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Thermal performance measurements of building panels by a new transient technique

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Abstract

In this study, we review common transient measurement techniques and introduce a new one, called as dynamic adiabatic-box technique, for thermal performance estimation of anisotropic building materials. The technique can be used for pre-estimation purpose for materials developed in a laboratory. Simple analysis of time-temperature curves for the specimens allows fair comparison of their effective thermal transmittances (or R-values) under specified conditions. The specimens used for sample calculation procedure are the ordinary concrete and the concrete with stripped scrap-rubber. The results show that R-value of ordinary concrete is enhanced nearly by 25% with addition of scrap-rubber.

Keywords: *measurement methods, thermal properties, adiabatic box technique, anisotropy, building composites*

1 Introduction

The building sector accounts for about 40% of total energy consumption of the European Union. The EU is committed to reducing emissions of greenhouse gases by 8% of the 1990 level up to 2012 according to the Kyoto protocol. Buildings have a major role to play in achieving this goal. The EU directive 2002/91/EC for energy performance of buildings adopted in 2002 is an attempt to reduce energy consumption by improving energy efficiency in buildings. Energy-efficiency improvements mean a reduction in the energy used for a given energy service while keeping the service at least the same. This reduction of energy use can be achieved by the use of more efficient components and technologies, as well as by more efficient ways of using the energy. The building sector is responsible for the consumption of a large share of energy, while energy demand in general is rapidly increasing. Space heating is the leading energy consumer in both domestic and commercial building sectors [1].

The new European energy regulation now thus considers a high standard of thermal protection in buildings with reasonable energy consumption, satisfactory thermal comfort conditions and low operational costs. The typical U-values required by the national regulations in most European countries have been sharply dropped in the last two decades. This has caused in increasing thermal insulation thicknesses in conventional building shells. Consequently; substantial percentage increase in structural cost and reduction in effective living space have been faced. The requirements have increased not only in terms of thermal properties, but also with respect to the environmental impact. An issue that arises out of this activity a search for innovative, environmentally-friendly and ready-to-use building composites that combine higher efficiency and quality in the building process with improved thermal resistance. This has set increased demands on the both thermal and mechanical (thermo-mechanical) performances of new building products integrated with various plasters, foils, particles and rubbers [2].

The thermal performance of a building panel can be evaluated by estimating its thermal resistance (R-value). The R-value of a material or assembly of materials is a quantity that is often used to describe the thermal performance of building construction. The standardized only few techniques are available for accurate thermal testing of building materials, and they are generally expensive [3-5]. In the present study, common thermal testing methods are reviewed in brief. A simple and inexpensive thermal testing technique is proposed. The measurement is based on analysis of transient data, which is suitable for comparing effective thermal transmittances of both isotropic and anisotropic building materials. Sample measurements with ordinary concrete and rubberized concretes are performed.

2 Thermal performance measurements

2.1 A brief review of common measurement techniques

Over the years a number of measurement techniques have been developed for the measurement of thermal transport properties of solid materials. The earliest group of measurement techniques is the steady-state techniques. The technique is based on establishing a temperature gradient over a known thickness of a sample and controlling the heat flow from one side to the other. Steady-state techniques are primarily suitable for analyzing materials with low or average thermal conductivities at moderate temperatures [6]. The transient (dynamic) techniques measure temperature-time response of the sample when a signal is sent out to create heat in the body. These methods can be used for measuring thermal diffusivity, thermal conductivity, or both, for broader range of temperatures and thermal properties [7]. A well-known transient method for thermal diffusivity is the Laser Flash [8, 9]. A group of new apparatus known as Contact Transient Methods has recently become very attractive and popular for all types of materials since they can be used to measure several thermal properties simultaneously or separately [10, 11]. Detailed review of these techniques can be found elsewhere [3].

