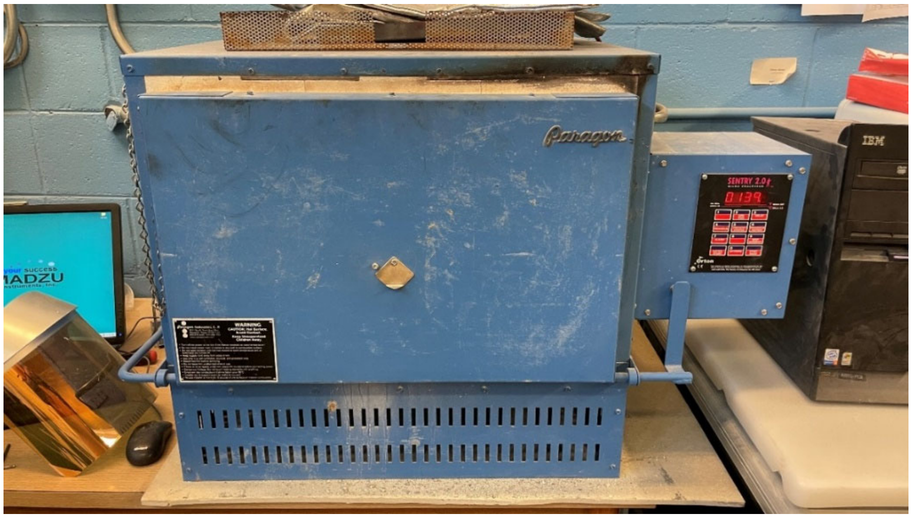


Figure 25Furnace used for experimental program.

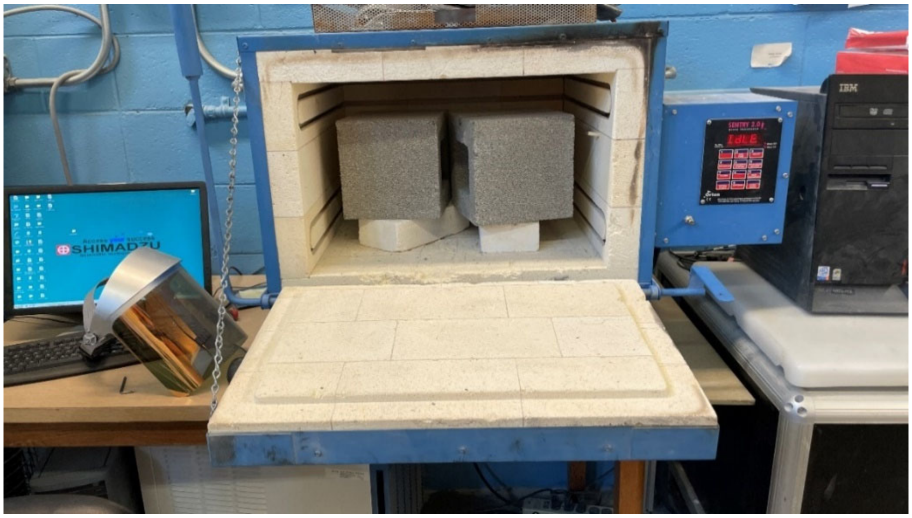


Figure 26 Furnace with concrete masonry specimen

b) Testing Equipment

A Universal testing machine of Capacity 56.2 kips was used for the compression testing of the test specimens of 800ºC. Figure below shows UTM used for the testing. UTM used was SHIMADZU AUTOGRRAPH Precision Universal Tester AG–IS 250 kN. Its features contain high rigidity frame, multi processors, high-speed sampling and accuracy, a smart controller equipped with a progressive user interface and software that supports the creation of test conditions (see figure 26-27). All the deflection and load measurements were taken using the data logging systems in-built in machine.

Figure 27 Universal Testing Machine used for Experimental Program.

Figure 28 Universal testing machine covered with Thermal Blanket to protect from radiation.

For testing of specimens under hot state temperatures of 25ºC, 200ºC, 400ºC, 600º and specimens under residual testing and ambient conditions were tested using compressive testing machine. The load capacity of available UTM at current facility was limited. Hence, Compressive testing machine was used for further testing. TEST MARK INDUSTRIES Compression Machine of capacity 400,000 lbs. and accuracy of +/-.5% was used. It contains high rigid frame, continuous-duty hydraulic pump and four digital load-indicating system (see figure 28). It also has option for area input of the specimen to be tested.

Figure 29 Compressive Testing Machine used for experimental program.

3.2 Test Procedures

This section presents the procedure used for testing the concrete masonry specimens under residual state and hot state testing at ambient and elevated temperature. The testing methodology for residual and hot state fire testing is here described.

3.2.1 Uniformity test

Although the heating rate for the fire testing was predetermined, it is crucial to check the uniformity of temperature throughout the specimen to obtain accurate results. Before deciding the retention time for the specimens, specimens were heated till 300ºC with heating rate of 200ºC/hr for 2 hours of retention time. For monitoring the temperature of the blocks, thermocouples (type K- max. temp. 1200ºC) were installed inside both vertical faces of the blocks. As the vertical faces of the blocks were of different thickness, 2 thermocouples were used (see figure 29). After verifying the thermocouple temperature readings with targeted temperatures, Retention time was decided for testing. Results of test can be found in Section 4.

Figure 30 Uniformity Test Setup (results of uniformity tests are shown in Ch. 4)

3.2.2 Unstressed Residual testing

Obtaining the residual compressive strength values of the fire exposed concrete blocks was one of the objectives of this testing. The block specimens were exposed to predetermined temperatures of 25ºC, 200ºC, 400ºC, 600ºC and 800ºC under no loading. After furnace temperature reaching to targeted value, blocks were retained in furnace for more 3 hours to fulfill the thermal equilibrium in specimen.

After 3 hours of retention time, the furnace was turned off and the block specimens were allowed to cool to ambient temperature naturally. Two thermocouples were installed for monitoring the temperature throughout the heating. Temperature readings of both thermocouple location (figure 30) was taken at interval of 5 minutes till it reaches to ambient temperature. When cooling down to the ambient temperature, blocks were stored at dry place for two weeks. Cooled specimens were then tested under compression to determine the compressive strength.

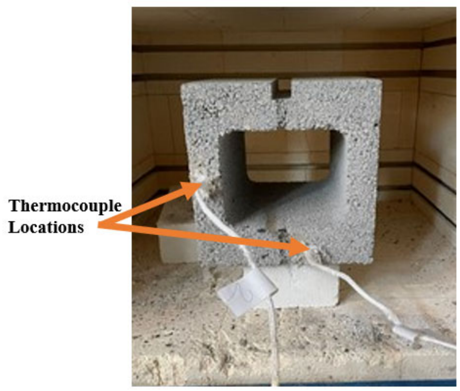


Figure 31 Thermocouple Locations

Compression testing of blocks were done using Compressive Testing Machine (CTM). The vertical uniform pressure was applied using a rate of 50 lb/s. The moving head of the machine was manually adjusted to rest on specimen. The loading rate was given as input in preinstalled computer program. Stress strain curve, compressive strength, and speed sampling (1 sec interval) was done by computer program. All the testing specifications were verifying against ASTM C140.

The transportation of blocks was done carefully from the curing places by hand and placed under CTM. It was checked that both the top and bottom block surfaces were completely dust free and free of particles for accurate test results. Bearing surfaces of the bottom and top testing plates were also cleaned. The blocks were perfectly aligned at the center of the testing setup. The loads were applied with constant loading rate till crushing. The strength of the blocks was calculated by dividing the total load applied by loaded surface area of the block (Net area of the block).

