THERMAL CHARACTERISATION OF COMPOSITE WALLS MADE FROM WASTE MATERIALS

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ABSTRACT

Sustainable development has been an ever-growing global concern over the years, especially with respect to the environment. The construction sector is a major cause for concern due to the devastating effects traditional building materials, manufacturing processes and procurement, have on the environment. Inadequate housing in developing countries is also another major sustainable development challenge. These illustrate the cogent need for developing new methods of delivering sustainable housing that can be accessible to low-income communities who have little or no access to finances. This study compares the thermal performance of low-cost building components made from incorporating waste materials in cement blocks, thereby reducing the quantity of new materials needed. Three samples (wall panels) were made. Each panel was 330mm × 330mm × 240mm and incorporated 25 × 500ml plastic bottles laid horizontally in rows. A sand and cement mixture (ratio 1:3) was used as a binder and filled the gaps between the plastic bottles. The bottles in the first sample were filled with sand, those in the second were filled with water, and those in the third with used plastic carrier bags. A guarded hot box was developed to experimentally measure the U-values of the samples following the BS EN ISO 8990 standards. It was observed that the samples with the plastic bags had the lowest U-value, about 60% lower than samples with sand. The results show a promising potential for low-grade plastic waste to be used as a means of improving the thermal performance of low-cost buildings.

INTRODUCTION

The use of waste materials in construction has garnered much interest from the scientific community and around the world. This is a result of the ever-growing concern on the use and manufacturing of traditional building materials as they cause significant harm to the environment. Traditional building materials are estimated to use up around 60% of the Earth's crust extracted as raw materials [1]. Furthermore, disposal of waste materials such as plastic bottles and bags are of great concern especially in developing countries as they lack the infrastructure to dispose of them correctly. As a result, waste materials such as plastics usually tend to be dumped illegally finding their way to the ocean, sewers, and across urban and rural areas[2].

Concern regarding buildings energy consumption has risen over the years [3] as buildings energy demand to supply light, heat etc. accounts for around 40% of the total primary energy globally used [4], [5]. Within the EU for example, the building sector needs to reduce its greenhouse gas emissions by around 90% to realise the European Union's aim of reducing the amount of greenhouse gases produced by 80% before 2050 [6]. For buildings in cooler climates, the most energy demanding task is heating which can produce up to 40% of their total greenhouse gas emissions [7], [8]. Typically, most building heat loss occur through the walls which places great importance on its thermal properties[9].

When observing the suitability of walls in terms of thermal performance one of the most important parameters to consider is thermal transmittance (U-value) [10]. This is defined as the rate of heat loss per unit area per degree temperature difference from inside to outside, usually in units of $W.m^{-2}K^{-1}$. This paper therefore, investigates the thermal performance and specifically the U-values of walls incorporated with waste materials.

NOMENCLATURE

R	[m^2K/W]	Thermal resistance
U	[W/m^2K]	U-value
Q	[W/m^2]	Heat Flux
T	[^oC]	Temperature
Special characters		
Δ	[-]	Uncertainty
Subscripts		
c		Cold chamber
h		Hot chamber

SAMPLE PREPARATION

Three wall panels consisting of a mixture of sand, Portland cement and water were made. The wall panels were reinforced with plastic bottles filled with waste materials. The materials used were plastic bags, sand and water. The wall panels each had dimensions of 330mm × 330mm × 240mm. Each wall panel consisted of 25 × 500ml plastic bottles filled with their respective materials. The bottles were arranged in an array of five rows and columns as shown in Figure 1. The wall panels were made by pouring the cement mixture into three wooden moulds. The mixing ratio of the cement mixture was around 8kg of Portland cement, 25 Kg of sharp concreting sand and 1.5 L of water. The materials were added in different stages to obtain a homogenised mixture. A layer of cement of 1cm was first laid on the base of the mould before placing the plastics bottles. The bottles were then inserted followed by the addition of the cement mixture onto the surrounding walls and in between the crevices of the bottles to ensure that a solid filled sample was obtained. The mixture in the moulds was levelled to ensure that a uniform and evenly spread mixture was achieved. A load was applied on the top surface of each sample during drying to prevent the plastic bottles floating up. The moulds were removed 72 hours after casting and the panels were stored in a cool, dry area and were left to dry for at least 28 days after casting[11]. This period was enough to ensure no moisture was present as moisture can significantly affect conductivity. The surfaces of the wall panels were grinded to obtain a smooth surface. A schematic of the composite wall is shown in Figure 2