Most of the techniques mentioned above have significant drawbacks for measuring effective thermal properties of building materials since they have relatively low effective thermal conductivity values; resulting in larger sample size and longer measurement time. The R-value of a material or assembly of materials, which is a quantity that is often used to describe the thermal performance of building construction, is instead evaluated with the standardized few techniques. Thermal performance evaluation methods can be mainly divided into two main categories: ASHRAE Handbook methods and experimental methods. ASHRAE Handbook [12] describes three methods to compute R-values through a material or assembly of materials using electric-circuit analogies. These methods are the parallel flow, isothermal plane, and zone methods. In these methods, the thermal resistances of the materials are treated as electrical resistances which are arranged in parallel, series, or a combination of the two to estimate the thermal resistance of the assembly. The most significant drawback of these methods is that they do not correctly include the lateral heat flow that occurs in many composites. Numerical approaches (i.e. finite element modeling, FEM) can be used to estimate the R-value for such cases. Several ASTM Standard Experimental Methods are also available to estimate the steady-state thermal resistance of building components. The most general test method in this sense is Guarded Hot Box Method. The method is based on establishing and maintaining a desired steady temperature difference across a test panel for a period of time under constant heat flow condition. The thermal conductivity is simply determined by measuring the temperature gradient and the heat flow through the sample.

2.2 A brief description of the transient adiabatic hot-box technique

The apparatus for new transient adiabatic-box technique used in present experiments is schematically shown in Fig.1. The technique is intended to overcome some difficulties mentioned above in thermal testing of building assemblies. The main component of the apparatus is the adiabatic-box, whose outer and bottom walls are heavily insulated (15 cm from each side) to minimize heat losses to its surroundings. The test specimen with much higher thermal conductivity and thinner in size forms the top wall of the box to provide one-dimensional axial heat flow. The box includes a temperature-controlled heater close to the bottom wall for heating small depth of water (8-10 cm) to a certain temperature. Using water in the box helps to obtain more homogenous temperature distribution in lateral direction during heating and transient experiments. The evaporation of water is prevented due to adjusted low operating temperatures (ranging between 35 and 55°C). The box is placed in a cold chamber operating at controlled fixed temperatures, humidity and air flow conditions. Temperature and relative humidity sensors are positioned at several points to measure the corresponding air conditions. A highly sensitive temperature sensor with internal data-logger is immersed into water to monitor its temperature. The specimen is tightly installed as soon as water is heated to a desired temperature. The heater is then turned off and transient data recording starts at this time (t=0). Cooling rate of water is considered a measure of specimen thermal transmittance since major part of the heat is transferred through the specimen surface. The analysis of time-temperature curve indeed allows estimation of R-value (from hot air to cold air). More details for utilization of the technique are given elsewhere [3].

2.3 Test samples

Test samples used here for thermal performance evaluation are the ordinary concrete (OC) and the rubberized concrete (RC). The stripped rubbers are obtained from plane surface of a scrap automobile tire without removing steel-belt wires from their construction. Geometric specifications of the test samples are given in Figure 2(a). The RC specimen used here can in principle be considered as fibrous composites and they are anisotropic at macroscopic level, as seen in Fig. 2(b). The main object in these sample measurements is to investigate effect of scrap-rubber addition on thermal transmittance of ordinary concrete. The subject is of practical interest in civil engineering community and there is lack of an appropriate thermal testing method due to complex structure of rubberized concretes (see [13] for recent review on the subject).