3.2.3 Unstressed Hot State testing

For the hot state testing, same testing setup and equipment were used. Compressive strength values were determined for Hot state testing under predetermined temperatures of 25ºC, 200ºC, 400ºC, 600ºC and 800ºC. Due to limitation of available Universal Testing Machine at the facility, only 800ºC testing was executed on Universal Testing Machine, hence stress-strain curves were obtained. Compressive Testing Machine was used for testing of specimen at other targeted temperatures to get compressive strength values. For this testing, specimens were placed in muffle furnace with the same heating rate and retention time as unstressed residual testing.

Further, the 3 hr retained specimens were then directly tested under the compression to get compressive strength and stress strain curves. The exposed area of the testing machines was covered with Glass fiber Thermal Blanket to 1) maintain the temperature and 2) prevent any accidents because of radiation from the heated specimens. Careful extraction of the specimens from furnace was carried out using a newly designed tool (see figure 31) and all the fire safety gears with 1200ºC ratings were used. Specimens were loaded until failure.

Figure 32 Tool used for extraction of block.

Compression testing of blocks at 800ºC were completed using UTM. The vertical uniform pressure was applied using a rate of 112.5 lbs/sec. Loading rate was decided referring to the loading time limit requirement according to ASTM C140. The moving head of the machine was manually adjusted to rest on specimen. The loading rate was given as input in preinstalled computer program. Stress strain curve, compressive strength, and speed sampling (1 sec interval) was executed by machine manufacturer's computer program. All the testing specifications were verified against ASTM C140. For testing at other temperatures, same procedure was used to extract and place the specimens under Compressive testing machine. The vertical uniform pressure was constant and reading for compressive strength of specimens were noted from the values displayed on the machine.

Total of three specimen for each targeted temperature were tested using same loading and heating rate. The average strength value was calculated. All the results are given in later section.

4. EXPERIMENTAL FINDINGS

4.1 Introduction

This chapter presents the results of experimental study executed for this research. Firstly, results from uniformity tests and time temperature curves are given. Temperature of furnace and inside the blocks with respect to time were monitored during heating and cooling phases. Secondly, degradation of compressive strength property with respect to temperature under Unstressed hot and unstressed residual are presented. The results are conferred as ratio compressive strength at targeted temperature to compressive strength at ambient temperature. In this section, these finding are compared with material behavior at elevated temperatures. The chemical changes in components of concrete block with respect to temperature are described.

4.2 Results

4.2.1 Uniformity Test

Prior to decide the heating rate and retention time for the testing, Uniformity test was carried out on the same concrete block specimen. To investigate the temperature distribution inside the block as compared to the temperature in the furnace was the main aim of this test. Figure 27 shows the temperature in furnace and two thermocouples inserted in the block. The rate of heating for this test was 200ºC/hour and retention time was 2 hours for targeted temperature of 300ºC. After these testing, heating rate of 300ºC and retention time of 3 hour was decided based on duration of exposure to fire and rate of heating.

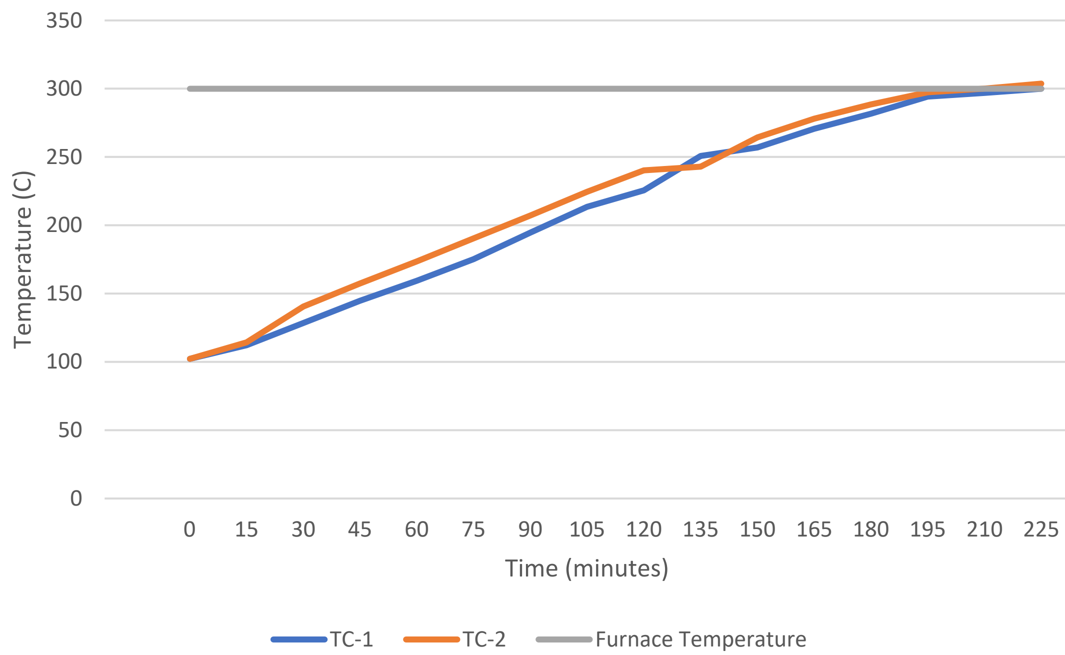


Figure 33 Uniformity test

Furthermore, at the time of the unstressed residual testing, temperature reading of same three points as uniformity test were taken. The time temperature curve for temperatures of 200ºC, 400ºC, 600ºC and 800ºC were established. Figure 33-36 shows heating and cooling with respect to time for each targeted temperature.

