EFFECTS OF HIGH TEMPERATURES ON MECHANICAL STRENGTH OF COMPRESSED AND STABILIZED EARTH BLOCKS

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Abstract

This study investigates the effects of high temperatures on the mechanical strength of compressed and stabilized earth blocks (CSEBs). 60 CSEB were manufactured by compacting a mixture of natural soil (sandy loam), water, and 9% (by weight) Type-II ordinary Portland cement using a manually-operated CINVA-RAM compression machine. The CSEBs were tested in flexure, dry compression, and wet compression after exposing them to five different temperatures, i.e., 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C using an electric kiln. The mechanical strengths of the CSEBs subjected to high temperature were compared to those of CSEBs left at room temperature (24 °C). The test results for increasing temperatures show: (1) a progressive reduction of the flexural strength due to development of internal cracks, (2) a small (not statistically significant) decrease in dry compressive strength, and (3) an increase in wet compressive strength due to the baking of the soil when exposed to high temperature. In addition, visual inspection of the CSEB specimens showed that the blocks exposed to 200 °C did not change color, whereas a progressively more evident change in color from brown to red was observed for increasing temperatures. In particular, for the CSEB exposed to 400 °C, 600 °C, and 800 °C, progressively thicker layers of the specimens' surface turned red, whereas the CSEB specimens exposed to 1000 °C turned completely red. This study represents a preliminary step toward the safety assessment of CSEB structures subject to severe wildfire conditions.

Introduction

An average of 62,693 wildfires occurred annually in United States and affected an average of 7.5 million acres in 2011-2020 [1]. In the same period and in California alone, 82,145 wildfires have burned over 11.9 million acres, damaging or destroying 51,086 structures, and killing 199 people. These losses have been increasing in the last 30 years and are bound to surge even more due to climate change. A significant portion of the economic losses and a disproportionate part of life losses caused by wildfires are associated with burning homes, which are mostly composed of light-frame wooden houses. Approximately one-third of these houses are located in the wildland-urban interface (WUI), where they are particularly vulnerable to wildfires. This study investigates the effect of high temperatures on the mechanical strength of compressed and stabilized earth blocks (CSEBs), which represent an alternative construction material with higher resistance to fire than wood. This study is a preliminary step toward the safety assessment of CSEB structures subject to severe wildfire conditions, and toward the goal of determining if a CSEB structure can be safely reoccupied after a wildfire. It also provides valuable data on CSEB mechanical properties that are needed for finite element modeling of CSEB structures [2].

Materials and methods

The experimental campaign included the preparation of 60 nominally-equal CSEB specimens by compacting a mixture of natural soil (sandy loam), water (20.16% by weight of the dry mix), and 9% (by weight of the dry natural soil) Type-II ordinary Portland cement. All CSEB had nominal dimensions of 290 × 150 × 90 mm and were manufactured using a single-stroke manually-operated CINVA-RAM compression machine [3]. The natural soil used in this investigation was collected in Paradise, California, by extracting soil from the layer between 1 m and 2 m below the ground surface to minimize inconsistency and inorganic content. Standard laboratory tests were performed to determine different physical properties of the soil (i.e., particle size distribution, Atterberg limits, and compaction characteristics), which are reported in **Table 1**. The natural soil is classified as “sandy loam” as per USDA, which corresponds to an optimal composition for the fabrication of CSEBs [3].

Laboratory tests	Standards	Properties	Values
Particle-size analysis	ASTM D6913-04 and D7928-16	Sand (2–0.063 mm) (%)	61.05
		Silt (0.063–0.002 mm) (%)	27.10
		Clay (<0.002 mm) (%)	11.86
Atterberg limits	ASTM D4318-10	Liquid limit LL (%)	32.00
		Plastic limit PL (%)	21.35
		Plasticity index PI (%)	10.65
Soil compaction tests	ASTM D698-12	Optimum moisture content (%)	20.16
		Maximum dry density (kg/m^3)	1711.75

Table 1. Properties of the natural soil.

