Chapter 29
Error Analysis on Thermal Conductivity Measurements of Cement-stabilized Soil Blocks

N. C. Balaji and Monto Mani

29.1 Introduction

The selection of materials in construction depends on their thermo-physical properties and thermal performance, because the materials regulate the indoor thermal comfort. The thermal properties of building materials are extensively available from various literatures representing various countries (Clarke et al. 1990). The basic thermo-physical properties such as density, specific heat capacity, and thermal conductivity of building materials have been extensively studied.

Cement-stabilized soil blocks (CSSBs) are modern alternative masonry units. CSSBs are also known as soil–cement blocks, stabilized soil/clay blocks, and compressed stabilized earth blocks. They are considered as low carbon and low embodied energy material. CSSBs do not require firing and can save up to 60–70% embodied energy compared with burnt clay bricks (Venkatarama Reddy 2009). The structural and mechanical characteristics of CSSBs have been extensively studied (production technique, density, soil–sand mix, soil–cement mix designs) and very well established in terms of varying clay content, cement content, and densities for durability and strength. Few studies have investigated the effects of CSSB constituents such as clay, cement content, density, and associated parameters (such as void ratio, porosity, and degree of compaction) on thermal conductivity of blocks. As the cement content increases, thermal conductivity of blocks affects pore size and pore structure (Horpibulsuk et al. 2011). Venkatarama Reddy and Gupta (2005) showed that the pore size of the blocks varies with the cement content and pore size decreases with an increase in cement content. The pores can affect the thermal conductivity

N. C. Balaji (✉)
Department of Civil Engineering, The National Institute of Engineering, Mysore, India
e-mail: balajinallaval@gmail.com

M. Mani
Centre for Sustainable Technologies, Indian Institute of Science, Bangalore, India
e-mail: monto.mani@gmail.com

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of materials (Sugawara and Yoshizawa 1961). Bhattacharjee (1989) studied thermal conductivity variation for varying porosity and cement contents in soil–cement blocks. The thermal conductivity obtained for blocks with cement content varying from 4% to 10% and porosity ranging from 36 to 43% were 0.5009–0.7675 W/(m K). Generally, it was known that thermal conductivity is a function of density (Jakob 1949; Koenigsberger 1975), which is a function of porosity (Van Straaten 1967). Lesser the density means higher the air-filled pores in the material, contributing to lower thermal conductivity. However, the thermal conductivity of CSSBs has been extensively studied and results were reported (Bhattacharjee 1989; Adam and Jones 1995; Nagih and Ali 1995; Bahar et al. 2004; Khedari et al. 2005; Balaji et al. 2017). Further, due to scanty information in the literature on the thermal conductivity value variations, it is essential to understand the statistical inferences.

However cautiously planned and instrumented, no comparable experimental results are alike or give comparable/similar values. Some errors were associated with the experimentally measured values. This associated error can be statistically calculated by means of sample mean, coefficient of variation, and standard deviation values for particular experimental values. Errors involved in the testing materials are important to understand the reliable use of the test results obtained. Mosquera et al. (2013) performed repeatability and reproducibility tests on the adobe bricks from Amayuelas, Spain. The repeatability tests were conducted on the thermal conductivity of adobe bricks by a series of tests run on the same spot of the same sample of each type. Feng et al. (2015) showed the importance of the error analysis of measured data by analyzing the material errors, repeatability errors, between-lab errors, and reproducibility errors in determining the hygric properties of porous building materials. Salient observations from the earlier investigations are detailed error analysis that is required to understand the reliability of measured thermal properties of building materials.

The main objective of the study was to investigate the CSSBs thermal conductivity values error analysis through statistical analysis and also to study the significance of the material test results for errors such as repeatability and material errors. The errors due to test conditions, methods, and instrumentations used are associated with repeatability error, and an error caused by heterogeneity (composite nature) of materials is termed as a material error. The scope of the study is limited to measure the thermal conductivity of CSSBs with varying mix proportions by varying cement content (5, 8, 12, and 16%), clay content (10.5, 16, and 31.6%), and dry densities (1.7, 1.8, and 1.9 g/cc) in the study under room temperature, and calculate the associated measured errors of thermal conductivity values.