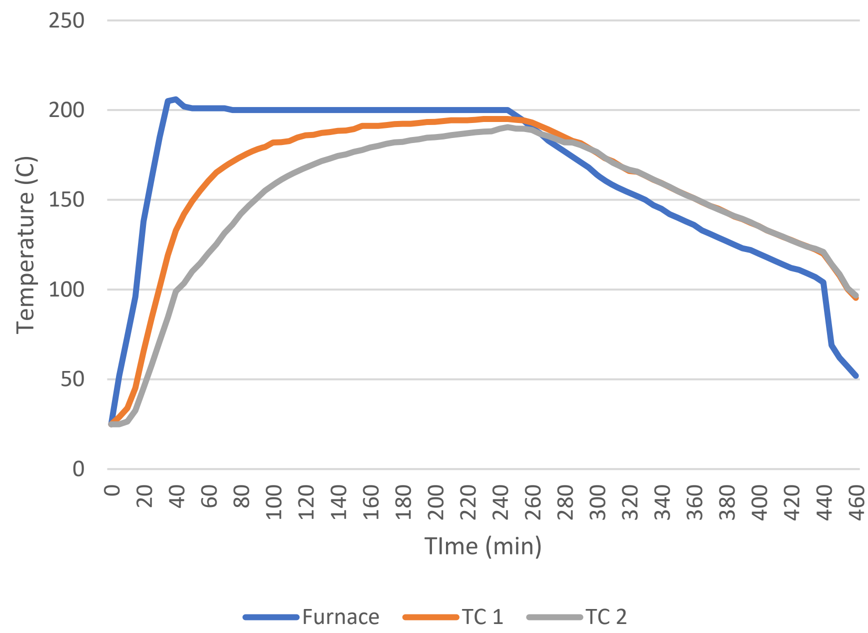


Figure 34 Heating and Cooling with respect to time for 200ºC

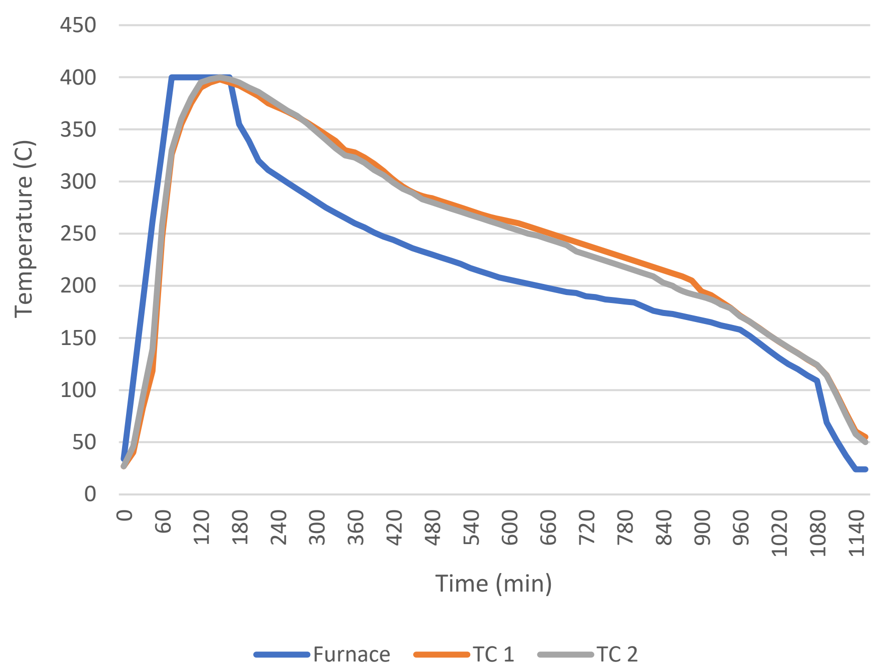


Figure 35 Heating and Cooling with respect to time for 400ºC

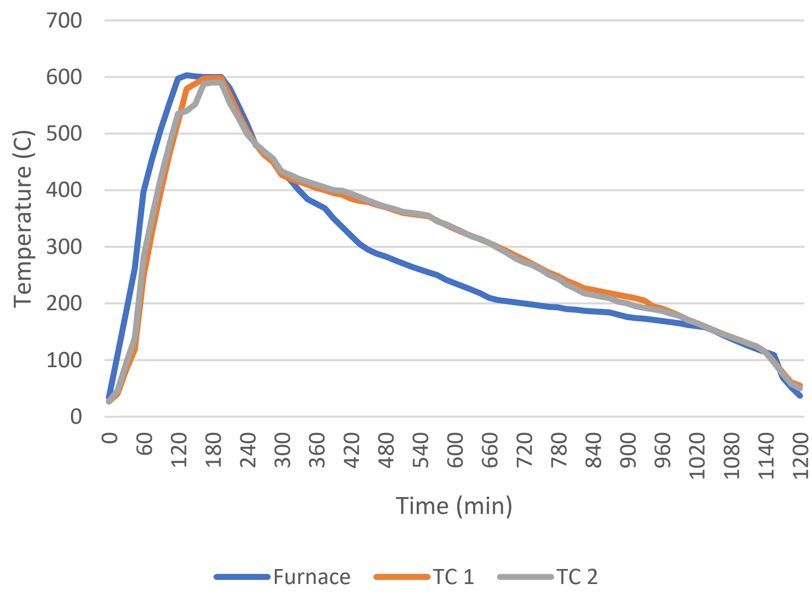


Figure 36 Heating and Cooling with respect to time for 400ºC

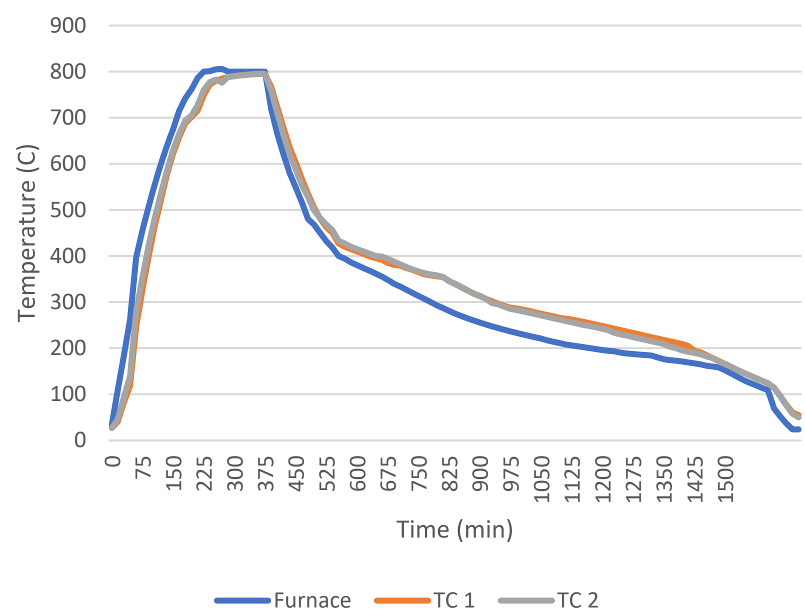


Figure 37 Heating and Cooling with respect to time for 800ºC

Every curve shows an increase in furnace temperature more than set targeted at first peak. This increase can be Furnace adjustment to regulate the temperature. No loss of heat during heating of specimen were observed. Loss of temperature with respect to time was during the end of the cooling phase. Hence, the door of the furnace was opened when temperature was reach to 100ºC in each case. It is clear from these curves that thermal equilibrium was attained inside the furnace and concrete specimen.

4.2.2 Unstressed Residual State Testing

In this section, the reduced compressive strength of the concrete blocks tested under unstressed residual conditions are presented. Three specimens at each targeted temperature were tested. The data includes the mean value of the residual state compressive strength obtained at each temperature. Figure below shows the variation in compressive strength with increase in temperature. The compressive strength was calculated using force values observed from testing machine divided by the net area of the tested concrete block.

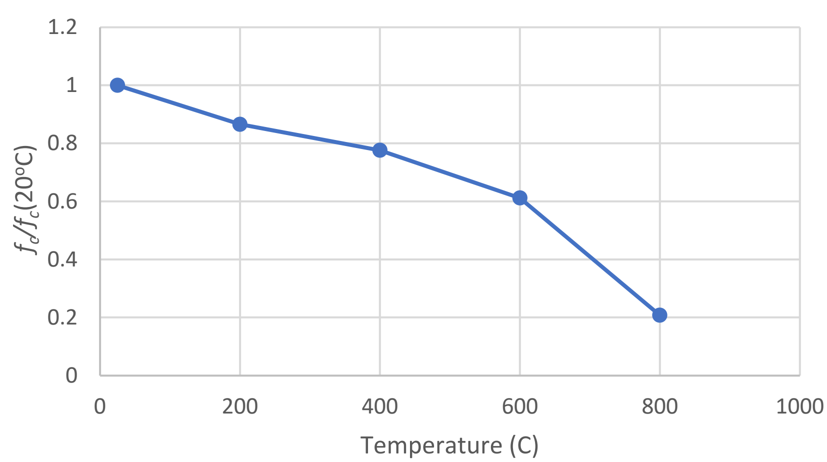


Figure 38 Compressive Strength reduction factor under residual state conditions

The residual strength of the CMUs obtained from the experimental study shows a general trend of degradation in compressive strength with increase in temperature. The reduced compressive strength of the CMUs at residual conditions can be explained by comparing its concrete counterpart. For instance, this degradation is a function of material strength at room temperature, heating rate, duration of exposure to fire [60]. This degradation is mainly due to physical and chemical changes in components of concrete, formation of micro cracks because of this and the internal stresses due to thermal expansion of aggregates. Furthermore, conversion of moisture content present in concrete under high temperature builds pressure inside the concrete, losing its strength. However, there is no data present at the moment that can correctly predict the changes occurs in concrete masonry. On the other hand, the finding from different researchers regarding behavior of concrete masonry under elevated temperature is identical to that of concrete. Hence, the degradation in compressive strength of concrete blocks can be justified with the help of these understandings.

