Residual Compressive Strength of Structural Masonry Clay Unit

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ABSTRACT

The ability of load-bearing clay unit masonry walls to maintain their mechanical integrity after severe thermal events is essential to guaranteeing the protection of lives and property in a fire situation. Reoccupying a building after a fire requires a thorough assessment, especially of changes in the mechanical properties of its components, such as the unit and mortar. There are, however, gaps regarding the changes in mechanical properties that can occur with the sintering of mineral phases at high temperatures in the ceramic material. This study investigates the residual compressive strength of burnt clay structural masonry units after exposure to high temperatures. A compression test was carried out on clay units at room temperature to establish a reference parameter for residual compressive strength. Subsequently, another sample of units was subjected to a thermal test in an electric furnace, where they were heated at 400°C, 800°C and 1000°C. After slow cooling, the units were tested for compression to evaluate changes in their compressive strength. The results indicate that structural masonry clay units retain their compressive strength even after being exposed at 1000°C. This work is part of a larger program that is currently under development.

KEYWORDS

Structural burnt clay blocks. Residual compressive strength. Fire safety.

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INTRODUCTION

The simplest masonry system consists in units (block or brick) and mortar in the joints. Several geometries of masonry units are on the market. Masonry clay units can also exhibit firing heterogeneities due to the low energy efficiency of the kilns used in their manufacture [1]. Each component has different properties and behavior in a fire situation. Ceramic materials are well-known for their good thermal insulation properties, more over, the clay units are fabricated at high temperature. The masonry behavior is a function of the unit and mortar working together. Changes in properties such as cementitious materials degradation and mineral structure sintering in the clay-origin materials may occur in fire situations. It is key to understand the individual behavior of the masonry components to explain their overall behavior. It is fundamental to assess the residual mechanical capacity to evaluate the rehabilitation of a building after a fire. However, the information on the residual mechanical properties of clay units after exposure to high temperatures presents a gap. This work aims to assess the residual compressive strength of clay units to contribute to the understanding of masonry fire behavior. A vertically perforated burnt clay masonry unit was chosen due to its widespread use in buildings and social housing in Brazil, as well as its similarity to the units manufactured worldwide. The results of this study can contribute to a better understanding of the fire performance of buildings and popular housing constructed with ceramic materials.

Properties of Fired Clay Units

The porosity [1] [2] [3], water absorption [3] [4] [5] [6], adhesion [2], compressive strength [3] [4] [5] [6] [7] and thermal insulation [7] of masonry units are influenced by various factors such as manufacturing temperature, cross-sectional geometry [7], mineralogical characteristics [2] [5] of the clay and waste additions [5]. These factors also influence the cost of producing the masonry units.

Clay units fired to 950°C have lower porosity compared with clay units manufactured at 850°C and 750°C [2]. Porosities below 29% can be attained at temperatures between 1050-1100°C [3]. The optimum temperature to reduce porosity is 1200°C based in [3]. Greater porosity results in lower adhesion of the plaster to the substrate and may also damage the structural integrity [2]. The high porosity and low density induce low thermal conductivity, which remains practically stable across temperature changes [1].

Water absorption by weight below 25% can be achieved at firing temperatures of 1050-1100°C [3]. Increasing the firing temperature (800°C to 1000°C) reduced water absorption, while higher clay plasticity increased it [4]. It was found that illitic clay exhibits lower water absorption than kaolinitic clay in clay units fired at 1000°C, and it can increase (4%-25%) with the addition of bottom ash to the clay mixture [5]. In limestone calcined clay cement-based lightweight bricks, water absorption can be reduced by partially replacing expanded clay with rock wool waste [6].