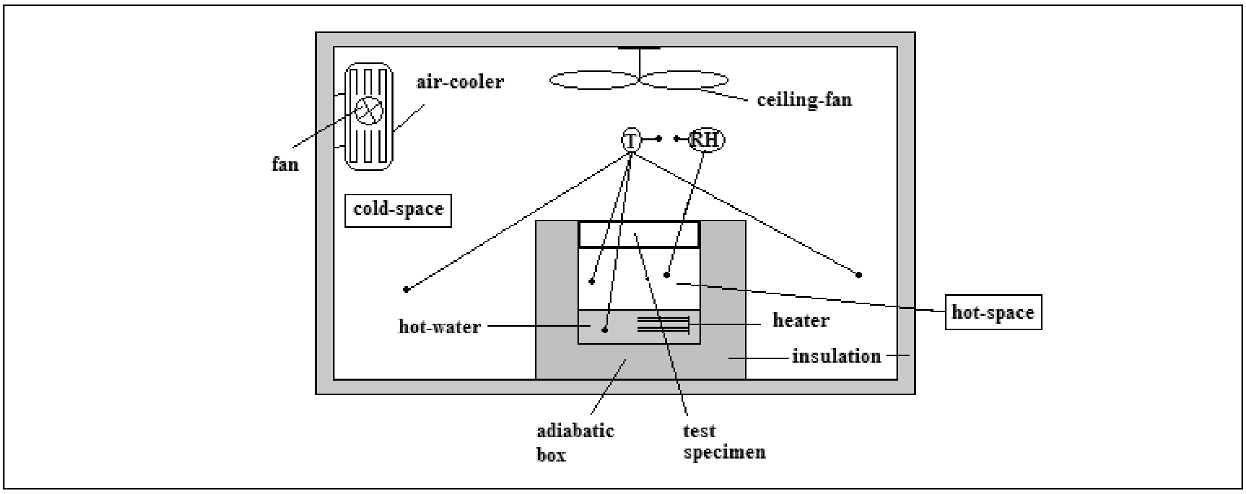
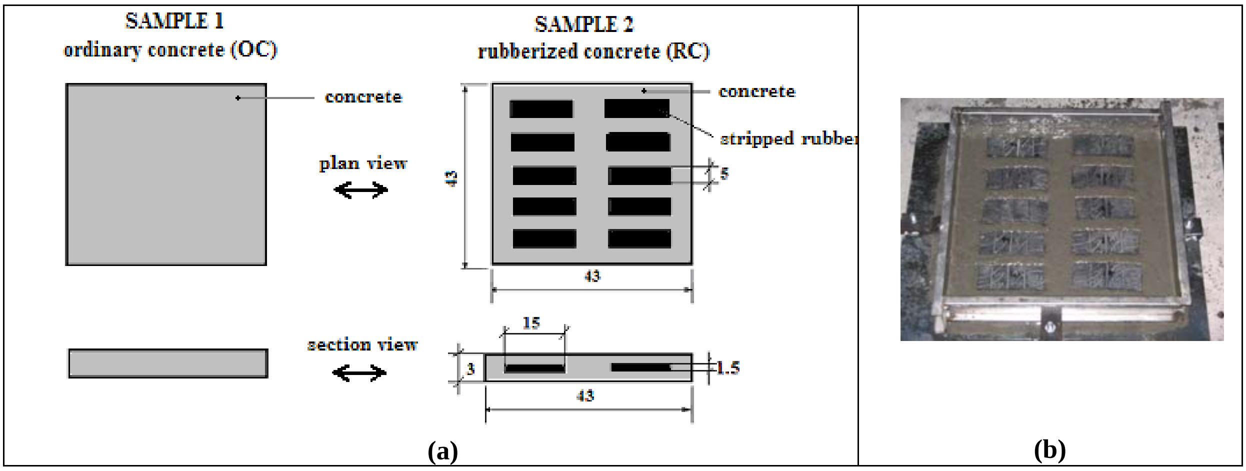


Fig. 1. Schematic of the transient adiabatic-box technique (T: temperature sensor, RH: relative humidity sensor).



(a)

(b)

Fig. 2. (a) Geometric specifications of the test samples, (b) The image of RC taken at sample preparation

3 Results and discussion

The main object in thermal tests presented here is to investigate effect of scrap-rubber addition on thermal transmittance of the conventional concrete. Transient thermal behavior of rubberized-concrete specimen (RC) is thus compared with the ordinary one (OC). Test results for these specimens are given in Figure 3. The instantaneous temperatures given in the graph represent temperature of water in the box, whose top surface is covered by the corresponding specimens. The comparative analysis for the specimens is made in cooling period. The cooling rate of water is directly related with thermal transmittance of the specimen in question since major heat loss pass through from the specimen surface. Temperature curve for each specimen is the average of temperatures obtained from the three identical samples. Reproducibility of the experiments with identical specimens was fairly good (deviations within 3%). The instant value of cold room temperature was obtained by averaging instant temperatures taken at three different points in the room. The local variations in cold-air temperatures were all remained within ±2°C. The time-averaged value (T_0) of instant temperatures in cold room is observed to be constant as shown with a solid trend line in Figure 3.

Transient modeling of the curves given in the Fig. 3 is possible since the cooling rate of water is equal to total heat loss from the box. By defining a dimensionless temperature as,

$$\theta^* = \frac{T - T_o}{T_i - T_o} = \frac{\theta}{\theta_i} \tag{1}$$

where T=$T(t)$ and T_i indicate respectively water temperatures at any instant time and at the beginning (t=0) of experiments, and T_o represents the time-averaged temperature of the cold space. The heat balance equation (for $t \geq 0$) then becomes,

$$mcd\theta = -U_T A_T \theta \,. \tag{2}$$

If this equation is solved under the initial condition, at t=0, $\theta = \theta_i$,

$$\theta^* = \exp\left(-\frac{U_T A_T}{mc} t\right) \tag{3}$$

is obtained. In equations given above; m and c are mass and specific heat of water in the box, U_T and A_T are respectively the total heat transfer coefficient and surface of the adiabatic box.