At 200ºC, as can be seen in the figure above, the compressive strength of blocks reduced by 14%. This change can be credited to loosen of mortar mix, build up water pressure and deterioration of ITZ at temperatures up to 300ºC. Above 400ºC, concrete blocks showed total of 23% reduction in residual compressive strength. Above 400ºC, dehydration and disintegration of hydration products of concrete like calcium hydroxide (CH) occurs, which can be the reason of the further degradation of properties [63].

Moreover, 39% of initial compressive strength was lost for blocks at 600ºC. This reduction can be because of decomposition of the Calcium Silicate Hydrate (CSH) which is the main constituent of stiffness of the concrete. Around 600-800ºC, due to different thermal expansions of aggregates in cement paste and instability because of decomposition of Calcium carbonate, further decrease in strength occurs. The results from experimental testing total aligns with this showing only 20% of initial compressive strength at 800ºC. To summarize the results, the trend of degradation of masonry can be explained in two different phases viz: first phase from 100-300^{0}C, gradual decrease in residual compressive strength due to presence of moisture content. Second phase from 300-800ºC, further decrease in residual compressive strength due to decomposition of strength giving compound of cement paste.

The behavior observed from the experimental analysis was in agreement with the concrete behavior stated by [64,65]. According to [64], in case of residual testing more than 7 days after exposure to fire, moisture content in atmosphere reacts with constituents in concrete. After heating from 400ºC to 600ºC, during the cooling phase and within the first few days after a heat exposure, Calcium Oxide CaO absorbs water from the surrounding air and expands, opening the cracks that have already formed. The compressive strength is reduced by a further 20% during the cooling phase and the minimum strength is achieved up to a week after the fire, depending on the geometry of the construction element. This occurs in each plain concretes (without pozzolanic mineral additive in concrete composition) which have certain amount of Calcium Hydroxide $Ca(OH)_2$ as is the case with the concrete used in this study. Abrams [65], also inferred the same behavior of concrete showing lower compressive strength values in residual state as compared to hot state.

4.2.3 Unstressed Hot State Testing

In this section, the fire-induced degradation in compressive strength of the CMUs tested under unstressed hot conditions are presented. Three specimens at each targeted temperature were tested. The data includes the mean value of the hot state compressive strength obtained at each temperature. Figure 34 shows the variation in compressive strength with increase in temperature. The compressive strength was calculated using force values observed from testing machine divided by the net area of the tested concrete block.

In hot state conditions, compressive strength of the concrete blocks, like residual state condition, decreases with increase in temperature. However, there was some abnormal behavior was observed. At 200ºC, 9% increase in compressive strength was obtained. This slight increase in strength can be credited to the hardening of cement paste due to evaporation of water present in concrete [6,57]. At 400ºC and 600ºC, a loss of 9% and 16% was noted in strength when tested hot. At this stage, due to thermal expansion of aggregates micro cracks in concrete occurs resulting in reduced compressive strength. After 600ºC till 800ºC, compressive strength of the block dropped by 70%. After 600ºC, components in concrete responsible for giving strength start to decompose. This decomposition results in sudden loss of strength showing only 30% of initial strength at 800ºC.

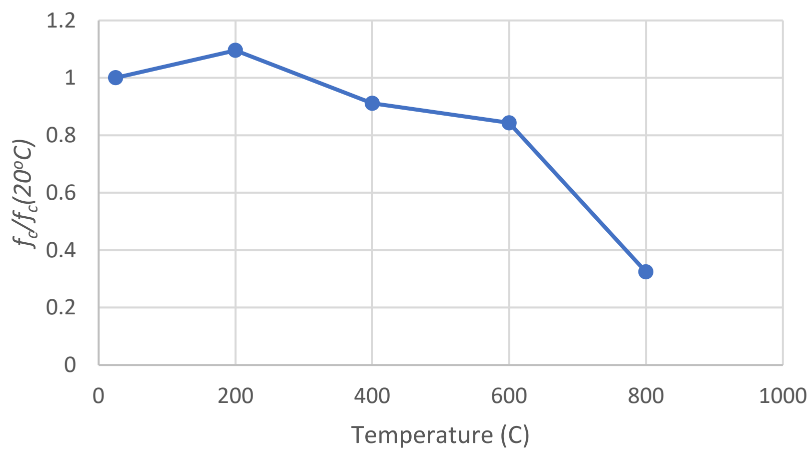


Figure 39 Compressive Strength reduction factor under hot state conditions

For unstressed hot testing at 800ºC, stress strain curve for masonry block was observed during testing under compression. Figure 31 below shows three stress strain curves of three concrete specimens used for testing. Negative strain in early stage of stress-strain curves was result of automatic head adjustment used by machine.

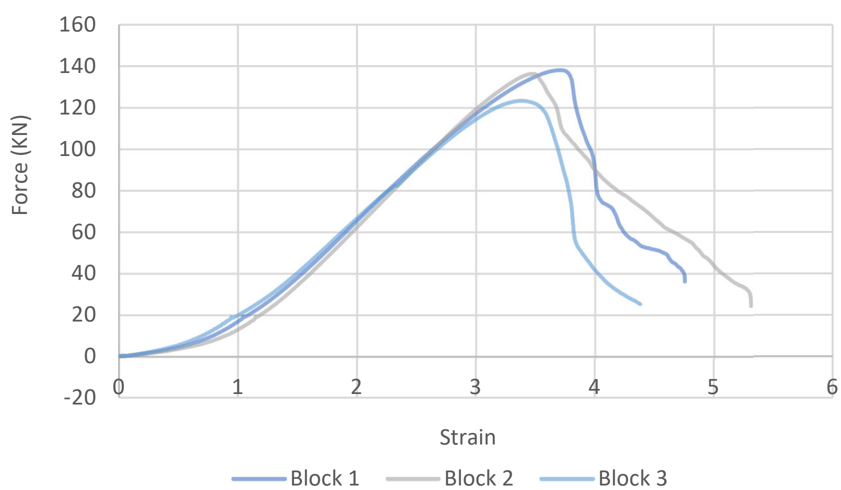


Figure 40 Stress Strain Curve for 800ºC hot state testing

4.2.4 Failure modes

The experimental study clearly infers that all the concrete masonry blocks tested under both hot and residual state testing failed due to shear splitting. Diagonal cracks throughout the load bearing membrane of the block were observed. Shear splitting due to diagonal rupture of the blocks progressing to corners was observed in blocks at ambient and elevated temperatures. Figure below shows all the failure patterns observed during testing under both residual and hot state conditions.