Figure 1 Arrangement of plastic bottles

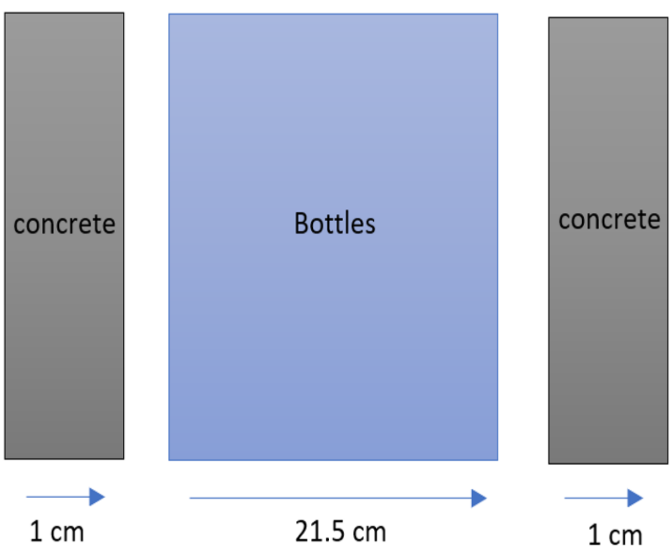

Figure 2 Schematic showing composite wall composition

TEST RIG SETUP

The experiment was carried out using an insulated hot box built from polystyrene. The actual box is shown in Figure 3 and a schematic is shown in Figure 4. The hot box conformed with the BS EN ISO 8990:1996 standards. The rig consisted of a hot and cold chamber. The temperature in the cold chamber was maintained by circulating water through a coil. A Thermo Scientific A25 refrigerated bath circulator supplied the working fluid at a constant temperature of 5°C. The temperature in the hot chamber was maintained using a heat mat powered by a power supply with a maximum power output of 60W (12V, 5A).

Figure 3 Hot Box apparatus

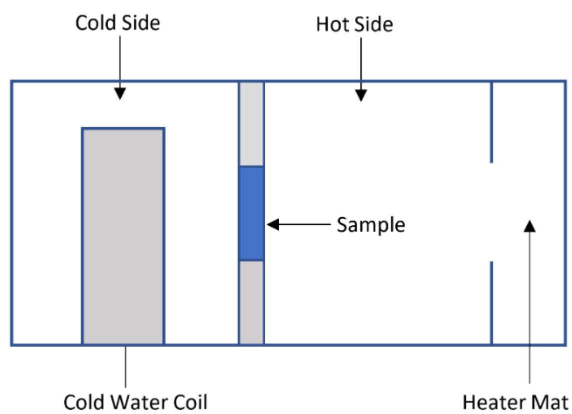

Figure 4 Schematic of Hotbox

EXPERIMENTAL SYSTEM

Temperatures were measured with type T thermocouples and Resistance Temperature Detectors (RTDs) while the Heat flux was measured using a Hukseflux Heat flux sensor (HFP01). These were connected to a National Instruments cDAQ-9174 multiple channel data acquisition module and logged via LabVIEW. Signals were sampled at 1 Hz, signal quality was studied using an oscilloscope to ensure they were clean and free from interference. Post steady state data were used for analyses. The criterion for steady state was defined by $\frac{dT}{dt} < 2.5 \times 10^{-5}°C/s$; this was reached after approximately 5 hours.

A backup measurement system- greenTEG gSKIN Heat Flux measurement kit was installed as backup. This gSKIN system had temperature sensors, a heat flux sensor as well as integrated data acquisition.

A total of 11 Type T 7/0.2mm PFA thermocouples were used in this experiment. 4 of them were placed on the front and back surfaces of the samples, 1 on the surface of the heater mat and 1 in the water inlet and outlet to measure. 6 RTDs were also used. 2 RTDs were placed near the centre of the samples on the front and back surfaces of the samples and 2 were used to measure the air temperature of the hot and cold chambers. The RTDs and thermocouples on the surfaces of the sample were positioned in parallel. Figure 5 is a schematic showing the arrangement of the sensors on the surfaces of the samples. The gSKIN Heat Flux Sensor were placed in the middle of the samples surface located in the hot chamber, while its temperature sensors were used to measure the air in the hot and cold chambers.

A wide temperature difference is recommended to reduce the uncertainty in the U-value [12]. Therefore, the cold chamber was maintained at about 15℃ while the temperature in the hot chamber was maintained at above 30℃. Each sample was placed between the two chambers for about 24 hours.