CSEBs were exposed to high temperatures with the help an electric kiln using the facility of the Ceramics Studio lab in the Art Department at UC Davis, see Figure 1(a-b). Five groups of 10 specimens were each exposed to five different temperatures, i.e., 200±5 °C, 400±5 °C, 600±5 °C, 800±5 °C, and 1000±5 °C (referred to as T0200, T0400, T0600, T800, and T1000, respectively, hereinafter), as per the time-temperature relationship reported in Figure 1(c). The remaining 10 CSEB specimens were left at room temperature (24±2 °C) and are referred to as T0024 hereinafter.

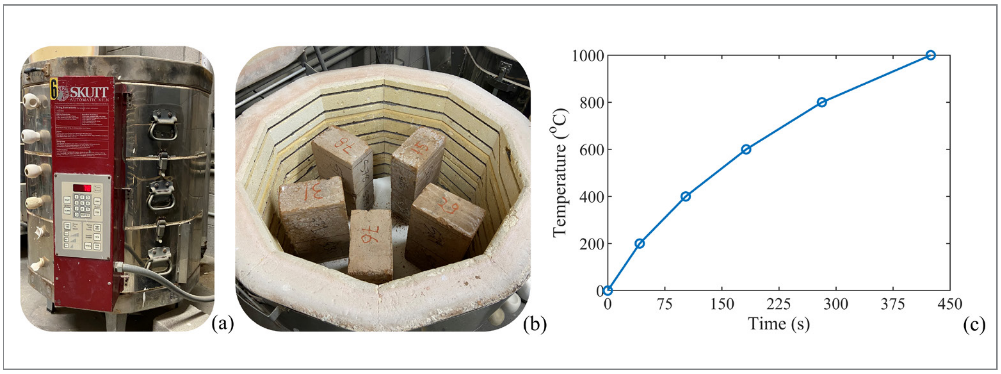

Figure 1. Experimental test setup for exposing CSEB to high temperatures: (a) electric kiln at Ceramics Studio lab in Art Department, UC Davis; (b) CSEB after exposure to high temperatures; and (c) timetemperature curve used for exposing CSEB to high temperatures.

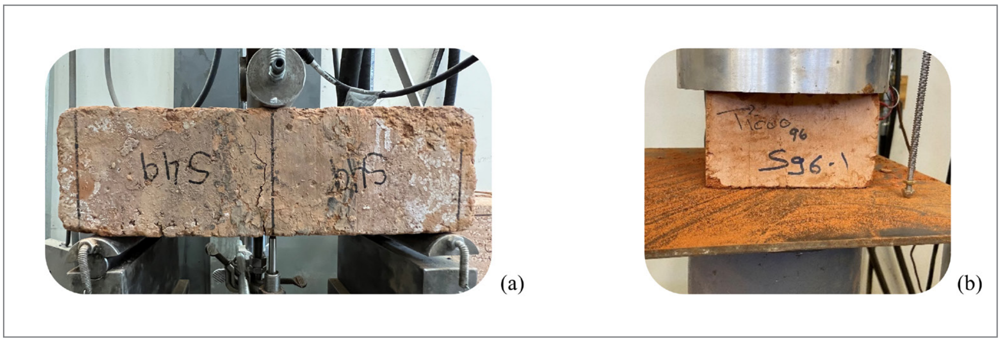

Figure 2. Mechanical tests: (a) specimen after flexure test and (b) specimen after compression test.

All CSEB specimens were first subjected to a standard three-point flexure test [4]. The displacement was applied in the middle of the block, with a distance between edge and support equal to 20 mm and a clear span equal to 250 mm. The flexure test resulted in the formation of a well-defined large crack, located approximately in the middle of the CSEBs, as shown in **Figure 2(a)**. The broken flexure specimens were trimmed using masonry cutting tools to produce smaller (half-block) specimens of dimension 122 x 150 x 90 mm. Some of the broken flexure specimens were not large enough to produce specimens for the compression test, due to asymmetry of the flexural cracks. For each temperature, five half-block specimens were tested for dry compression strength, and five specimens were immersed in water for 24 hours before being tested for wet compressive strength. The three-point flexure test was performed using displacement control via a 100 kN MTS dynamic materials 322.21 test systems, and the direct compression tests were performed using displacement control via a 444 kN MTS 311.21 load frame (**Figure 2(b)**).