1)


2)

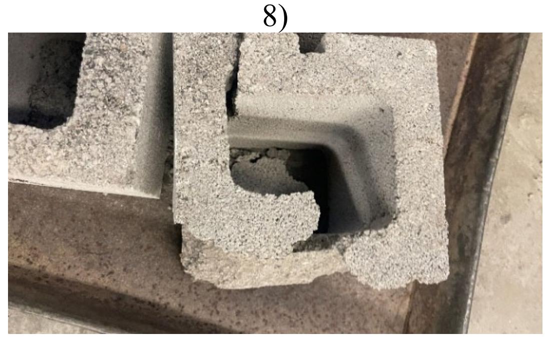

3)


4)


5)


6)

7) 8)

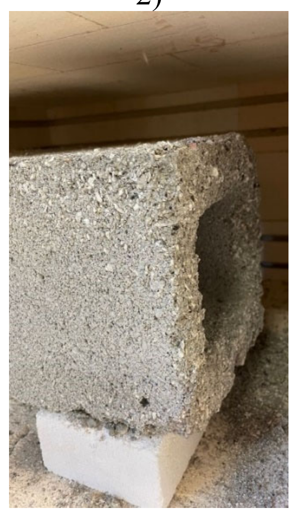


9) 10)

Figure 41 Failure mode of testes CMUs (Residual) (ambient- 1-2, 200ºC- 3-4, 400ºC- 5-6, 600ºC- 7-8, 800ºC- 9-10)

The blocks tested at 600ºC and 800ºC showed shear cracks more self-evident as compared to cracks in blocks tested under lower temperatures. It is also worth mentioning that blocks prepared for residual testing at 800ºC showed surface scarring after resting period. This can also be justification of sudden drop in compressive strength above 600ºC. Figure below shows masonry blocks prepared for 800ºC residual state testing.

1) 2)



3) 4)

Figure 42 Block prepared for 800ºC residual state testing after 15 days (Residual)

5. DATA ANALYSIS METHODS

This chapter presents data analysis methods used on data obtained in literature review stage and experimental findings. Firstly, statistical mean method is used according to ACI 216. Secondly, Bayesian method is used for accounting more variables for calculation compressive strength reduction factor values. Lastly, artificial neural network was used to predict the values for reduction facto at elevated temperatures based on training data. Results from these three methods were compared in this section.

5.1 Statistical Method

For purpose of verifying the results of the Artificial Neural Network and analyzing the data with statistical method, arithmetic mean method was adopted. The data points collected in literature review process were used for this analysis. Classification of all the values of Reduction Factors corresponding to the value of temperatures were carried out. The property data are examined at intervals of 100°C. Arithmetic mean of available values at each temperature was calculated for temperature of 25ºC, 100ºC, 200ºC, 300ºC, 400ºC, 500ºC, 600ºC, 700ºC and 800ºC. Figure 47 below shows the mean values of reduction factors with respect to temperature. This method had been used in publications by ACI 216 committee.

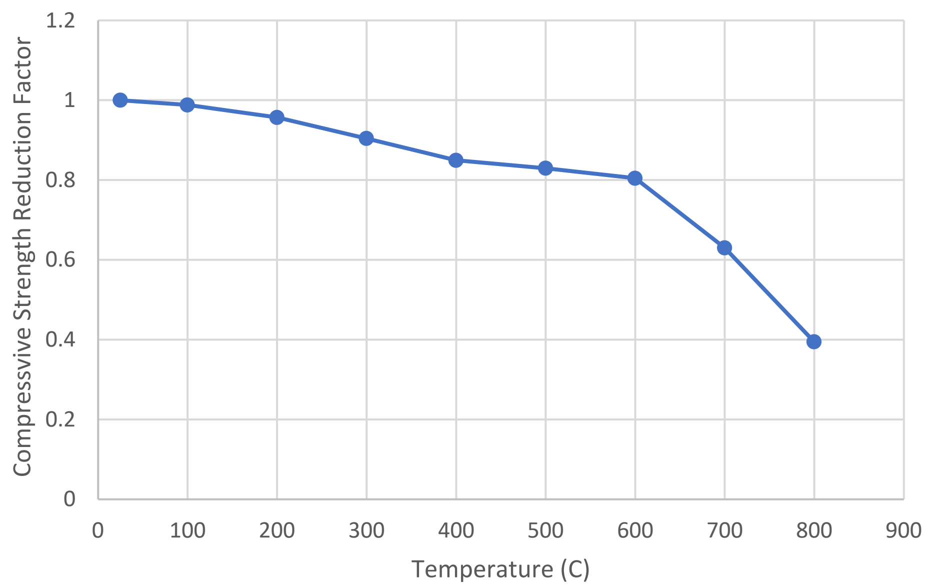
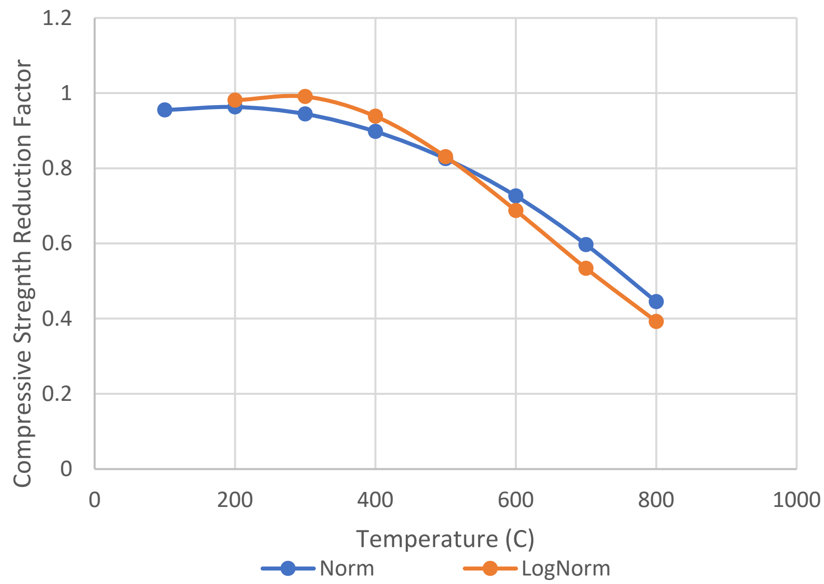


Figure 43 Compressive Strength reduction factors with respect to temperature using Statistical Method.

5.2 Bayesian Method

For the statistical analysis of the collected data, Bayesian method was adopted as stated in [66]. The data are fitted to basic distribution functions requiring a small number of parameters to define them. Normal, lognormal, Weibull, and Gamma distributions were tried. Bayesian Information Criterion (BIC) is used to determine the best distribution for the examined data at different temperatures. Normal and Lognormal distribution was found to be best fit for compressive strength data. The detail steps for the this analysis can be found in [66].

Figure 39 below show the probabilistic model of the compressive strength of masonry as a function of temperature following normal and lognormal distribution at 50th quantile, and for the normal distribution for 5 and 95% quantiles.



