Thermal characteristics of rammed earth stabilized using cement, fly ash, and bentonite

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ABSTRACT
The traditional rammed earth construction is currently regaining popularity in North America for several reasons, such as low maintenance cost, high energy efficiency, locally available raw materials, low CO_2 emissions, and better recyclability. Previous studies have proved that the strength and durability of rammed earth can be further improved by adding cementitious materials such as Portland cement, fly ash, natural and synthetic fibers, and steel slag, but no significant research has been conducted to evaluate the thermal behavior of these modified RE materials. In this study, the effect of chemical additives such as cement, wood fly ash, and calcium bentonite on the thermal properties of rammed earth (RE) material is evaluated to assess the viability in hot and cold climates. The time lag and peak temperature were measured by testing compacted and cured hollow RE samples. An environmental chamber was used throughout this study for curing the RE specimens under simulated weather conditions. A hot climate with 40% and 80% humidity and temperature that decreases from 45°c to 27°c with a uniform slope and a cold climate with a humidity of 40% and temperature that increases from -7°c to 12°c with a uniform slope were simulated. While the partial replacement of cement in RE with fly ash improved the thermal properties of the material in both hot and cold climates, incorporating 15% calcium bentonite in the mix design further enhanced the thermal efficiency of RE in cold climates. Also, the thermal conductivity tests have shown that substituting a major fraction of cement in RE with wood fly ash can improve the thermal conductivity by up to 20%. Hence, the results of this study indicate that the wood ash-stabilized rammed earth is suitable for construction in colder climates.

RÉSUMÉ
La construction traditionnelle en pisé est actuellement en train de regagner en popularité en Amérique du Nord pour plusieurs raisons telles que le faible coût d'entretien, l'efficacité énergétique élevée, les matières premières disponibles localement, les faibles émissions de CO2 et une meilleure recyclabilité. Des études antérieures ont prouvé que la résistance et la durabilité du pisé peuvent être encore améliorées en ajoutant des matériaux cimentaires tels que le ciment Portland, les cendres volantes, les fibres naturelles et synthétiques et les scories d'acier; mais aucune recherche significative n'a été menée pour évaluer le comportement thermique de ces matériaux pisés modifiés. Dans cette étude, l'effet d'additifs chimiques tels que le ciment, les cendres volantes de bois et la bentonite de calcium sur les propriétés thermiques du matériau de pisé est analysé pour évaluer la viabilité dans les climats chauds et froids. Le décalage temporel et la température maximale ont été mesurés en testant des échantillons de pisé creux compactés et durcis. Une chambre climatique a été utilisée tout au long de cette étude pour durcir les spécimens de pisé dans des conditions météorologiques simulées. Un climat chaud avec 40% et 80% d'humidité et une température qui diminue de 45°c à 27°c avec une pente uniforme et un climat froid avec une humidité de 40% et une température qui augmente de -7°c à 12°c avec une pente uniforme a été simulée. Alors que le remplacement partiel du ciment dans le pisé par des cendres volantes a amélioré les propriétés thermiques du matériau dans les climats chauds et froids, l'incorporation de 15% de bentonite calcique dans la conception du mélange a encore amélioré l'efficacité thermique du pisé dans les climats froids. De plus, les tests de conductivité thermique ont montré que le remplacement d'une fraction majeure de ciment dans le pisé par des cendres volantes de bois peut améliorer la conductivité thermique jusqu'à 20%. Par conséquent, les résultats de cette étude indiquent que le pisé stabilisé à la cendre de bois convient à la construction dans les climats froids.

1 INTRODUCTION

The traditional building materials such as rammed earth (RE) were replaced by a great range of new composite materials like concrete due to their better thermomechanical properties. However, the major downsides of concrete, such as high energy consumption and carbon footprints, have resulted in environmental issues such as air pollution and climate change problems (Liu et al., 2018). Because of these problems, rammed earth material as one of the earthen materials has become popular again due to several advantages such as low production cost, less energy use, availability, low CO2 emissions, and recyclability. However, there is still a low market demand for this sustainable material due to its relatively low compressive and tensile strength. It is mainly used only in low-rise buildings and for aesthetic construction. Therefore, the need to address the structural problems of using RE material in high-rise buildings has become more acute.