The higher the compressive strength, the greater the thermal insulation of the masonry [7]. The impact of firing temperatures between 800°C-1250°C on the phase changes and microstructure of clay bricks was investigated by [3], who found a maximum compressive strength at temperature of 1200°C (89.5 MPa). Enhanced compressive strength can be achieved by increasing the firing temperature from 800°C to 1000°C, with more plastic clays resulting in higher strength [4]. Another way to improve compressive strength was found with the addition of bottom ash in the manufacture of clay units fired at 1000°C, increased it by 12-19 MPa [5]. The replacement of expanded clay with 10% waste rock wool in the manufacturing of limestone calcined clay cement-based lightweight bricks fired at 1000°C resulted in a 42.4% increase in compressive strength at room temperature, while a 5% replacement achieved a 34.88% increase [6]. To minimize manufacturing costs, ceramics intended for structural or non-structural wall applications can be produced at firing temperatures between 1050-1100°C, yielding compressive strengths ranging from 40-70 MPa [3].

The clay unit geometry affects the thermal performance of the masonry [7]. Masonry with vertically perforated units has greater thermal insulation than masonry with cellular units because of their higher void percentage, air retention and lower thermal transmission at high temperature [7].

The mineralogical characteristics of the clays also affect the final properties of the burnt clay units. The predominance of kaolinite in the production clay results in greater tensile adhesion [2]. The bricks (discs with a diameter of 50 mm and a thickness of 50 mm) produced with illitic clay showed greater mechanical performance, this result being attributed to the higher content of alkaline oxides which act as melting agents [5]. The addition of bottom ash reduced manufacturing costs, increased encapsulating heavy metals and enhanced the potential for using these units in severe climatic conditions, moreover serving as a sustainable alternative to disposing of urban solid waste in landfills [5].

Prisms, Wallets and Walls of Clay Units

The mechanical performance of prisms built with solid clay units, coated with sand, vermiculite and perlite plaster, exposed to ISO 834 standard fire was investigated in [8]. Prisms coated with perlite and vermiculite mortar showed greater resistance to fire, while those with sand showed a greater reduction in elastic modulus. Prisms with perlite maintained 70% of the strength of prisms with sand, while prisms with vermiculite maintained 45% at 1029°C. Equations were proposed to predict the elastic modulus and residual compressive strength in [8].

The residual compressive behavior of clay and calcium silicate solid units, mortar and prisms was analyzed in [9]. The specimens were heated to a target temperature, maintained for at least 2 hours, followed by slow cooling. The stiffness of the prisms was significantly reduced due to the mortar degradation, indicating that the residual stiffness is more affected by the mortar than by the units. The calcium silicate units showed substantial damage when kept in ambient conditions after firing. The calcium silicate bricks had completely disintegrated four days after firing at room temperature. This is likely due to the rehydration of components that were previously calcined at high firing temperatures, leading to material expansion and further structural damage. Details on clay units are presented in the next section. Computational finite element models and a temperature-dependent constitutive law were validated with experiments in [9].

Mechanical and thermal properties of clay units and recycled concrete units with rice husk ash, manufactured with the same external dimensions as the clay units, were investigated in [10]. Wallets were built to evaluate the fire resistance of rice husk-filled, wood fiber-filled and unfilled blocks, which were compared to small wallets built with unfilled vertically perforated clay blocks. The concrete units filled with rice ash showed greater compressive strength and the wallets built with these blocks showed greater thermal fire performance than the wallets with clay units, but lost load-bearing capacity at high temperatures. The proposed hollow rice ash blocks showed greater compressive strength, modulus of elasticity and deformation capacity than the clay units. The final deformation of the rice ash unit exceeded that of the clay unit by more than ten times. This resulted in a superior ability to withstand thermal expansion and maintain integrity at elevated temperatures of up to 1000°C.

The permeability, thermal insulation and mechanical performance of masonry built with four different clay units exposed at a temperature of 900°C were evaluated in [7]. The maximum temperature on the unexposed face of the masonry with hollow cellular units with compressive strengths of 10 MPa, 15 MPa and 18 MPa resulted in 179°C after 3 hours, 173°C after 3.5 hours and 171°C after 4 hours, respectively. Another masonry with vertically perforated units, compressive strength of 7 MPa, resulted in 163°C after 4 hours of exposure to 900°C. The result indicates that the perforated geometry has more influence on the increased thermal insulation than the compressive strength of the masonry units. All the masonry units fulfilled the gas permeability criteria. Masonry built with both four different units satisfied the mechanical performance criteria, with no lateral displacement or excessive deformation that could cause collapse or any other consequences that could affect their mechanical integrity. The service load (85 kN, 120 kN, 185 kN and 220 kN for masonry with 7 MPa, 10 MPa, 15 MPa and 18 MPa units) was reapplied 24 hours after cooling, yet there was no rupture. The lateral displacement of each wallet was not reported.