One-way analysis of variance (ANOVA) was performed on the experimental results in order to determine the statistical significance of the obtained data [5]. A significance level value = 0.05 was used to decide rejection of the null hypothesis. In addition, the homogeneity of data variances was explicitly checked by employing Levene's test [6]. For the groups that failed to meet the assumption of variance homogeneity, a Welch's ANOVA test [7] was performed to identify if the differences between mean values were statistically significant. In the cases in which the (classical or Welch's) ANOVA tests rejected the null hypothesis, the Games-Howell post-hoc test [8] was used to determine the mean of

Figure 3. Visual inspection: (a) CSEB specimens after exposure to different temperatures, (b-g) typical cross-sections of CSEBs after exposure to 24 °C, 200 °C, 400 °C, 600 °C, 800 °C, and 1000 °C.

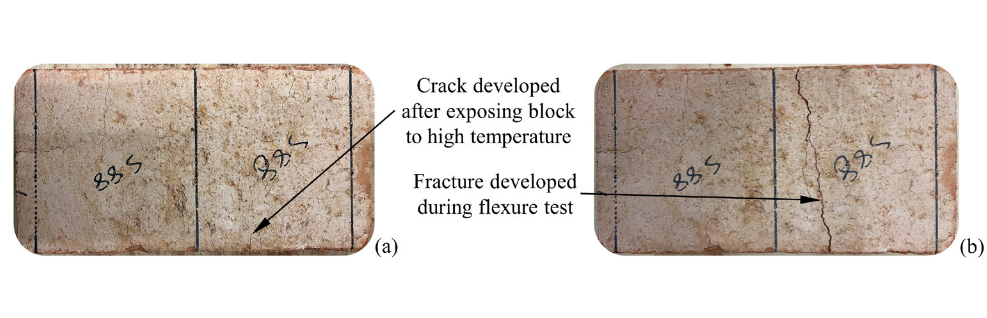

Figure 4. CSEB T1000 specimen: (a) before and (b) after flexure test.

which group(s) presented statistically significant differences from the means of the other groups. The statistical analysis was performed using the commercial software MATLAB R2019b [9].

Results and discussion

Visual inspection. CSEB specimens exposed to 200 °C did not change color, whereas a progressively more evident change in color from brown to red was observed for increasing temperatures, see **Figure 3(a)**. In particular, for the CSEB exposed to 400 °C, 600 °C, and 800 °C, progressively thicker layers of the specimens' surface turned red, see **Figure 3(c-e)**, whereas the CSEB specimens exposed to 1000 °C turned completely red, see **Figure 3(b)**.

Mechanical properties. The results of the experimental tests are reported in **Table 2** in terms of sample means and coefficients of variation (COV) of the modulus of rupture (MOR), dry compressive strength (f_{bd}), and wet compressive strength (f_{bw}). The mean value of MOR progressively decreases with increasing temperature, with reductions ranging from 19.2% to 53.3% when compared to the mean MOR of the T0024 specimens. The MOR's trend is explained by the fact that CSEBs exposed to high temperature developed internal cracks, as shown in **Figure 4**, which controlled the flexure failure of CSEB specimens.

The mean value of f_{bd} also progressively decreases when the temperature increases from 200 °C to

600 °C, with reductions ranging from 3.4% to 16.0% when compared to the mean value of f_{bd} for the T0024 specimens. The mean value of f_{bd} stabilizes at higher temperatures, with reductions equal to 13.0% and 14.4% for the T0800 and T1000 specimens, respectively, when compared to the T0024 specimens' mean value of f_{bd}. The average values of f_{bw} for the T0024, T0200, T0400, and T0600 specimens are 71.3%, 66.0%, 58.2%, and 18.60%, respectively, lower than the corresponding f_{bd}. This reduction in the f_{bw} can be attributed to the development of pore water pressures and a decrease in clay cohesion [10,11]. It is observed that the reduction in the f_{bw} becomes less pronounced with increasing temperature. In fact, the mean value of f_{bw} for the T0800 and T1000 specimens is 2.7% and 2.1%, respectively, higher than the corresponding f_{bd}. Unlike f_{bd}, the mean value of f_{bw} shows a progressive increase with increasing temperature from 200 °C to 800 °C, with increments ranging from 14.1% to 211.0% when compared to the mean f_{bw} of the T0024 specimens. This observed trend of f_{bw} is due to the fact that the earth blocks were baked when exposes to high temperatures, as also confirmed by the visual inspection shown in **Figure 3(b-g)**. The CSEB specimens exposed to 1000 °C almost fully transformed into fired clay bricks and turned completely red, whereas CSEB exposed to 400 °C, 600 °C, and 800 °C showed progressively thicker layers of the specimens' surface that turned red and corresponded to fired clay layers.