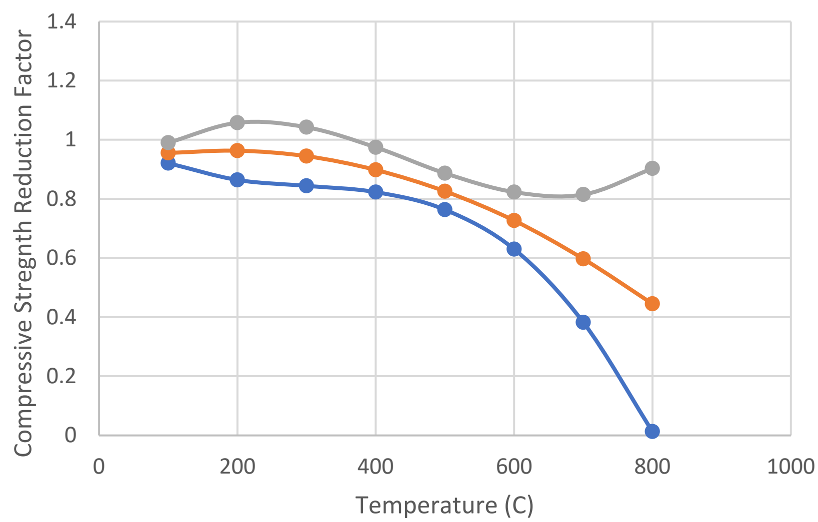


Figure 44 Compressive Strength reduction factors with respect to temperature using Bayesian Method [Note: Grey and Blue series in the bottom figure represent 5 and 95% confidence intervals].

5.3 Artificial Neural Network (ANN)

5.3.1 Introduction

The scope of this chapter is to describe the used of Artificial Neural Network (ANN) to predict the generalized behavior of variety of masonry blocks under fire exposure. In this study, results from experimental studies and data collected by various researchers as output of fire testing will be used as training data set to predict the generalize temperature dependent material model. Data points from only hot state testing were included in this program. The behavior of mechanical property of masonry is predicted with the help of correlation analysis and machine learning. Results of this methods are presented and verified with the results from statistical method.

The results are obtained from the variety of data set available from the open research. Fire test data for mechanical properties of different types of masonry blocks carried out by different researchers on variety of specimens were included in data set. The results from experimental study carried out by author are also included in primary input data set.

5.1.2 Model development and Neural Network

For the development of model, open-source data analytics Python program is used. This program is general data analytics tool to execute correlation analysis and machine learning with any available data set of moderate quality. Correlation methods allow researchers to establish relationships between input (training data set) and output (prediction data set). This features the evaluation of influence of features on the properties of materials and identifies the correlation between them. Machine learning involves two tasks: classification and regression. Classification is the way to classify the input data in a discrete set or category. Regression is the process of fitting a function in order to gain output values from input. Artificial Neural Network (ANN) is developed to mimic the way human brain processed and evaluates the information. It is a foundation of Artificial intelligence that analyses the problem and solves it which can be difficult or in some instances impossible by human or statistical methods. Due to its own topology, ANN can learn capabilities on its own and produces better results with increasing input data provided by the user. ANN are structured in a same way as human brain, with neuron links connected between them to process information. In the human brain these cells called neuron. In case of ANN this function is done by hundreds of thousands of processing units. The main function of these processing unit is same as neurons to process information towards and away from the brain. Every processing unit are divided in to two parts: input and output. Input unit receives the information provided by the user and through the neural network it attempts to learn the patterns present in it. Based on this, it creates output report. Figure 40 below shows typical structure of neural network.

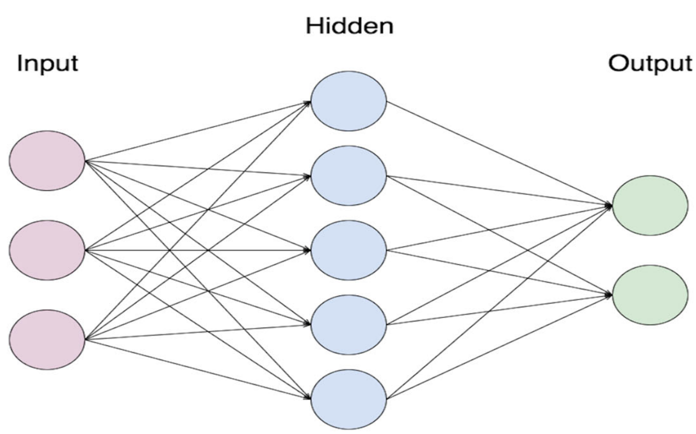


Figure 45 Typical ANN Structure

Firstly, an ANN goes through a training phase where it attempts to learn and recognize all the patterns in data. For this research, all the data points available were trained into ANN. The ANN is program to run the different types of combinations up to 1000 iterations. During this processing phase, ANN actually produces the output and compare it with the desired results. These results are then improvised by repeating number of iterations of the data increasing its accuracy. ANN literally goes backward path to recognizes the differences and corrects it to get most accurate results.

5.1.3 Results

The property model predicted by Artificial Neural Network follows the same property degradation code as obtained from experimental program. Both the property models can be said to be following two phases:

a) Gradual decrease in compressive strength till 400ºC will almost no loss till 200ºC.

b) After 400ºC, rapid reduction in compressive strength till 800ºC was observed.

The output of the artificial neural network is the generalize temperature dependent property model. Figure 47 shows the prediction of property model based on data collected from various researchers along with data from this experimental program. Both experimental outcomes and ANN predictions are seemed to in fair agreement with each other.

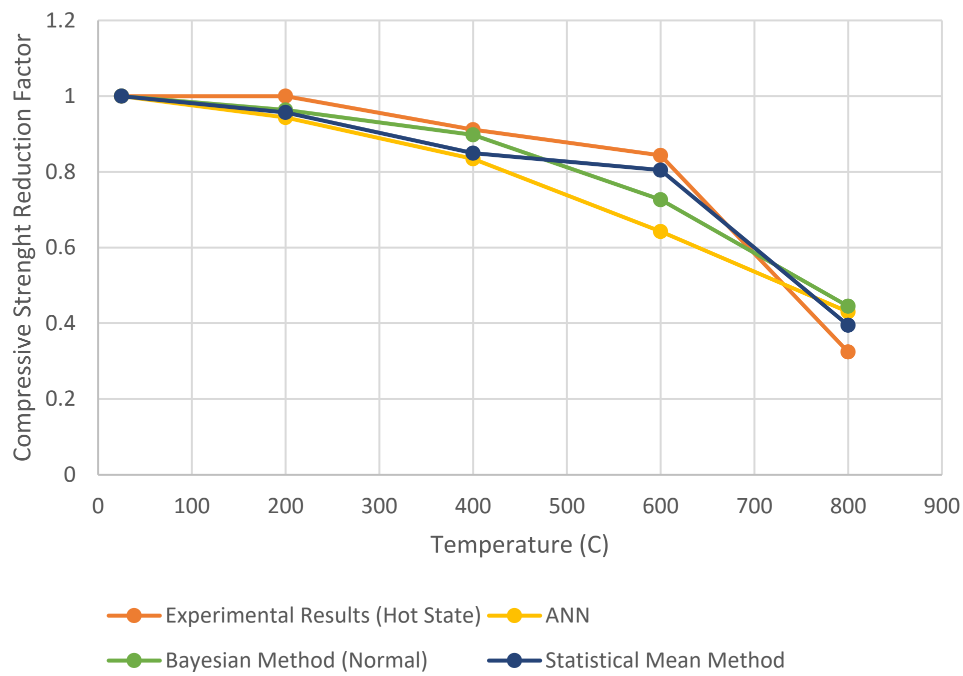


Figure 46 Compressive Strength reduction factors obtained from Experimernal Testing and ANN for Hot state conditions

However, the degradation in compressive strength from ambient to 200ºC predicted by the ANN was 6% that of strength at ambient. Difference in compressive strength at 400ºC predicted by ANN and by experimental investigation was observed to be 8%. On the other hand, notable reduction by 36% is predicted compared to only 16% loss was noted in experimental testing at 600ºC. After 600ºC, very sudden decrease of compressive strength was observed up to 800ºC. Compared to 68% loss observed in experimental study, ANN predicted 57% loss till 800ºC.