The variations of θ^* obtained from experiments and the model are shown with semi-log$x$ plot in Fig. 4 for the specimens tested. The agreement between curves appears to be fairly good. The U_T values were determined numerically in Matlab software, by searching the value giving the best fit to the experimental data. As an approximation, if we neglect heat losses from side and bottom surfaces due to being heavily insulated, the total heat resistance of the box then becomes equal to R-value of the specimens as:

$$R_T \cong R = \frac{1}{U_T} \,. \tag{4}$$

The R-values of the specimens with corresponding standard deviations (σ) from best-fitting were calculated as,

$$R_{OC} = 0.592 \;\; m^2 K / W \;\text{ with }\; \sigma_{OC} = 0.009121 \;,$$

$$R_{RC} = 0.790 \;\; m^2 K / W \;\text{ with }\; \sigma_{RC} = 0.002745 \,.$$

The percentage-wise improvement on R-value of ordinary concrete is nearly 25%, which was found by the following relation,

$$X(\%) = \left(1 - \frac{R_{OC}}{R_{RC}}\right) \text{x}100. \tag{5}$$

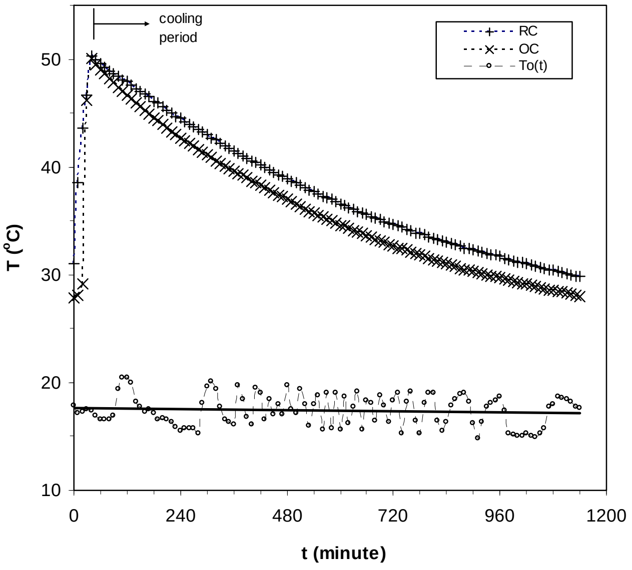


Fig.3. The transient temperatures during dynamical thermal test; in dimensional form. The dashed lines are for easier tracking of data.

4 Concluding remarks

The technique described here is found to be functional and robust for thermal testing of flat building specimens. Although testing time is quiet long, the measurement and evaluation procedures are simple and straightforward. Maintaining the required cold space conditions during experiments is relatively easy. The sample measurements with specimens of the ordinary concrete and the concrete with stripped scrap-rubber show that R-value of concrete can be enhanced nearly by 25% with addition of scrap-rubber. More work and tests are necessary for validation of assumptions applied to theoretical model presented here.

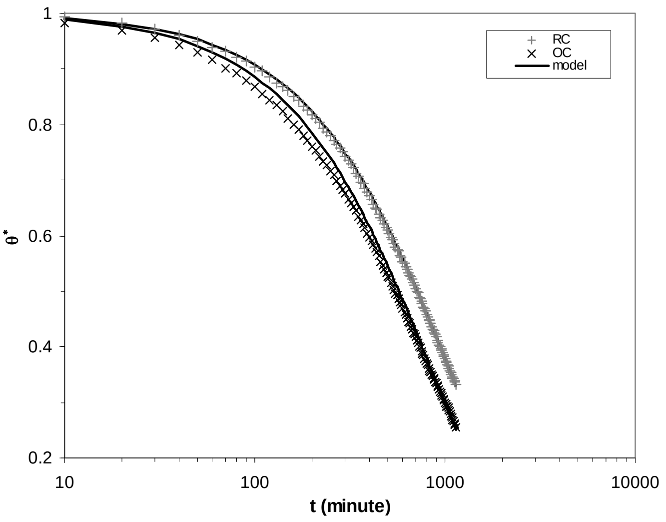


Fig.4. The transient temperatures during dynamical thermal test; in dimensionless form.

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