Influence of varying mix proportions on thermal performance of soil-cement blocks

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Abstract

Soil-cement blocks generally comprise graded soil, cement and sand to varying proportions to achieve desired structural performance and durability. In their actual integration as part of a building masonry element (envelope), the thermal performance of these blocks determines the climate-responsiveness of the building. However, little study has been done in discerning the influence of varying mix-proportion on the thermal performance of these blocks. The current study examines the role of physio-chemical properties, determined by the varying mix-proportions, on the thermal performance of soil-cement blocks. The paper discerns the influence of the clay content, cement content and dry density on the thermal conductivity of the soil-cement blocks. For this study, soil-cement blocks casted with locally available materials been adopted. Preliminary results revealed that as the clay content increases from 10.5 to 31.6% the thermal conductivity value increases. Further, with an increase in cement content from 5 to 16% the thermal conductivity values also increases.

The thermal conductivity tests conducted using QTM-500 thermal conductivity testing instrument. Further investigation included the influence of soil-cement blocks' thermal properties on dynamic building thermal performance such as time lag and decrement factor. The results of the study are expected to support design of climate-responsive building envelopes for various climatic conditions.

1. Introduction

The physio-chemical properties of soils can be altered or modified by adding stabilizers (admixtures) such as cement and lime, a process termed as soil-stabilization. Cement stabilized soils are used in the constructions of roads, pavements, slope protections, canal linings, etc. They are also used for preparing high-density soil-cement blocks for load-bearing masonry structures. A block-making machine used to compact soil into high-density blocks.

Earlier studies on the soil-cement blocks give broad guidelines to select suitable soils for making blocks and the range of strength and water absorption values for blocks. Most soil-cement blocks' properties (mechanical and durability), production techniques, density, soil-sand mix, soil-cement mix designs (% of clay content, soil, sand cement contents) etc. is very well established. Mechanical properties such as compressive, flexural and direct tensile strength and moisture content of soil-cement blocks are most commonly studied properties of soil-cement blocks. More information on such properties of soil-cement blocks can be found in the studies of Venkatarama Reddy (1995, 2006 and 2007).

There are barely any studies specifically dealing with thermal properties of soil-cement blocks. There is a need for understanding and also for a methodology for such studies. Thermal properties of building materials include thermal conductivity,

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diffusivity, emissivity and specific heat, and for practical purposes they are generally determined through their thermal conductivity and specific heat. Hence, the present paper focuses on understanding thermal properties such as thermal conductivity and specific heat capacity of soil-cement blocks having different cement content, densities and clay content, while still retaining structural performance and durability.

2. Experimental Programme

2.1 Materials used for soil-cement blocks

A locally available natural red loamy soil has been used for block making. The soil having a composition of sand (48%), silt (28.6%) and clay (23.4%) is used. The natural soil is reconstituted by blending with river sand in the ratios so that the resulting soil-sand mixture comprises varying clay, silt and sand fractions. Thus, 3 completely different soils (varying clay content) were generated without altering the characteristics of clay mineral; Ordinary Portland cement conforming to IS 8112 - 1989 is used for the casting of blocks as a binder material.

2.2 Soil-cement block making procedure

Soil-cement blocks are manufactured by using natural soil and the reconstituted soil-sand mixture to obtain 8 different types of blocks with different percentages of cement contents, dry density and clay content. The block density controlled during the manufacturing process (for each set of blocks). Soil-cement blocks of the size 230 x 100 x 75 mm are used in this study. Three varying dry densities of the soil-cement blocks were adopted for this study. A total of 48 blocks consisting of 6 blocks in each category were manufactured. Thus, there are 3 different clay fractions in combination with 4 cement contents and 3 different densities; further the details are given in Table 1. The thermal conductivity and specific heat capacity values of the soil-cement blocks are experimentally determined.