A method that has an extraordinary effect on mechanical properties is improving the properties of RE walls with stabilizers. Some used stabilizers in research are fly ash, cement, date palm fiber, polypropylene fiber, and steel slag. Researchers are trying to find the best proportion of added material to achieve the mentioned amount in standards, such as the Mexico Earthen Building Materials Code (Maniatidis & Walker, 2008), which sets 2MPa for minimum compressive strength. Likewise, Cristelo et al. (2012) demonstrated the effect of Na_2O, $Ca(OH)_2$, NaCl, and coal fly ash in different proportions under process time up to seven days at 60°C curing temperature. These results showed a substantial improvement of the RE compressive strength with various chemical treatments. Also, the effect of binders such as wood fly ash and calcium carbide residue was tested by Siddiqua et al. (2018) and Naeini et al. (2021). They added different binder contents to the RE recipe, and compacted specimens were tested after different curing times, between 3 and 60 days; they significantly increased strength.

In another investigation, Liu et al. (2018) found a dramatic improvement in rammed earth's mechanical property and thermal conductivity by adding steel slag. These researches used representative volume element (RVE) or compressed earth blocks (CEB) instead of real-size samples. Bui et al. (2009) examined the impact of sample size on the compressive strength, and they compared the results of RVE and CEB models with in-situ walls. They found that sample size affected results and suggested that researchers use the real-size models to more accurately investigate. Their results showed a good correlation with similar research by Maniatidis and Walker (2008). Also, Bui and Morel (2009) studied the anisotropy of RE walls by checking the strength of the walls in two parallel directions. They found that the differences in results are minor, and RE materials can be assumed as isotropic materials.

1.1 Thermal Properties of Rammed Earth

Some studies were also carried out to evaluate the thermal properties of modified RE. Pakand and Toufigh (2017) found the best composition of additive materials, namely phase change material (PCM), expanded polystyrene (EPS), and cement, by using an analytical network process (ANP) and genetic algorithm (GA). The used criteria in their research were construction cost, the weight of the building, carbon footprint, mechanical properties, and thermal performance. They found that cement is more efficient because of the lower construction cost despite good improvement in thermal properties by using EPS and PCM. Samadianfard and Toufigh (2020) measured the dynamic thermal properties of un-stabilized and stabilized rammed earth walls using a hygrothermal chamber and compared them with the results of masonry walls. The measured parameters are heat flux, time lag, decrement factor, and time lag. To evaluate the thermal conductivity, the hot wire method was used. The results showed better performance than masonry walls. They found that using an acrylic insulator has a low effect on the performance of masonry walls and improves the thermal capacity of rammed earth walls.

Another additive material used to improve the thermal performance of rammed earth walls is rice husk used by Milani and Labaki (2012). Their results showed improved energy use efficiency in the building by adding a maximum of 7.5 percent rice husk to cement stabilized RE. They built a prototype building and collected the temperature inside and outside the building in winter and summer. The evaluated thermal conductivity for SRE with 7.5 percent of ash and 10 percent of cement is 0.65 w/mK, which shows significant improvement, compared with 0.80 and 1.00 for a 10-percent cement stabilized rammed earth and ceramic brick, respectively. It is concluded that rice husk improves the thermal properties by increasing the porosity of samples.

Serrano et al. (2016) compared the thermal performance of rammed earth, insulated RE with REF, PU, and XPS. They used controlled temperature conditions and real-size samples in their research. Using six-centimeter wooden insulation material for insulating rammed earth samples improved the thermal efficiency. The results for these samples were close to the results of PU and XPS. Insulated RE increased the temperature difference between inside and outside the building by about 90 percent, while the reduction for RE samples was about 10 percent. This difference shows that cement stabilized RE needs modification to improve its thermal performance.

Thermal comfort and energy use in a rammed earth building are evaluated by Taylor et al. (2008). Based on a questionnaire, they found the building in summer is too hot and too cold in winter. By comparing the energy use in RE building with a conventional building in that area, it was observable that it has more energy use for heating, which is more than the amount specified by the Australian Building Codes Board. Their evaluation showed that 70 percent of the time in winter, the temperature was outside of the comfort zone, which is worthier than summer by 20 percent. They simulate the inside temperature of the building, and by comparing its result with the measured temperature, this simulation is evaluated. The validated model was used to improve the design of the building.

In this study effect of adding fly ash and ca-bentonite on thermal properties of rammed earth samples are evaluated. Dynamic thermal parameters of rammed earth walls such as time lag, peak temperature, and thermal conductivity are measured.