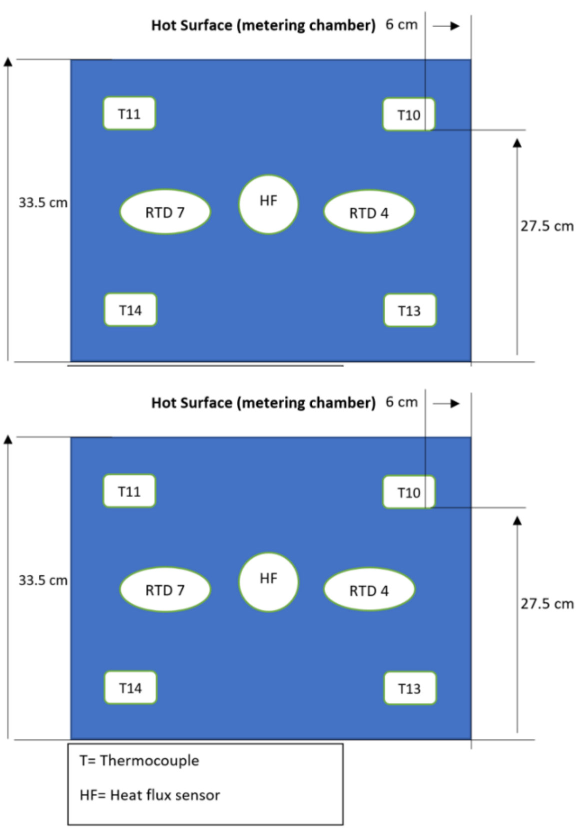

Figure 5 Schematic showing sensor arrangement

UNCERTAINTY

The National Instruments data acquisition system has a function for calibrating all channels. This procedure compensates for the inaccuracies in the whole measurement system. The thermocouples and RTDs were bonded together, put in the bath and calibrated at a number of temperatures to match bath temperature read. The heat flux sensor was calibrated with the gSkin heat flux kit. After calibration, steady state measurements were recorded for about 60 minutes. The standard deviation observed in each parameter was taken as the instrument's uncertainty. Uncertainties in geometric parameters were estimated using high precision measuring instruments as well as manufacturers' specifications. The deviations were used to estimate the uncertainties in the calculated values, assuming that the deviations in each term were uncorrelated. Eq. (1) [13] was used to estimate the uncertainty in the U-value. This was found to be less than 15%. A polystyrene sample with known U-value was tested and resulted in an uncertainty of $\pm 0.02\ W/m^2K$ (about $\pm$5.5%).

$$\frac{\Delta U}{U} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta T_c}{T_c - T_h}\right)^2 + \left(\frac{\Delta T_h}{T_c - T_h}\right)^2} \quad (1)$$

RESULTS AND DISCUSSION

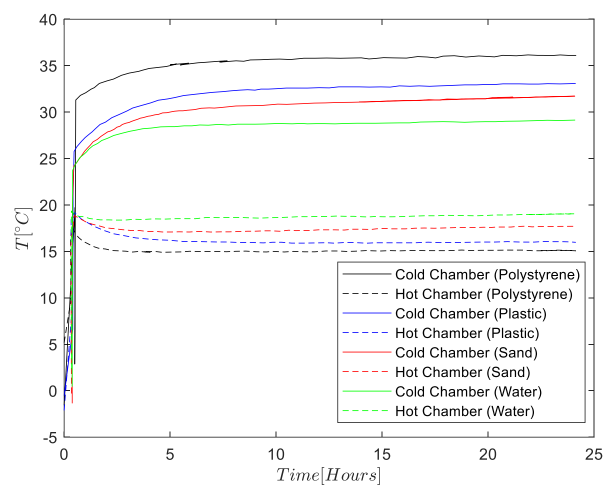

Figure 6 Chamber temperatures for all tests

Figure 6, shows the temperatures recorded in the hot and cold chambers for all samples, including the control sample (Polystyrene wall). The figure shows that the water filled bottles reached steady state faster compared to the other two samples (sand and plastic filled bottles). This was surprising as it was expected that the sand filled bottles sample would reach steady first, followed by the plastic and water filled bottles samples due to their specific heat capacity. The results observed could be due to the varying masses of the bottles. The bottles containing sand and plastic possibly had more mass due to the higher compaction rate. Further investigation is required to determine these results. The steady state of the water filled bottles sample was reached within around 4.4 hours followed by the sand and plastic filled bottles after 5 and 7.2 hours respectively.

Table 1 Theoretical and Experimental U-values

Sample	Theoretical U-Value (W/m^2K)	Experimental U-Value (W/m^2K)	Temperature Difference across chambers (°C)
Polystyrene	0.34	0.36	21
Plastic	1.48	1.58	17
Sand	3.62	2.94	14
Water	2.63	5.22	10

Table 1 compares the theoretical and experimental U-values of all samples including the control sample. The theoretical U-values were determined by estimating the total thermal resistance of the sample, R_{total} (using measured thickness and published thermal conductivities of concrete, plastic, Polystyrene, water, etc.) and using equation (2)

$$U_{theory} = \frac{1}{R_{total}} \qquad (2)$$

While the experimental U-values were determined by

$$U_{experiment} = \frac{Q}{T_c - T_h} \qquad (3)$$

The data presented illustrates that two (polystyrene and sand) of the four samples exhibited lower experimental U-values compared to the theoretical values.