The residual mechanical behavior of masonry wallets, solid structural clay units and mortar after exposure to 300 °C and 600 °C, simulating short fires with a heating rate of 19 °C/min and a duration of one hour at maximum temperature was investigated in [11]. Exposure to 600 °C caused cracks at the unit-mortar interface and microcracks in the units, resulting in a significant reduction in strength and stiffness, while ductility increased due to greater final deformations. At 300 °C, the reduction in properties was less pronounced. Decay functions of the mechanical properties as a function of temperature were proposed.

Nguyen and Meftah [12] verified four natural-scale walls with structural and non-structural vertically perforated clay units to the REI criterion simulating the ISO 834 standardized fire. The non-structural walls, without cladding, with a thickness of 10 cm and 20 cm failed due to insulation in 43 min and 104 min, respectively. The walls with structural units, both with the same geometry, failed according to the resistance criterion. For the structural wall without cladding and with conventional mortar and a constant load of 130 kN/m, a fire resistance time of 136 min was obtained. In the structural wall with a plaster counter wall filled with rock wool on the hot face and plaster on the cold face, with thin joints and a constant load of 90 kN/m, a fire resistance time of 60 min was obtained. The two load-bearing walls failed due to mechanical performance criteria. The thin joint was a determining factor in the shorter fire resistance time. During burning, displacement towards the fire was observed. It was also observed that the occurrence of spalling changes the thermomechanical behavior, reducing the wall's resistance capacity and rigidity. A complementary study with a computer model able to simulate the effects of spalling was carried out in [13] for both load-bearing and non-load-bearing walls.

The fire performance of prisms, wallets and walls depends on the combined behavior of their components, which varies according to their isolated behavior. Studies on the residual compressive strength of clay units are presented as follows.

Residual Strength Analysis in Clay Units

Residual compressive strength can increase as the ceramic is re-fired, but it can also decrease if thermal damage occurs as a result of thermal stresses.

The residual mechanical behavior of clay briquettes manufactured at 1050°C, made with five proportions of two raw clays, one richer in silicate (61%) and alumina (31%), the other in iron oxides (4.8%), was investigated in [14]. The burnt briquettes were exposed to temperatures range 95-950°C. The combination of clays aimed to improve vitrification during sintering due to the presence of illite and to increase refractoriness due to iron oxide. The clay with the highest silicate and alumina content showed greater mechanical resistance compared to the clay with the highest concentration of iron oxides. The study proposed a stress-strain behavior model that includes the effect of temperature on the ceramic material. It was noted that increasing the temperature modifies the stress-strain curves and leads to thermal damage, affecting and, in general, decreasing both the modulus of elasticity and the compressive strength.

Limestone calcined clay cement-based lightweight bricks with the addition of waste rock wool were developed and analyzed in [6]. The partial replacement of expanded clay with rock wool waste, 5-15% by volume, increased compressive strength, thermal conductivity and fire resistance. The bricks had densities ranging from 1200-1360 kg/m³, compressive strength exceeding 8.60 MPa and water absorption below 17%. The residual compressive strength of reference sample was 70% of initial strength, while adding 5%

waste rock wool resulted in a 90% residual strength after one hour of standard fire exposure. There was also a reduction of up to 13% in carbon emissions with greater use of waste rock wool.