2 MATERIALS AND METHODS

2.1. Characterization of soil:

The used soil in this study is collected from a local construction site in Kelowna, British Columbia. This soil was sieved, and particles greater than 2 mm were removed. The modeled soil based on the Unified Soil Classification System, USCS (ASTM D2487), is graded as poorly graded sand (SP) (figure 1). Less than 2 percent is fines, 45 percent is fine sands, and 53 of that is coarse sand. The particle size distribution graph is presented in figure 1.

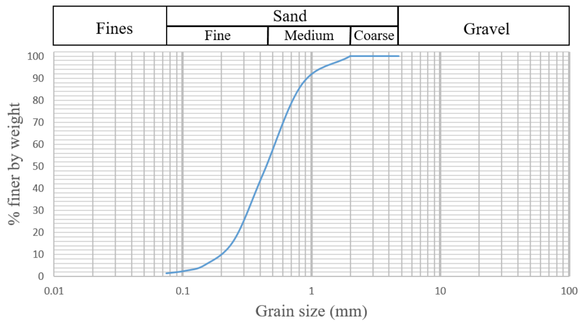

Figure 1. Particle size distribution of soil

2.2. Wood Fly Ash from Pulp and Paper Industry

Solid waste from burning wood and coal generates fly ash. Mostly fly ash is classified based on particle size. The chemical composition and pozzolanic activity of fly ash are related to its particle size. As the particle size decreases, the number of modifiers ($CaO+MgO+Na_2O+K_2O$) increases, and conversely, the amount of Fe_2O_3 decreases. These changes mean the finest fly ash has higher pozzolanic activity and compressive strength than coarser fly ash in stabilized rammed earth walls. (Feng & Li, 2021).

The wood-based fly ash used in this study (denoted as PFA) was collected from a local Kraft pulp mill in Kamloops, BC. Based on the USCS, it was classified as non-plastic silty sand (SMN).

2.3. Sample Preparation and Curing Process

These samples are cylindrical hollow specimens with an outer and inner diameter of 114 and 32 millimeters, respectively. The height of these samples is 200 mm. These samples were compacted in 10 layers using the optimum moisture content for each recipe, and they were cured in the mold for 48 hours. Samples were kept in a moist room for 21 days with a temperature of 22°c and humidity of 80%, and after that, they were cured at room temperature for the last seven days. The schematic of the used mold for making these samples is presented in Figure 2. For each mixture, three samples were prepared, and the average results were presented.

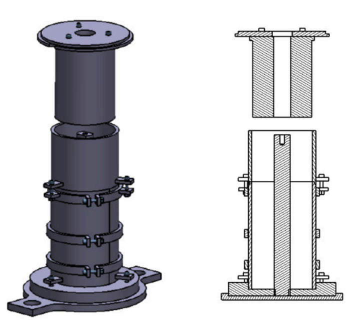

Figure 2. Schematic of used mold for sample preparation

An environmental chamber was used to check the samples' heat transfer. This chamber was used to simulate the outside temperature and humidity. During the test, the humidity was constant at 40 and 80 percent. To have the same moisture content, samples were placed in the chamber with the same humidity 24 hours before the test. Two temperature sensors were placed outside and two inside the samples to monitor the temperature. For sealing the hole, insulation material was used (Figure 3).

DS18B20 temperature sensors with an accuracy of 0.5°c are used to monitor the temperature. The Arduino Due sends collected data from sensors to the computer. In this process, two software, Arduino IDE 1.8.15 and CoolTerm, are used. The temperature was controlled and collected simultaneously for all used sensors every three minutes.

Figure 3. Test setup to simulate outside temperature to find time lag and decrement factor

2.4. Mix Design

The same mixes in sample preparation are used to compare the results of different tests. The summary of these mixes is presented in Table 1. Control specimens were prepared using 10 percent Portland cement and 90 percent soil.

Table 1. Summary of rammed earth mixes

Sample ID	Mass ratio (%)			
	Soil	PC	PFA	Ca-bentonite
SC10	90%	10%	0%	0%
SCP55	90%	5%	5%	0%
SCP105	85%	10%	5%	0%
SCP510	85%	5%	10%	0%
SCP1010	80%	10%	10%	0%
SCPB5515	75%	5%	5%	15%
SCB10515	70%	10%	5%	15%
SCPB51015	70%	5%	10%	15%
SCPB101015	65%	10%	10%	15%

A modified proctor compaction method was used to find the optimum moisture content of the mixes. The results of that are presented in table 2.