Specimen I.D.	MOR		*fbd*		*fbw*	
	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)
T0024	0.784	35.7	9.67	19.3	2.78	06.6
T0200	0.634	25.5	9.34	16.9	3.17	12.2
T0400	0.582	29.2	8.83	11.0	3.69	20.5
T0600	0.570	28.0	8.12	07.7	6.61	11.7
T0800	0.442	33.4	8.41	26.7	8.64	14.8
T1000	0.366	36.9	8.28	11.7	8.45	25.9

Table 2. Mechanical properties of CSEBs expose to different temperatures.

Statistical analysis. The results of the statistical analysis performed on the experimental test results are reported in **Table 3** and **Table 4**. The statistical study indicates that: (1) the mean value of the T1000 specimens' MOR is statistically different from those of the T0024, T0200 and T0400 specimens, and the MOR mean value of the T1000 specimens is statistically different from that of the T0024 specimens; (2) the differences in the mean values of f_{bd} for specimens corresponding to different temperature is statistically insignificant; and (3) the mean values of f_{bw} for the T0600, T0800, and T1000 specimens presents a statistically significant difference from those of the T0024, T0200 and T0400 specimens. In addition, the statistical analysis also shows that the mean values of f_{bw} for the T0024, T0200, T0400, and T0600 specimens is statistically different from the corresponding f_{bd}, whereas the differences between the average f_{bw} and f_{bd} values for the T0800 and T1000 specimens are statistically insignificant.

Test	MOR	f_{bd}	f_{bw}
Levene's test	0.15	0.10	<u>0.02</u>
ANOVA/Welch	<0.01	0.51	<0.01

Table 3. Statistical tests and corresponding p-values for the experimental test results.

Specimen I.D.		Games Howell Test			Specimen I.D.		Games Howell Test		
group 1	group 2	MOR	*fbd*	*fbw*	group 1	group 2	MOR	*fbd*	*fbw*
T0024	T0200	0.682	-	0.417	T0200	T1000	<u>0.009</u>	-	<u>0.030</u>
T0024	T0400	0.349	-	0.258	T0400	T0600	0.999	-	<u>0.003</u>
T0024	T0600	0.405	-	<u>0.002</u>	T0400	T0800	0.473	-	<u>0.002</u>
T0024	T0800	<u>0.039</u>	-	<u>0.003</u>	T0400	T1000	0.072	-	<u>0.038</u>
T0024	T1000	<u>0.010</u>	-	0.025	T0600	T0800	0.364	-	0.130
T0200	T0400	0.952	-	0.746	T0600	T1000	<u>0.046</u>	-	0.544
T0200	T0600	0.980	-	<u>0.001</u>	T0800	T1000	0.837	-	1.000
T0200	T0800	0.109	-	<u>0.002</u>	-	-	-	-	-

Table 4. p-values of the Games-Howell post-hoc tests for the experimental test results.

Conclusions

This study investigates effect of high temperatures on the mechanical strength of compressed and stabilized earth blocks (CSEB). The visual inspection of the CSEB specimens showed that the blocks exposed to 200 °C did not change color, whereas a progressively more evident change in color from brown to red was observed for increasing temperatures. For the CSEB exposed to 400 °C, 600 °C, and 800 °C, progressively thicker layers of the specimens' surface turned red, whereas the CSEB specimens exposed to 1000 °C turned completely red. The experimental test results and their statistical analysis of CSEBs exposed to high temperatures show: (1) a progressive reduction of the flexural strength with increasing temperature due to development of internal cracks, which is statistically significant for temperatures equal to or higher than 800 °C; (2) a small and statistically insignificant decrease in dry compressive strength with increasing temperature; and (3) an increase in wet compressive strength due to the baking of the soil when exposes to high temperatures, which is statistically significant for temperatures equal to or higher than 600 °C . These findings present a preliminary step toward the safety assessment of CSEB structures subject to severe wildfire conditions.

Acknowledgments

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