The residual mechanical and thermal properties of burnt clay units produced by extrusion and molded by hand after exposure for one hour at 200°C, 400°C and 600°C were investigated in [1]. The units were manufactured at 950°C. Greater uniformity of firing was observed in the manually molded units and greater defects in the extruded units. Uniformly fired units, produced by hand, showed a progressive reduction in residual compressive strength from 200°C, even though above 1.0 at all high temperatures, while units with non-uniform firing, extruded, showed a slight decrease in residual compressive strength up to 400°C, between 0.9-1.0, followed by strengthening. Greater brittle rupture was noted with increasing temperature, which was more pronounced in extruded units. These units act as thermal insulators, but have insufficient mechanical performance after exposure at high temperatures. They are recommended for use as non-structural or cladding elements, rather than as structural components in buildings.

The residual strength of the clay units was maintained up to 500°C, remained relatively high with strength above the normative values for the hot state up to around 700°C and increased the closer they got to the sintering temperatures [9]. An abrupt increase of compressive strength was observed in [9] after 1100°C reaching 188 MPa, the clay unit lost volume and darkened to a reddish color, suffered visible defects and ruptured instantly at peak load.

The compressive strength before and after 90 min of standard fire exposure in vertically perforated clay units was investigated in [10] for comparison with an innovative material for units as reported in the previous section. The compressive strength of the clay unit before standard fire exposure was 14.9 MPa. The compressive strength after exposure was obtained with precision image software, because it was only shown on the graph, resulting in 14 MPa. The residual strength at around 1000°C resulted in 0.94.

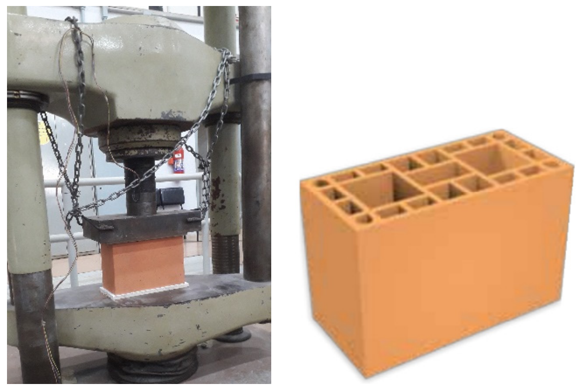
Residual mechanical behaviour of cut solid clay units was investigated in [11] at 300-600°C. The larger faces of the masonry units were clad in rock wool to simulating its place in the masonry wall. The residual compressive strength results were 0.91 and 0.62 to 300°C and 600°C, respectively. The compressive strength decrease was attributed to the high silicate content of the ceramic and was compared to similar behavior of the concretes with siliceous aggregates.

Regarding structural masonry components, several studies have examined mortar at high temperatures [8] [9] [11] [15] [16] [17] [18] [19]. Few studies have evaluated the residual compressive strength of structural masonry clay units [1] [9] [10] [11] while other studies assessed ceramic materials without considering masonry unit geometries [6] [14]. Solid clay bricks were studied in [1] [9] [11], only [10] assessed vertically perforated unit with external dimensions 115 mm x 71 mm x 240 mm and 117 mm x 115 mm x 240 mm manufactured between 900-1200°C and widely used in Germany. The residual compressive strength was assessed simulating standard fire in [10]. To contribute to the understanding of the behavior of structural masonry at high temperatures the present study was carried out with vertically perforated clay blocks with external dimensions 140 mm x 190 mm x 290 mm manufactured between 900-1000°C and widely used in Brazil and used the low and constant heating rate differently than standard fire used in [10].

METHODOLOGY

Thirty-two vertically perforated clay units, shown in Figure 1 (b), with nominal characteristic compressive strength-8 MPa based on the gross area, external nominal dimensions of 0.14 m x 0.19 m x 0.29 m, water absorption by weight of 14%, and industrially manufactured in the state of São Paulo, Brazil, were tested according to the RILEM methods [20] [21] adapted by [23].

A hydraulic compression machine, Figure 1 (a), with a capacity of 10,000 kN was used to carry out compression tests, pieces of mineral fiber ceiling tiles were placed above and below the clay unit to cap and level its surface. The traditional capping cement paste was replaced by pieces of mineral fiber ceiling tiles, as previous thermal heating would degrade the cementitious material or alter the humidity of the clay unit if the capping was done after thermal heating.