Table 2. Maximum dry density and optimum moisture content of mixes

Sample ID	MDD (gr/mm^3)	OMC (%)
SC10	1.723E-03	11.55%
SCP55	1.609E-03	15.54%
SCP105	1.629E-03	14.22%
SCP510	1.545E-03	17.18%
SCP1010	1.626E-03	16.59%
SCPB5515	1.666E-03	15.49%
SCB10515	1.676E-03	15.88%
SCPB51015	1.580E-03	17.55%
SCPB101015	1.600E-03	18.69%

3 RESULTS AND DISCUSSION

3.1. Thermal Properties

3.1.1. Time lag and decrement factor

To confirm the effectiveness of adding additives, it is essential to check their effect on other RE materials' characteristics. For this reason, dynamic thermal parameters of rammed earth walls such as time lag and peak temperature must be measured.

The parameter 'Time lag' is the duration time of transferring heat from the outside of the wall to the inside and changing the internal temperature, which can be calculated through equation 1:

$$TL = T^t_{max,out} - T^t_{max,in} \qquad [1]$$

$T^t_{max,out}$= the time of maximum temperature outside of the wall

$T^t_{max,in}$= the time of maximum temperature inside of the wall

The decrement factor is the ratio of max variation of inside and outside of the wall, which is calculated by equation 2:

$$DF = \frac{T_{max,in} - T_{min,in}}{T_{max,out} - T_{min,out}} \qquad [2]$$

$T_{max,in}$ and $T_{min,in}$ are the maximum and minimum temperatures inside the wall, respectively.

$T_{max,out}$ and $T_{min,out}$ are maximum and minimum temperatures outside the wall.

Figure 4 shows the temperature gradient outside of the samples. The duration of the test was 150 minutes.

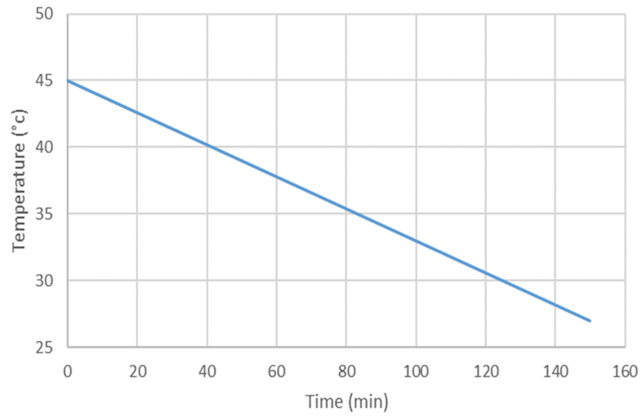

Figure 4. Temperature gradient outside of samples

To find the effect of ambient humidity on thermal properties, this test was performed for two different humidities, 40 and 80 percent. The test results with 40 percent humidity and temperature that decreases from 45°c to 27°c are presented in Table 3.

Table 3: results of time lag and decrement factor for hot climate and 40 percent humidity

Sample ID	TL (min)	DF
SC10	92.38	0.761
SCP55	96.68	0.788
SCP105	99.68	0.753
SCP510	95.01	0.781
SCP1010	103.24	0.724
SCPB5515	97.37	0.761
SCB10515	103.92	0.733
SCPB51015	100.99	0.673
SCPB101015	114.28	0.701

Based on these results, samples with 5 percent cement, 10 percent fly ash, and 15 percent ca-bentonite had the best thermal properties. Results showed samples with the same amount of fly ash and ca-bentonite, the thermal properties of samples would improve by decreasing the amount of cement by 5 percent. Also, comparing SCP105 and SCP1010 by the reference sample shows that adding fly ash improves this material's thermal performance. Also, the test results with 80 percent humidity and temperature that decreases from 45°c to 27°c are presented in Table 4.

Table 4: results of time lag and decrement factor for hot climate and 80 percent humidity

Sample ID	TL (min)	DF
SC10	63.39	0.833
SCP55	53.48	0.778
SCP105	59.19	0.802
SCP510	66.18	0.806
SCP1010	60.06	0.834
SCPB5515	64.46	0.806
SCB10515	73.67	0.816
SCPB51015	69.74	0.802
SCPB101015	65.44	0.806

This test showed that samples with ca-bentonite have better performance in higher humidity. In this test, SCPB51015 has the best properties. By comparing the test results with humidity of 40% and 80%, it is observable that rammed earth walls have better performance in dry climates.