Table 1 – Details of Soil-cement blocks proportion, density, specific heat capacity, and thermal conductivity values

SI No.	Material ID	Clay content in %	Cement content in %	Dry density in kg/m^3	Specific heat capacity in J/kg K	Thermal conductivity in W/ (m K) *(SD, CoV)
1	SCB 1	31.6	8	1700	1096.4	1.065 (0.029, 2.710)
2	SCB 2	10.5	8	1700	1016.7	1.008 (0.042, 4.139)
3	SCB 3	16	5	1700	1028.4	0.842 (0.026, 3.069)
4	SCB 4	16	12	1700	1053.1	1.076 (0.065, 6.072)
5	SCB 5	16	16	1700	938.3	1.097 (0.073, 6.658)
6	SCB 6	16	8	1700	1065.3	1.066 (0.056, 5.277)
7	SCB 7	16	8	1800	1065.3	1.201 (0.033, 2.751)
8	SCB 8	16	8	1900	1065.3	1.303 (0.051, 4.250)

SCB = Soil-cement block, and *within parenthesis is standard deviation (SD) and coefficient of variation (CoV) of thermal conductivity values

3. Testing Procedure

3.1 Thermal Conductivity

Thermal conductivity (λ) is a property of a material that determines how much heat conducted through it for a given temperature gradient. As per IS 3792-1978, thermal conductivity can be defined as "The quantity of heat in the 'steady state' conditions flowing in unit time through a unit area of a slab of uniform material of infinite extent and of unit thickness, when unit difference of temperature is established between its face".

3.2 Measurement of Thermal Conductivity

Methods for measuring thermal conductivity can be classified into two broad categories: steady-state methods and transient-state heat transfer methods. The line heat source method / hot wire method is the most widely used transient-state method for measuring thermal conductivity of materials. In this study, the instrument used is QTM-500 which measures thermal conductivity based on the transient hot wire method.

3.3 Thermal conductivity test

The quick thermal conductivity meter QTM-500 instrument from Kyoto Electronics Manufacturing Company Ltd, used to measure thermal conductivity values.

In actual conditions, the hygroscopic property of a building masonry element also influences its thermal performance. This is not within the scope of the current study. However, to maintain consistence in the hygroscopic test conditions amongst the samples tested, all the specimens were conditioned (for ~72 hours) and tested at 25°C temperature and relative humidity in the range of 50% to 60%.

4. Results and Discussions

4.1 Thermal Conductivity of Soil-cement blocks

Thermal conductivity of soil-cement blocks with different cement contents, dry densities and clay contents examined. It is a function of material (mineral) composites. The details of the soil-cement blocks tested for thermal conductivity value given in Table 1.

Figure 1 shows the variation in thermal conductivity with the varying clay content, cement content, and dry density of the soil-cement block. The analysis and results discussed in the following sections.

4.1.1 Thermal conductivity with varying clay content of the soil-cement block

The investigation by Reddy and Latha (2013) shows the influence of clay fraction in the soil mixture and void ratio on the characteristics of cement stabilised soil compacts. In this study, the thermal conductivity of soil-cement blocks lies in the range of 1.008 W/ (m K) to 1.065 W/ (m K) for the different clay content of 10.5% to 31.6%. With the increase in the clay content from 10.5 to 16% and 16 to 31.6%, there is an increase of 5.8% and 0% of the thermal conductivities respectively. The overall increase in the thermal conductivity values for clay contents of 10.5 to 31.6% is 5.8% (Figure 1). It can be seen that over a certain percentage of clay content the thermal conductivity value becomes constant.

As the size of clay particles are less than 0.002mm, it acts as a filler material and forms a fine pore structure in material. The effect of increasing clay content on soil-cement blocks decreases their porosity while increases the thermal conductivity, thereby making soil-cement blocks more solid in nature. As the solidity of the block increases, total pore volume reduces, thereby increasing thermal conductivity.

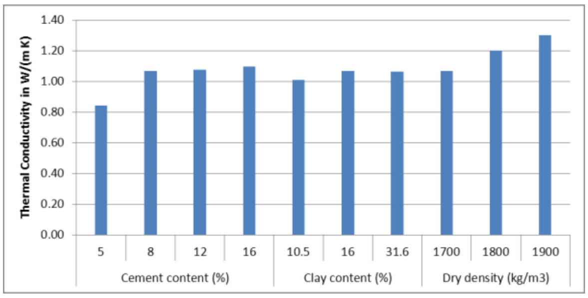

Fig. 1 – The variation in thermal conductivity with clay content, cement content, and dry density of the soil-cement block

4.1.2 Thermal conductivity with varying cement content of the soil-cement block

Bhattacharjee has obtained thermal conductivity values for dry soil-cement blocks for varying cement contents of 4% 6%, 8% and 10%, the thermal conductivity value ranges from 0.437 to 0.670, 0.490 to 0.572, 0.565 to 0.630 and 0.570 to 0670 respectively.