Trend of reduction in compressive strength from ambient temperature to 400ºC was observed similar when predicted different data analysis methods. Reduction in strength till 400ºC was slightly less in case of Bayesian method. The identical trend was also observed for temperature range from 400ºC to 800ºC. The rate of reduction in compressive strength increases significantly as temperature increases above 600ºC. Less than 50% of the original strength was retained by the CMU when calculated by each method. This shows fair agreement between the results from various analysis methods and can be validated with the help of experimental results.

6. CHALLENGES, FUTURE SCOPE AND LIMITATIONS

6.1 Challenges and Future Scope

The above-mentioned literature 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 presented 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 [42], ISO 834 in Europe [41,45], AS 1530.3 in Australia [67], only contains 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 [23,60,68–71].

Currently available standard testing methods for masonry illustrate procedures and specifications that are applicable for only ambient temperature conditions. On one side, it can be inferred that 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 and size etc.) which was also noted in the works of [10,25,30–38]. These noted parameters are not responsible to triggering chemical reactions and phase changes within masonry during testing but are main factors governing 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. [22,24,72,73].

While the presented test data by various researchers 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 [74–76]. The applicability of these available testing methods is worth of examinations. Despite of the proper extensibility of such tests to masonry, this investigation also rises 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 [77–79]. This further complicates fire safety design, where engineers and practitioners aim to achieve safe and optimal design.

Whether via traditional methods or advanced simulations, the lack of reliable material properties could 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) [80,81]. Hence, the deriving more reliable standard testing methods for measuring temperature dependent properties can improve the quality of results and can help in developing more reliable design manuals for masonry.

The application of Artificial Intelligence to predict the property models is still underrated in Civil Engineering but one of the most reliable and easy method [23,71]. The property model predicted from Artificial Neural Network and Statistical method are observed to be in agreement with the experimental results from testing program. However, the quality and accuracy of the results can be significantly improved to get more reliable temperature dependent property model if more data points were taken into account. Hence, there is need of more extensive experimental studies on masonry samples made up of different constituent materials to obtained more promising property model.

In addition to such methods, there is also a need for reliable equipment and instrumentation that can withstand severe and repeated elevated temperatures [81–84]. 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 [85,86].

6.2 Limitations of Experimental Program

Following mentioned are Limitation of experimental program executed by the author.

1. Testing of masonry blocks at more smaller temperature ranges are recommended to get more profound idea about behavior of masonry under elevated temperatures. Testing at every 100ºC intervals can give more details view of properties of masonry.
2. To increase the accuracy of the experimental studies, more specimens at each targeted temperature should be tested to obtain mechanical and thermal properties of different masonry materials.

3. For this experimental program, only compressive strength at elevated temperature was investigated with stress strain curves on for 800ºC hot state testing. For better understanding of physical and chemical changes in different constituents of masonry, other mechanical properties such as tensile strength of masonry of different material and different types of mortar is also recommended. Along with mechanical properties, Thermal properties of masonry material also plays important role in degradation of strength. Changes in Thermal properties of masonry material like Thermal Conductivity and Specific heat under elevated temperature are also recommended by the author.
4. The equipment available at the testing facility were not equipped with testing setup needed for testing of material under elevated temperatures. Experimental program was conducted in existing setup at Institute used for material testing. Hence, more reliable equipment and instrumentation require for fire testing of material is recommended.
5. The predictions yielded by using Artificial Neural Network represents degradation of compressive strength properties of generalize masonry material. It does not explicitly take into account the different parameters (e.g., heating rate, cooling rate, constituent materials of masonry) involved in actual physical testing. However, the influence of these factors is embedded into the algorithms for ANN. It can be said that provided more testing and data set will be available, accuracy of ANN can be increased significantly.

7. CONCLUSIONS

This chapter outlines all the conclusions of this complete research program. For better understanding this chapter is divided into three steps. Firstly, review of various experimental research programs conducted by different researchers is presented. The findings of these research were collected as input for data analysis using Statistical Method, Bayesian Method and Artificial Neural Network. Secondly, experimental program was conducted on industry standard concrete blocks to determine the compressive strength at elevated temperature. Observations from this study was also included in input for data analysis. Finally, with the help of Statistical Method, Bayesian Method and Artificial Neural Network, generalize temperature dependent compressive strength model was predicted. These results were then compared with results from Statistical Method.

7.1 Review of various masonry testing methods (Data Collection)

This thesis comprises of review of a collection of experimental methods conducted on masonry material and components over the past few decades to evaluate the mechanical and thermal properties of common masonry material used in construction applications. Furthermore, this also covers the various types of methods (full scale, half scale and small scale) adopted by different researcher to examine the response of masonry material. Owing to 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 inferences can also be drawn from this study:

Available testing methods available in current standards lack guidance towards testing of masonry materials at elevated temperatures. As such, there is an urgent need to develop standardized testing methods to evaluate mechanical and thermal properties of masonry at elevated temperatures [25,37,60]. 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 [12,26–29]. 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 [60,87]

7.2 Experimental Program

The Experimental program involved fire testing of Concrete masonry blocks under unstressed residual and hot state conditions. Conclusively, it can be said that CMUs perform well under hot state conditions as compared to residual state conditions. Below mentioned is list of key findings from this experimental study.

7.2.1 Unstressed residual testing

For determining compressive strength of the concrete masonry blocks in residual conditions, this testing was performed. The blocks were heated to targeted temperature and cooled down under unstressed conditions.

- The residual strength of the concrete blocks obtained from the experimental study shows general trend of decrease in compressive strength with increase in temperature.
- Residual compressive strength values at 200ºC, 400ºC, 600ºC and 800ºC were observed to be 14%, 23%, 39% and 80% respectively.

- Gradual decrease in compressive strength from ambient to 400ºC can be attributed to the built-up water pressure and decomposition of hydration products of concrete.
- On the other hand, much larger rate of reduction was observed between 400ºC to 800ºC. This can be credited to the thermal expansion of aggregates and decomposition of strength giving components in concrete reducing strength further.
- All the tested specimen followed the same failure pattern. Concrete specimen tested showed shear failure along the load bearing side of the blocks.

7.2.2 Unstressed Hot state

For determining the strength of concrete blocks at elevated temperature, unstressed hot state testing was carried out on same specimens. The blocks were heated to the targeted temperature and tested hot under compression.

- The hot state compressive strength of the blocks also follows the general trend of decrease as increase in temperature.
- Hot state compressive strength values at 200ºC, 400ºC, 600ºC and 800ºC were found to be 0%, 9%, 17% and 68%.
- Slight increase in strength at 200ºC can be attributed to hardening of cement paste due to evaporation of moisture content upon heating. Above 200ºC to 400ºC strength reduced further to 91% and further decreases to 87% and 32% till temperature reaches to 800ºC.
- The sudden decrease in compressive strength above 800ºC can said to cause by the decomposition of strength giving compounds. It is worth mentioning that the

blocks tested at temperature more than 200ºC were completely broke off after failure. On the other hand, for lower temperature major cracking in same pattern was observed.