(a) (b)

Figure 1: Compression test (a) vertically perforated clay unit (b)

The horizontal furnace, as shown in Figure 2, was used to fire eight clay unit samples at a time. A heating rate of 1°C/min was used to ensure uniform heating of the samples until the target temperatures (400°C, 800°C, and 1000°C) were reached and maintained constant for one hour. Several studies indicate changes in clay unit compressive strength beyond 800°C [3] [4] [9] [14], due to mineral phase sintering [9] [14], with an abrupt change at temperatures above 1000°C [9]. A few studies report strength reduction starting at 400°C [1] [11]. For this reason, this research was conducted at target temperatures of 400°C, 800°C, and 1000°C.

(a) (b)

Figure 2: furnace (a) exterior, (b) interior

The values of heating rate and plateau to keep the target temperature were based on [22] and [23] in applying characterization of residual properties to concrete and masonry concrete units, respectively. The same rate was used for cooling. Three K-type thermocouples were used for automated temperature control, located at the mid-height of one side of the furnace. After cooling, the units were taken for the compression test.

Statistical analysis was conducted using the Shapiro-Wilk test to determine whether the results follow a normal probability distribution, the statistic W_S is obtained with Eq (1), where x_i represents the data points, $\bar{x}$ the mean, and the coefficient a_i corresponds to eight samples; the Levene test to evaluate variance homogeneity, the statistic W_L is obtained with Eq (2), where κ is the number of different groups to which the sampled cases belong, N_i is the number of cases in the i[th] group, N is the total number of cases in all groups, Y_{ij} is the value of the measured variable for the j[th] case from the i[th] group, $\bar{Y}_{i\cdot}$ is a mean of the i[th] group, $Z_{ij\cdot}$, Eq. (3), is the mean of the Z_{ij} for group i, $Z_{ij\cdot\cdot}$, Eq. (4), is the mean of all Z_{ij} and $Z_{ij} = | Y_{ij} - \bar{Y}_{i\cdot}|$; and the analysis of variance (ANOVA) to identify significant differences. For all tests, the null hypothesis (H0) was accepted for p-value > 0.05.

(1) $$W_S = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

(2) $$W_L = \frac{(N-\kappa)}{(\kappa-1)} \cdot \frac{\sum_{\iota=1}^{\kappa} N\iota\left(Z_{\iota\cdot} - Z_{\iota\cdot\cdot}\right)^2}{\sum_{\iota=1}^{\kappa}\sum_{\iota=1}^{N_\iota}\left(Z_{\iota j} - Z_{\iota\cdot}\right)^2}$$

(3) $$Z_{\iota\cdot} = \frac{1}{N_i}\sum_{j=1}^{N\iota} Z_{\iota j}$$

(4) $$Z_{\iota\cdot\cdot} = \frac{1}{N}\sum_{\iota=1}^{\kappa}\sum_{j=1}^{N\iota} Z_{\iota j}$$

RESULTS

Test Results

The results of the 32 units (U) are shown in the Table 1, organized into columns according to the corresponding temperatures. A wide variation in results was observed, with a minimum value of 9.30 MPa from unit U6 at room temperature and a maximum value of 15.41 MPa from unit U8 at 800°C, respectively. Compressive strength was calculated using the gross area of the units.

Table 1: Clay Units Compressive Strength Results

	Room Temperature	400°C	800°C	1000°C
U1	13.96	9.55	11.67	10.70
U2	14.16	10.87	11.40	10.00
U3	9.40	11.32	12.47	15.01
U4	9.34	11.81	10.78	13.94
U5	11.47	11.73	13.16	13.63
U6	9.30	10.65	13.06	10.68
U7	12.55	10.14	11.43	12.16
U8	11.48	10.81	15.41	11.72

Even though the clay material showed notable variation, with the highest found being 17.49% at room temperature, the means and medians yielded values close to each other and across the different groups, as shown in the Table 2. The residual compressive strength showed differences of less than 10% compared to the values obtained at room temperature, as presented in the Table 2. The residual strength results agree with the literature [1] [9] [10] [11] showing few differences despite geometry, heating rate and methodology, the most notable changes occur with a sharp increase after 1100°C in [9] and a sharp decrease after 600°C in [11].