Adam and Jones (1995) studied thermal conductivity of stabilised soil blocks for the oven dry samples is in range of 0.25 – 0.55 W/ (m K). Studies by Akinmusuru (1995), on thermal conductivity values of the lateritic soil-cement bricks show the addition of cement decreases the thermal conductivity value for plain brick. Bahar et.al, (2004) studied the electrical conductivity of compacted cement-stabilised soil in order to assess thermal conductivity of the material. The result shows that conductivity decreases slightly with the increase of cement content and sand content. As the cement content of the block increases, the total pore volume reduced and tends to increase heat flow through the block by increasing thermal conductivity. Increasing cement content of the soil-cement block increases the quantity of hydrated products, which helps to reduce the pore volume by developing hydration products (Generally, C_2S, C_3S, C_3A and C_4AF are the main components formed during the hydration of the cement) into the pores of the blocks. Venkatarama Reddy and Ajay Gupta (2006) showed that the pore size of the blocks varies with the cement content, and pore size decreases with an increase in cement content. Blocks having lower cement content show larger size pores compared to blocks with higher cement content that has a large number of smaller pores. Rübner and Hoffmann (2006) studied the variation of total pore volume (one of the pore parameters) under different bulk densities of the same standard brick materials. They found that the denser the materials, the smaller the total pore volume, thereby resulting in the conductive heat transfer being more dominant in comparison with other modes of heat transfer.

The thermal conductivity of soil-cement blocks lies in the range of 0.842 W/ (m K) to 1.097 W/ (m K) for the cement content variation of 5% to 16%. The thermal conductivity of the blocks depends on the cement content and it increases with an increase in cement content (Figure 1). Cement content of the block predominately reduces the internal pore volume as the cement content increases. With the increase in the cement content from 5 to 8%, 8 to 12% and 12 to 16%, there is an increase of 26.60%, 0.94% and 1.93% of the thermal conductivities respectively. The overall increase in the thermal conductivity values from 5 to 16% is 30.28%

4.1.3 Thermal conductivity with varying density of the soil-cement block

Generally, thermal conductivity of the material increases as the density increases from literature (Max Jakob, 1959). Khedari et.al, (2005) casted soil-cement blocks having a composition ratio of 1:1:6 (cement: sand: soil) by volume and obtained thermal conductivity value of 1.4823 W/ (m K); bulk density is 1913.17±27.65 kg/m^3, and tested according to the JIS R 2618 standard. Balaji (2012) studies the thermal conductivity of soil-cement blocks having a composition of 1:7:7 (cement: sand: soil) by weight. The thermal conductivity test done as per ASTM C 1113-99 and conductivity value of 1.231 W/ (m K) obtained having a block density 1800 kg/m^3. Adam and Jones studied the effect of a stabilizer on density and obtained an exponential relationship with dry density and thermal conductivity for the stabilized soil building blocks. They suggested the need for research to correlate between thermal conductivity and soil type, and to determine the effect of density on thermal conductivity of the soil-cement blocks by varying the density. Balaji (2014) showed that the pore parameter (such as total pore volume) entirely depends on the particle packing. In building materials, this pore parameter depends on the density of the materials.

As the density of the block increases, the percentage of total pore volume decreases and thermal conductivity increases proportionally. The thermal conductivity of soil-cement blocks lies in the range of 1.066 W/ (m K) to 1.303 W/ (m K) for the dry densities variation of 1700 to 1900 kg/m^3. Generally, density of material is taken as an indicator of the thermal conductivity (Koenigsberger et. al., 1975), as the denser the material, the higher the thermal conductivity values (Figure 1). Density of the block depends on how the particles of the materials packed with minimal voids/pores. With the increase in the density from 1700 to 1800 kg/m^3 and 1800 to 1900 kg/m^3, there is an increase of 12.7% and 8.5% of the thermal conductivities respectively. The overall increase in the thermal conductivity values from 1700 to 1900 kg/m^3 is 22.2%, is almost 1.22 times of 1700 kg/m^3 block thermal conductivity value. As an increase in density by 100 kg/m^3, the thermal conductivity value increases approximately by 1/8th times. The thermal conductivity value varies as the density of the material increases. For this study, a total number of 51 test results considered for obtaining a regression equation, which has a coefficient of determination of 0.987. Experimentally determined thermal conductivity values of soil-cement blocks under varying dry density were used to obtain equation (1). The equation (1) is applicable for the soil-cement blocks having 8% cement content, 16% clay content and for 1700 to 1900 kg/m³ densities.

$$\lambda = 0.1945 \exp^{\left(1.0044 \frac{\text{Density}}{1000}\right)} \qquad (1)$$

Where,
Density in kg/m³
Thermal conductivity (λ) in W/ (m K)
The equation (1) cannot be a generalized thermal conductivity value based only on density. Other than density, several other parameters influence the block thermal conductivity, such as porosity, mineralogical composition, cement content, clay content, degree of saturation, temperature and others. The density is one of the indicative properties which can be used to derive thermal conductivity of the soil-cement blocks.