7.2 Artificial Neural Network and Statistical Method (Data Analysis)

The experimental observations from all the collected data were compiled along with experimental results from this study. This collected data was used as a training data set for Artificial Neural Network to simulate property model. The variation present in current data is reduced by adopting the regression principle. These results were also compared with the results from the Statistical Analysis of the exact same data. The following list of inferences can also be drawn from this study: The predicted compressive strength model was in fair agreement with results from experimental testing. In experimental study, compressive strength of masonry blocks at 200ºC was 100% retained. However, ANN predicted loss of only 6%. Above 200ºC up to 400ºC, compressive strength of tested block was observed 9% less than that of ambient temperature. 17% reduction in Compressive strength was obtained through ANN at 400ºC. The reduction in compressive strength after 400ºC to 800ºC was observed much greater both in experimental testing and in ANN predicted model. At 600ºC and 800ºC, 16% and 68% loss were observed in testing. On the other hand, reduction of 36% and 57% was obtained from the ANN. The results from Statistical Method, Bayesian Method and ANN are fairly in agreement with each other. Experimental findings also verify the results.

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APPENDIX

Table A 1Experimental Results reported by Harmathy [34]

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
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

Figure A 1Reduction factors for Clay and Lightweight concrete (LWC) given by Andreini et al. [30,36]

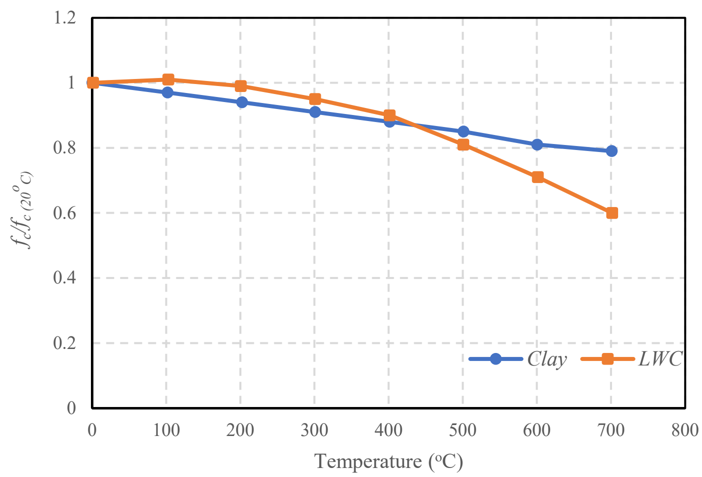


Table A 2Experimental Results from Russo et al. [33]

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 A 3Experimental Results derived by Xiao et al. [38]

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 A 2 Compressive strength reduction factors for mortar from Bosnjak et al. [10]

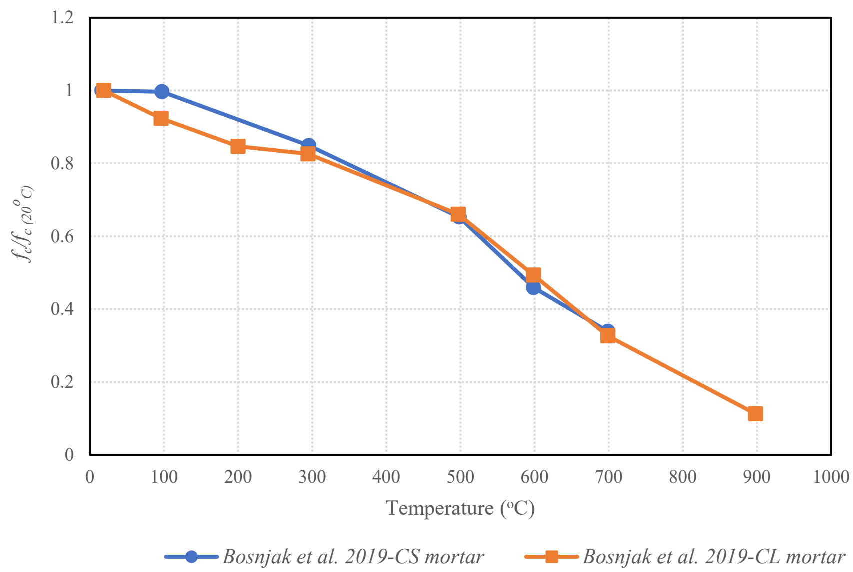
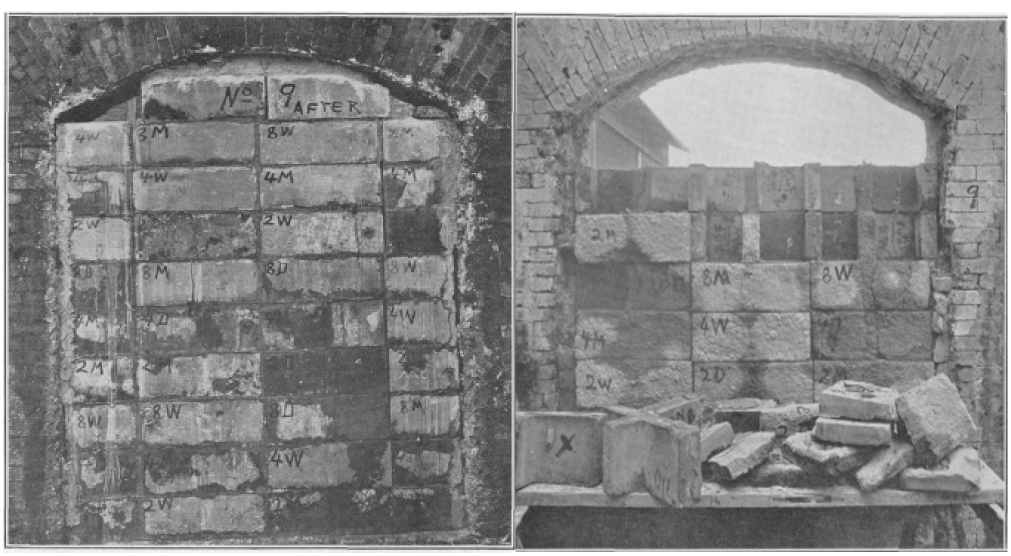


Figure A 3 Experimental test photos of walls after fire exposure, quenching (Hose Stream) and during dismantling by Humphrey et al. [46]

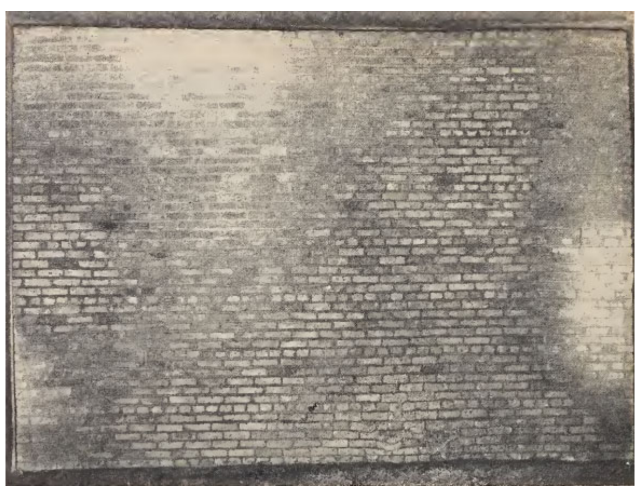


Face of Panel 9, Cement mortar building blocks after fire test, quenching (Left)

and during dismantling (Right)

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

Figure A 4 Experimental test photos of walls after fire test by Ingberg et al. [47]



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