29.2 Experimental Program/Experimental Study

29.2.1 Selection of Building Materials

The CSSBs building material having low embodied energy (EE) was selected having EE in range of 0.45–0.85 MJ/kg (Hammond and Jones 2008; Sabapathy 2011; Hashemi et al. 2015). CSSBs with varying clay content, cement content, and densities were considered for the study. As such, thermal property data related to these materials are scanty and extensive data are required to understand the performance of CSSB as building envelopes.

29.2.2 Materials Used for CSSBs

Locally available natural red loamy soil comprising sand (48%), silt (28.6%), and clay (23.4%) was used for block making. This soil was reconstituted by blending river sand in three ratios so that the resulting soil–sand mixture comprised varying clay, silt, and sand fractions. The characteristics of clay mineral were altered; ordinary Portland cement conforming to IS 8112—1989 (BIS 1989) was used as a binder/stabilizer material.

29.2.3 The Manufacturing Process

CSSBs of dimensions 230 × 100 × 75 mm^3 for eight mix types with varying percentages of clay contents, cement contents, and dry density were studied (see Table 29.1). The blocks were cast by controlling the dry density of the blocks. The density of the material in this study is referred to as dry density and is determined during mix design and casting of the CSSBs. A total of 48 blocks consisting of six blocks in each category were cast.

29.2.4 Thermal Conductivity

Thermal conductivity (λ) of a material indicates the heat flux for a given temperature gradient. As per IS 3792—1978 (BIS 1978), thermal conductivity is “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.” In this study, the testing instrument QTM-500 (Fig. 29.2a), manufactured by Kyoto Electronics Manufacturing Co., Ltd. (KEM) Japan, was used to measure thermal conductivity, based on the transient hot

Table 29.1 Details of CSSBs having different clay, cement contents, and dry densities and their designation

S. No.	Material designation	Clay content (%)	Cement content (%)	Dry density (g/cc)
1	CSSB 31.6	31.6	8	1.7
2	CSSB 10.5	10.6	8	1.7
3	CSSB 5	16	5	1.7
4	CSSB 12	16	12	1.7
5	CSSB 16	16	16	1.7
6	CSSB 1.7	16	8	1.7
7	CSSB 1.8	16	8	1.8
8	CSSB 1.9	16	8	1.9

Fig. 29.1 Thermal conductivity testing instrument QTM-500

wire method. This method is a transient/non-steady-state process used to measure the thermal conductivity of the material under constant heat source and to measure the rise in temperature of the material. The thermal conductivity tests were carried out as per ASTM C1113-99 (ASTM 1999).

To ensure uniformity of test conditions, all the test specimens were conditioned (for ~72 h) and tested at 25 ± 1 °C room temperature and relative humidity in the range of 50–60% complying with ASTM C870-11 (ASTM 2011) standard. The materials have been assumed to be homogeneous and isotropic. The thermal conductivity tests at higher temperatures were also conducted using a QTM-500 instrument (see Fig. 29.1).

29.2.5 Error Analysis—Test Repeatability and Material Errors

In this study, the repeatability and material error involved in thermal conductivity of building material were analyzed. The materials considered have been illustrated in Table 29.1.

29.2.5.1 Basics of Error Analysis

Errors exist in all measurements, as no test is perfectly reliable (Feng et al. 2015) or repeatable. As per IS 15393 (part 1)—2003 and ISO 5725-1—1994, accuracy is termed as the closeness of agreement between a test result and the accepted reference value, and it is described as reliability of measured results. The two aspects of accuracy are trueness and precision. As per IS 15393 standard, trueness represents "*the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value.*" It is expressed in terms of bias and precision representing "*the closeness of agreement between independent test results obtained under stipulated conditions,*" and it is expressed in terms of standard deviation. It is evident that the trueness is related to systematic errors ($e_{\text{systematic}}$) and precision defines random errors (e_{random}). Systematic errors in experimental observations are usually based on the measuring instruments and methods adopted. Random errors in experimental measurements are caused by unknown and unpredictable changes in the experiment. These changes may occur in the measuring instruments and/or in the environmental conditions (Hill 2015).

In this study, systematic error is an intrinsic behavioral attributed to instrumental error and it is corrected through instrument calibration using calibrated specimens. This error does not apply in the current study as the instrument has been regularly calibrated in between experimentation. Random errors may be due to the materials heterogeneity, material surface preparation (surface made even before testing, i.e., nearly even test surface), test conditions, materials temperature, and unsteady ambient conditions.