5. Envelope Studies

The design of the building materials for a required thermal performance is crucial (Richard Hyde, 2000), which depends on the constituent material and microstructure (Balaji et.al. 2013). In the current section, an attempt being made to understand the influence of soil-cement blocks with varying mix proportion and densities through dynamic thermal properties such as time lag and decrement factor. These properties been computed as per UNI EN ISO 13786 – 2008.

5.1 Studies on time lag and decrement factor

The thermal characteristic of the building wall envelope depends on the individual material configuration and its thermal properties. The heat flow through the material is a combined influence of the heat storage capacity and thermal resistance characteristics of the wall elements, which consequently regulates the indoor temperature conditions. The building envelope configuration and its thermal properties such as heat capacity and thermal diffusivity affect the time lag and decrement factor (Koray Ulgen, 2002; Vijayalakshmi, 2006). These can be obtained based on the materials' thermo-physical properties (Asan, 1998). Time lag (Φ) is the time difference between the temperature maximum at the outside and inside when subjected to periodic conditions of heat flow (IS 3792-1978), and a decrement factor is the ratio of the maximum outside and inside surface temperature amplitudes (Koenigsberger, 1973). Asan and Sancaktar (1998) found thermo-physical properties of the envelope material and the type of material (Asan, 2006) has a profound effect on the time lag and decrement factor, and computed time lag and decrement factor for different building materials. Jeanjean et.al (2013) also shows the time lag will increase by lowering thermal conductivity or by increasing its Specific heat capacity. Asan (2006) in another study shows different building materials results in different time lags and decrement factors. Like that, each mix-proportion block behaves differently and has different thermo-physical properties.

In this section, dynamic thermal properties such as time lag and decrement factor calculated for different soil-cement blocks and obtained values shown in Table 2. Further, the same has been plotted in figure 2, 3 and 4 shows the variation in time lag and decrement factor with respect to varying clay content, cement content and dry density of the soil-cement blocks

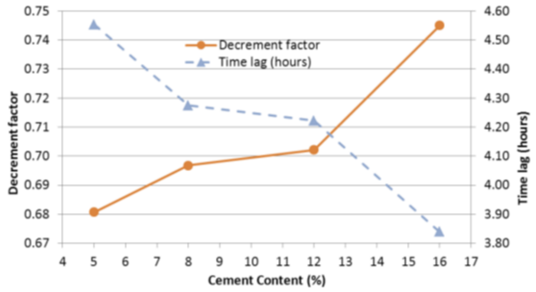

Fig. 2 – Variation of Time lag and Decrement factor on the varying cement content of the soil-cement block

Figure 2 shows the time lag and decrement factor variation on varying cement content. There will be decrease in time lag values as the cement content of block increases, and similarly, the decrement factor value also increasing as the cement content increases.

The time lag and decrement factor depends on the thermal properties of the materials. From figure 1, it can be seen that an increase in cement content increases the thermal conductivity value. These conductivity values directly affect the time lag, and the decrement factor, which also depends on the specific heat capacity of the material. As the cement content increases, the heat capacity of the materials also increases. This shows that the increase in the heat capacity of material directly influences the inside surface temperature of the material, by storing the sufficient amount of heat energy in the material. To obtain a better time lag and decrement factor by using soil-cement block material, it can be recommended that 5 to 12% cement content is suitable.

Table 2 – Calculated dynamic thermal properties of the soil-cement blocks

Material ID	Density in kg/m³	Specific heat capacity in J/kg K	Thermal conductivity in W/ (m K)	Thermal Mass in kJ/K m²	Decrement factor	Time lag in hours
SCB 1	1700	1096.4	1.065	1863.9	0.69	4.37
SCB 2	1700	1016.7	1.008	1728.4	0.71	4.21
SCB 3	1700	1028.4	0.842	1748.3	0.68	4.55
SCB 4	1700	1053.1	1.076	1790.3	0.70	4.22
SCB 5	1700	938.3	1.097	1595.1	0.75	3.84
SCB 6	1700	1065.3	1.066	1811.0	0.70	4.27
SCB 7	1800	1065.3	1.201	1917.5	0.74	3.84
SCB 8	1900	1065.3	1.303	2024.1	0.73	3.93