In another test, the thermal properties of this material in a cold climate are evaluated. The temperature gradient of the test is presented in Figure 5. The results of this test are presented in Table 5.

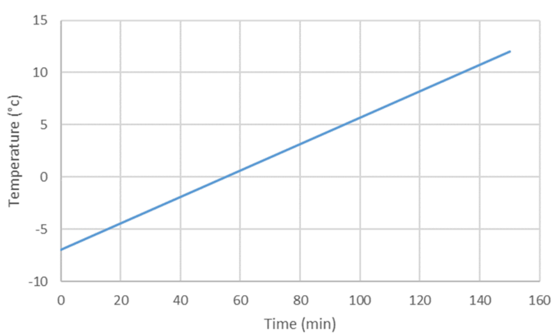

Figure 5. Temperature gradient outside of samples

Table 5: results of time lag and decrement factor for cold climate

Sample ID	TL	DF
SC10	96.03	0.753
SCP55	99.53	0.727
SCP105	92.1	0.779
SCP510	94.56	0.793
SCP1010	93.54	0.747
SCPB5515	130.35	0.687
SCB10515	111.95	0.704
SCPB51015	102.06	0.720
SCPB101015	101.85	0.714

These data have shown that samples with 15 percent have a better thermal performance. It could be concluded that using 10 percent fly ash in cold climates to improve the thermal properties of rammed earth walls is beneficial.

3.2 Thermal Conductivity

The thermal conductivity tester was used to find the thermal conductivity of rammed earth materials (Figure 6a). The samples were prepared with the same recipes. The cylindrical samples with an outside diameter of 54 mm and thickness of 10 mm and 20 mm were prepared (Figure 6b). Samples with lower thickness were compacted in one layer, and samples with 20-mm thickness were compacted in two layers. After 30 days of curing, these samples were tested, and the results are reported in Table 6.

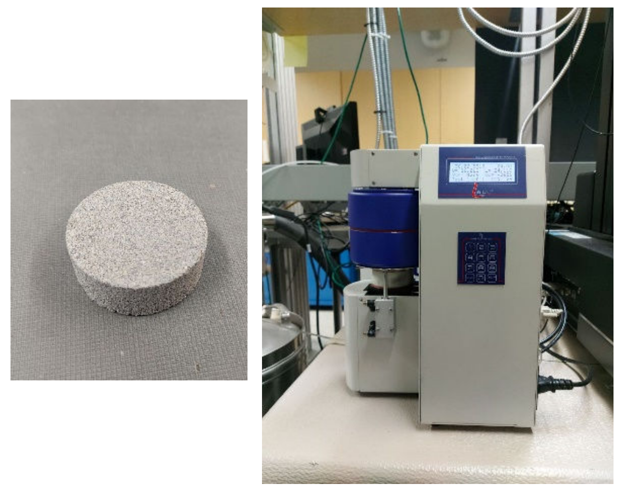

Figure 6. Sample and equipment for the thermal conductivity test

Table 6: results of Thermal conductivity

Sample ID	Thermal conductivity (w/mK)
SC10	0.562
SCP55	0.448
SCP105	0.530
SCP510	0.362
SCP1010	0.444
SCPB5515	0.487
SCB10515	0.524
SCPB51015	0.385
SCPB101015	0.509

The results confirmed that using fly ash as an additive material could improve the thermal properties of rammed earth material. Also, adding ca-bentonite has a good effect on the thermal performance of the buildings.

4 CONCLUSIONS

This study aims to find a way to consume fly ash made by burning woods in power plants and reduce the consumption of cement used in rammed earth walls. In this research, the effect of fly ash and ca-bentonite as an additive on the thermal properties of rammed earth materials is evaluated. A conventional mix with 90 percent soil and 10 percent cement was used as a control specimen. In sample preparation, different dosages of additives are used. Two types of samples, hollow samples to evaluate the time lag and decrement factor and cylindrical samples to find thermal conductivity, were prepared. The results showed that adding fly ash could increase the time lag and decrease the decrement factor that improves the thermal performance of buildings. Results of the thermal conductivity test also confirmed this effect. Using fly ash in a hot climate with 40 and 80 percent humidity and in a cold climate improved the thermal properties. Another additive, ca-bentonite, had a good effect on thermal properties in these three climatic conditions and significantly improved the properties at low temperatures.

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