Besides the above-mentioned errors, there are other factors that influence accuracy of experiments according to the IS 15393. These include standard measurement method, accuracy maintained in the experiment (equipment user, type of equipment used, calibration of equipment), identical test specimens, short intervals of time (time elapsed between measurements), and participating laboratories. Repeatability is the precision obtained, under the "same" conditions, when independent test results are obtained with the same method, on identical test items, in the same laboratory, by the same operator, using the same equipment, and within short intervals of time; these are termed repeatability conditions. Repeatability leads to an estimate of the minimum value of precision (Pryseley 2010).

If the test material used and above conditions, methods, and instrumentations remain unchanged in replicate tests, these test conditions are defined as repeatability conditions (Feng et al. 2015) and the error will be expressed in relative standard deviation as repeatability error or $e_{\text{repeatability}}$. Another error termed material error is caused by heterogeneity (composite nature) of materials, and it is expressed in relative standard deviation as material error or e_{material}. This can be attributed to variation in how a specimen is made, stored, and prepared for the experiment and includes aging, material stability, and ambient exposed conditions.

29.2.5.2 The Calculation Methods for Repeatability and Material Errors ($\text{rs}_{\text{material}}$ and $\text{rs}_{\text{repeatability}}$)

In this study, two errors namely repeatability error and material error have been considered. Repeatability error is calculated for each experimental cycle, within the single sample, and by comparing the errors from duplicate samples to original material error. Errors such as $e_{\text{repeatability}}$ and e_{material} will be expressed in $\text{rs}_{\text{repeatability}}$ and $\text{rs}_{\text{material}}$, respectively.

For a single result

$$x_{i,j} \tag{29.1}$$

Average of one sample in replicate tests

$$\overline{x_{i,j}(j)} = \frac{1}{q}\sum_{j=1}^{q} x_{i,j} \tag{29.2}$$

Standard deviation of single sample

$$s_{x_{i,j}}(j) = \sqrt{\frac{\sum_{j=1}^{q}\left(x_{i,j} - \overline{x_{i,j}(j)}\right)^2}{q-1}} \tag{29.3}$$

Relative standard deviation of single sample

$$\text{rs}_{x_{i,j}}(j) = \frac{s_{x_{i,j}}(j)}{\overline{x_{i,j}(j)}} x100\% \tag{29.4}$$

Repeatability error

$$\text{rs}_{\text{repeatability}} = \overline{\text{rs}_{x_{i,j}}(j,i)} = \frac{1}{p}\sum_{i=1}^{p} \text{rs}_{x_{i,j}}(j) \tag{29.5}$$

For average of all results

$$\overline{x_{i,j}(i,j)} = \sum_{j=1}^{q}\sum_{i=1}^{p} x_{i,j} \tag{29.6}$$

Standard deviation of all results

$$s_{x_{i,j}}(i,j) = \sqrt{\frac{\sum_{j=1}^{q}\sum_{i=1}^{p}\left(x_{i,j} - \overline{x_{i,j}(i,j)}\right)^2}{p\cdot q - 1}} \tag{29.7}$$

Relative standard deviation of all results

$$\mathrm{rs}_{x_{i,j}}(i,j) = \frac{s_{x_{i,j}}(i,j)}{\overline{x_{i,j}(i,j)}} x100\% \tag{29.8}$$

Material error

$$\mathrm{rs}_{\mathrm{material}} = \sqrt{\left(rs_{x_{i,j}}(i,j)\right)^2 - \left(\mathrm{rs}_{\mathrm{repeatability}}\right)^2} \tag{29.9}$$

where p and q, respectively, represent the number of samples and tests; i and j, respectively, represent the test results of sample i in the test j; x is measured value; $\mathrm{rs}_{\mathrm{repeatability}}$ is relative standard deviation for repeatability errors; $\mathrm{rs}_{\mathrm{material}}$ is relative standard deviation for material errors; $s_{x_{i,j}}$ is the standard deviation.