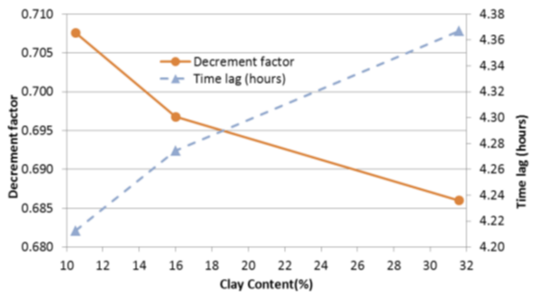

Fig. 3 – Variation of Time lag and Decrement factor on the varying clay content of the soil-cement block

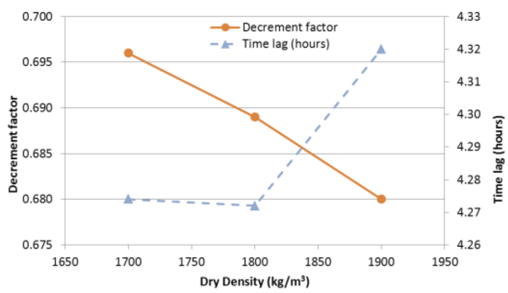

Fig. 4 – Variation of Time lag and Decrement factor on the varying dry density of the soil-cement blocks

Figure 3 shows the time lag and decrement factor variation on varying clay content. There will be increase in time lag value as the clay content of the block increases, and similarly, decrement factor value also decrease as the clay content increases. The effect of varying clay content of blocks has a negligible variation on time lag and decrement factor.

Figure 4 shows the time lag and decrement factor variation on varying dry density. In general, an increase in density of the material reduces the decrement factor and increases the time lag. For this study, the blocks' mixed proportion used are the same for all the three type of density blocks, and same specific heat capacity value. The time lag value is almost the same for 1700 and 1800 kg/m³ density material, but for 1900 kg/m^3 density the value is a little higher than previous values. The decrement factor value gradually falls as the density of the materials increases. The variation in time lag and decrement factor values is not showing any significance in this study. Use of 1800kg/m^3 density soil-cement blocks is more preferable in construction, because casting 1900kg/m^3 density blocks through static compaction is impractical; up to 1800kg/m^3 density blocks can be casted efficiently. The reason is that human (animate) energy required to cast higher (1900 kg/m^3) density soil-cement blocks will be high compare to other lower (1700 & 1800 Kg/m^3) density blocks.

6. Summary and Conclusions

Thermal conductivity of soil-cement blocks with different cement contents, dry densities and clay contents examined. The general details of the soil-cement blocks tested for thermal conductivity value given in Table 1.

The thermal conductivity of soil-cement blocks for different clay contents of 10.5% to 31.6% for blocks having 1700 kg/m^3 dry density and 8% cement content increases from 1.008 to 1.065 W/ (m K). The overall increase in the thermal conductivity values for clay contents of 10.5 to 31.6% clay content is 5.8%. The percentage of clay content in blocks increases by the decreasing porosity of the block, thereby making blocks more solid in nature. The blocks' conductivity will gradually increases by increasing the clay content.

An increase in the cement content of blocks increases thermal conductivity values from 0.842 to 1.097 W/ (m K) by 30.28% increase. This is due to an increase in hydration products into pores of the blocks, which reduce porosity and conducts more heat through blocks.

Generally, thermal conductivity of material increases by increasing density. Soil-cement blocks under different dry densities (1700 to 1900 kg/m^3) show increasing thermal conductivity value from 1.066 to 1.303 W/ (m K). For every 100 kg/m^3 increase in density of soil-cement blocks, the thermal conductivity value increases approximately by 12.5%. Density of the block depends on the particles packing of the materials: the higher the density, the lower the porosity of the block. However, the lower the material porosity, the higher the thermal conductivity value will be.

The thermal conductivity of the soil-cement blocks found to influence by the density, cement content and clay contents. The mix-proportion of the blocks directly regulates the heat storing capacity and thermal resistance characteristics of blocks. The study on time lag and decrement factor shows that the thermal properties of the materials play an important role in regulating these factors. Soil-cement blocks having 16% clay content, 1700 kg/m^3 to 1800 kg/m^3 density and 5% to 12% cement content may be recommended to obtain better results.

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