The greatest dispersion of results occurs at room temperature and 1000°C, as evidenced by the larger interquartile range (IQR, the difference between the 75th and 25th percentiles) shown in the Figure 3. Nevertheless, no outliers were found in the results, with all being considered in the evaluation of the variation in compressive strength at each high temperature and in the residual strength. The residual strength was calculated using the means shown in the Figure 3.

Table 2: Median, Mean, Standard Deviation, Coefficient Variation and Residual Strength

	Room Temperature	400°C	800°C	1000°C
Median	11.48	10.84	12.07	11.94
Mean	11.46	10.86	12.42	12.23
Std. Dev.	2.00	0.77	1.47	1.79
CV	17.49%	7.10%	11.86%	14.67%
Residual Strength	1.00	0.95	1.08	1.07

A slight skewness was observed in the boxplots for all temperatures, with a greater concentration in the lower part of the range at room temperature and in the upper part for the other temperatures. It is noticeable that the results are more centralized at higher values at 800°C, as evidenced by the higher median of 11.94 MPa. The smallest interquartile range at 400°C indicates greater homogeneity.

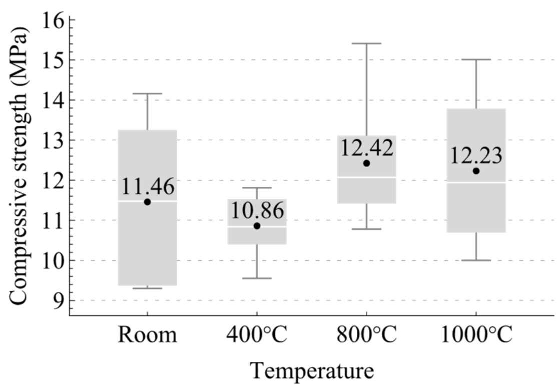


Figure 3: Temperature *vs* Compressive Strength in Median Boxplot Graph

The greatest range in maximum values, the difference between the third quartile and the maximum, was observed in units heated to 800°C, while the greatest range in minimum values, the difference between the lowest value and the first quartile, occurred at 400°C.

Results of the statistical analysis

The normal distribution of the data was confirmed with the results of the Shapiro-Wilk statistic $W_{Room} = 0.872$, $W_{400} = 0.955$, $W_{800} = 0.897$ and $W_{1000} = 0.937$, with p-values of 0.158, 0.760, 0.269, and 0.579, for the respective temperatures Room, 400°C, 800°C, and 1000°C. The homogeneity of variances was confirmed with a p-value of 0.09996 using Levene's test. Analysis of variance (ANOVA) revealed that there was no significant variation in compressive strength across the different tested temperatures, with a p-value = 0.1976. All tests were checked at a 5% significance level (p-value > 0.05). In other words, temperature has no influence on the compressive strength of the units, and statistically, there are no significant differences between the means of the compressive strengths.

CONCLUSION

High temperatures, such as those experienced in a fire, have no great influence on the compressive strength of the burnt clay units assessed in this study, as the differences between the values obtained at different temperatures are not statistically significant. The compressive strength of the units has some variation, but the mean and median values remain close at all the temperatures tested. The greatest coefficient of variation occurred at room temperature and 1000°C, while the lowest coefficient of variation was recorded at 400°C, indicating greater homogeneity in this condition. Residual strength showed a variation of less than 10% in relation to the room temperature strength, with no outliers. The data showed a normal distribution and homogeneity of variances. The analysis of variance (ANOVA) confirmed that temperature does not influence compressive strength up to 1000°C. The compressive strength results presented in the literature jointed with this work indicated the decrease on masonry walls, wallets and prisms occur owing the mortar degradation since the clay units results were less affected to high temperature. Future studies should investigate units made with different clays, focusing on the sintering of mineral phases, as well as prisms, wallets, and walls to consider the effects of mortar degradation on the structural masonry system.

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