Figure 29.2 illustrates the calculation process of the repeatability and material error of building materials in the study. Calculation process is adopted from Feng et al. (2015) study. Both the errors were calculated for all the materials considered in the study as shown in Table 29.2. The relative standard deviation of each sample over replicated tests has been calculated through Eqs. 2–4, and the $\mathrm{rs}_{\mathrm{repeatability}}$ is derived by taking average for all samples from a set using Eq. 5. By adopting Eqs. 6–8 for calculating the relative standard deviation of all results, $\mathrm{rs}_{\mathrm{material}}$ is calculated by eliminating the $\mathrm{rs}_{\mathrm{repeatability}}$ from samples according to Eq. 9.

29.3 Results and Discussions

For studying repeatability error tests, the number of sample (p) and tests (q) used is shown in Table 29.2. Repeatability conditions in thermal conductivity measurements were calculated through experimental results obtained from repeated/replicate tests on multiple specimens.

Test results show sound repeatability for all material, except for CSSB 31.6, CSSB 10.5, and CSSB 5 materials (see Table 29.2). The repeatability error and material error are calculated as described in above Sect. 29.2.5.2. The relative standard deviation of each sample over replicate tests has been found to be greater than relative standard deviation of all results (i.e., $\overline{rs_{x_{i,j}}(j,i)} \geq rs_{x_{i,j}}(i,j)$), showing that the error caused

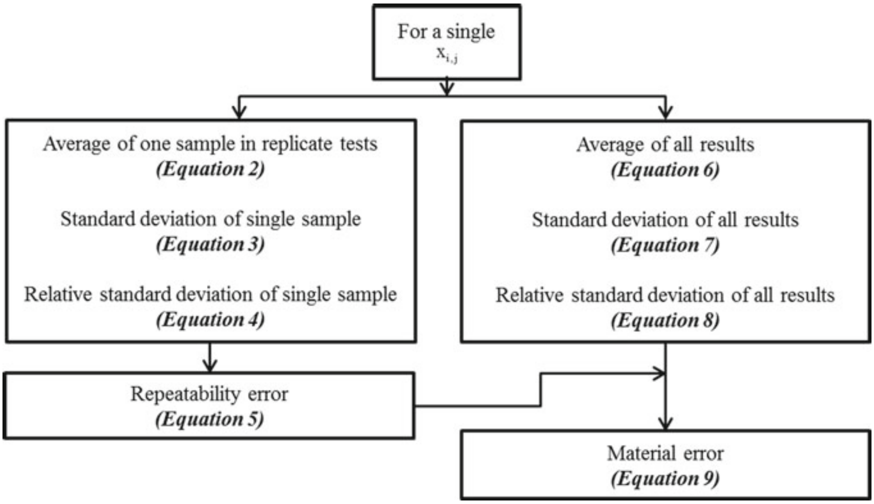

Fig. 29.2 Calculation process for repeatability and material errors (Feng et al. 2015)

Table 29.2 Details of relative standard deviation error for repeatability of thermal conductivity values and building material errors

Materials	$rs_{repeatability}$	$rs_{material}$	Samples (p)	Tests (q)
CSSB 31.6	10.123	0.555	6	3
CSSB 10.5	10.419	1.786	6	3
CSSB 5	11.159	–	6	3
CSSB 12	8.787	5.549	6	3
CSSB 16	9.756	6.069	6	3
CSSB 1.7	7.445	4.188	6	3
CSSB 1.8	6.845	–	6	3
CSSB 1.9	7.367	2.665	5	3

by materials heterogeneity is understood by repeatability errors. In that case, no $rs_{material}$ value is provided. Similar kind of observations were made by Feng et al. (2015) in their studies.

For the CSSBs of varying mix proportions, the materials and repeatability errors reveal the high random variations in resulted errors. The low cement content block CSSB 5 has a high-value $rs_{repeatability}$ of 11.159 and CSSB 1.8 block has $rs_{repeatability}$ of 6.845. Further, for these blocks the error caused by materials heterogeneity is understood by repeatability errors and no $rs_{material}$ value is obtained. The $rs_{material}$ has 0.555 and 6.069 for CSSB 31.6 and CSSB 16, respectively.

Figures 29.3 and 29.4 reveal the repeatability error and material errors plotted versus thermal conductivity of CSSBs. The $rs_{repeatability}$ value varies from 3.838 to 11.159. Similarly, $rs_{material}$ value varies from 0.555 to 8.297. These variations in error

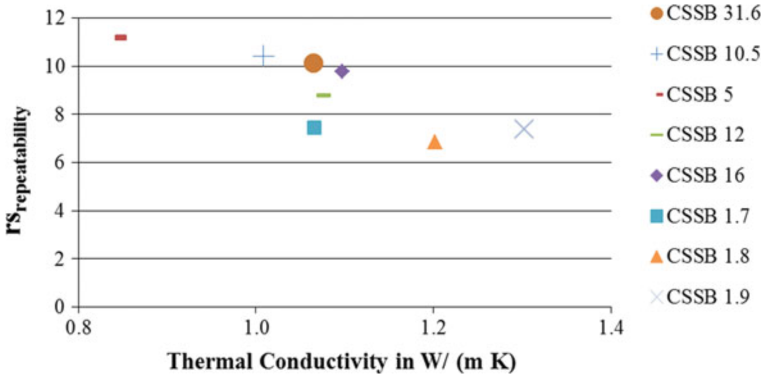

Fig. 29.3 Repeatability error versus thermal conductivity values of materials tested

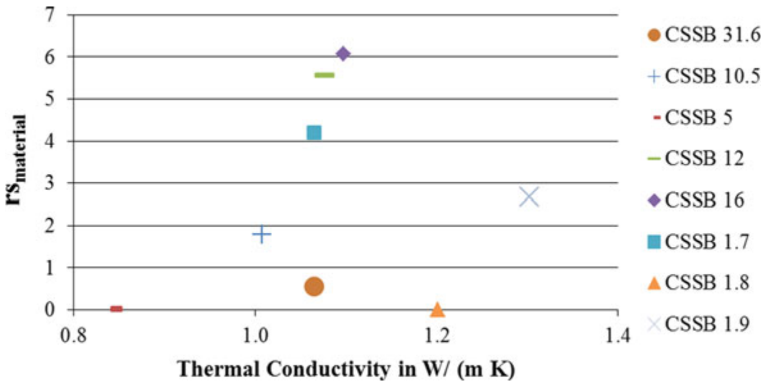

Fig. 29.4 Material error versus thermal conductivity values of materials tested

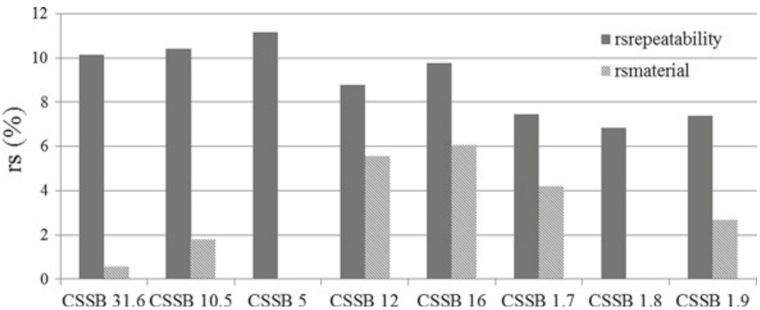

Fig. 29.5 Repeatability and material errors for thermal conductivity tests on different building materials

may be due to the material compositions, method of thermal conductivity testing, and the surface finish condition during repeatability tests. Figure 29.5 shows the repeatability and material errors for thermal conductivity tests of CSSBs. The $rs_{repeatability}$ and $rs_{material}$ values of CSSBs are plotted together for comparison. The $rs_{repeatability}$ values are 2.014, 4.951, and 3.838 for AAC, TMB, and FAL-G, respectively (Balaji 2016). The value of $rs_{repeatability}$ for CSSB materials varies from 6.845 to 11.159, which is higher than the other materials.

29.4 Conclusion

In this study, the CSSB material selected was low embodied energy material. The thermal conductivity of the CSSBs was experimentally determined at room temperature as per ASTM C 870–11. CSSBs at varying cement content, clay content, and dry densities were studied for its thermal conductivity error measurements. Detailed error analysis was carried to ascertain the repeatability and material errors ($rs_{material}$ and $rs_{repeatability}$) of the CSSBs for thermal conductivity measurements.

The repeatability errors were found to be low for all the materials tested except for CSSB 31.6, CSSB 10.5, and CSSB 5 materials; it can be attributed to the number of tests carried on same sample. The material errors can be attributed to the materials heterogeneity and the inherent characteristics of the materials.

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