The results obtained were as expected in terms of which samples had the lowest U-values. This was based on the thermal conductivity of the materials. It is known that materials with lower thermal conductivities will also display lower U-values. However, interestingly, the water filled bottles sample did not follow this trend and showed a U-value, nearly two times greater than the predicted. This difference can be as a result of convective heat transfer in the water bottles, as the theoretical calculations only account for conduction through the samples. Also, the high thermal mass of water could be another factor contributing to this difference. Due to high thermal mass, the water can absorb and store large amounts of thermal energy and release it at a slow rate, increasing the heat flux measured. Higher heat flux values in turn increase the measured U-value. The study by [14] also observed a higher U-value for the water sample compared to the sand sample.

Some uncertainties in calculations of the theoretical values can be attributed to assumptions made. For instance, the sand used in this study was sharp concreting sand, however, the thermal conductivity of this material was not available in the literature and as such assumptions were made. It should also be noted that it is not uncommon for the predicted U-values to be lower than the U-values obtained from experiments as shown by [15]. The importance of the thermal conductivity of materials and its effect on the overall U-value of a wall was highlighted by [16] where the overall U-value was reduced by up to 20% as a result of reducing the thermal conductivity of the clay by up to 50%

From Table 1, it can be observed that as the U-Value of the sample increases, the temperature difference across the sample reduces. This can be explained by the fact that the thermal resistance of the sample is inversely proportional to U-value, thus higher U-value samples will result in more heat flux through the sample.

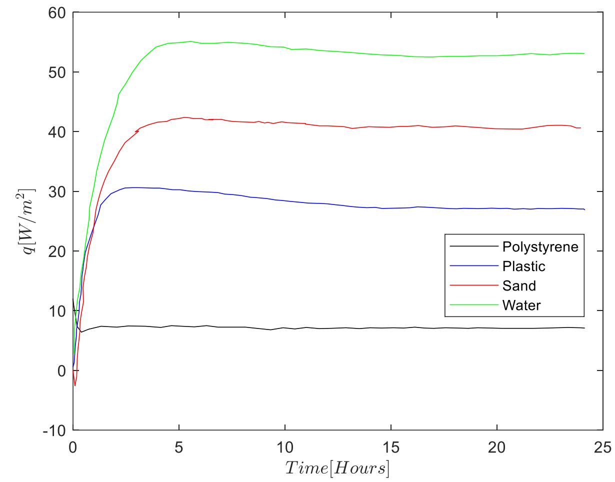

Figure 7 Heat flux values for all samples

Figure 7 shows the measured heat flux values of all samples. The results confirm the trend that higher heat flux values ultimately mean higher U-values which is a logical outcome as heat flux is the flow of energy per unit area per unit of time, and U-value is the rate of transfer of heat across a structure. As can be seen from the graph, the highest recorded heat flux value was obtained from the water filled sample consequently resulting in the highest recorded U-value.

The results obtained show that the plastic bags filled bottle samples produced the most promising results out of the materials investigated, as it obtained the lowest overall U-value. Although plastic filled bottles yielded the best U-value they have a compressive strength of around 2.7 MPa[17] which is nearly 2.5 time lower than that of sand filled bottles (6.3 MPa)[11]. Thus, the use of these materials in construction is promising but is limited to non or light load bearing construction such as low-cost ground floor houses or other uses such as benches and decorative purposes. The moderate U-value and higher compressive strength of the sand filled bottles sample makes it more practical for building applications. It is common for low cost construction in developing countries to have poorly built or damaged building envelopes. As a result, the thermal mass of building materials may have a greater impact and play a more pivotal role in the thermal comfort of homes compared to the U-value of the materials. Therefore, though the water filled bottles sample, may have the highest U-value, it may be the most promising alternative for low cost construction in hot and humid climates as it is likely to have more thermal mass[14].

CONCLUSION

Samples made from the same cement mixture, containing a matrix of plastic bottle with three different fillings; crushed plastic bags, sand, and water were investigated. The samples were thermally analysed in steady-state to obtain the thermal transmittance (U-value). The water filled bottles sample produced a much higher U-value (5.22 W/m^2K) than expected.

This is probably due to convective flow within bottles which was not included in the theoretical U-value calculation. The plastic bags filled bottles sample produced the lowest U-Value (1.58 W/m^2K), however, their low compressive strength is a practical challenge in construction. The sand filled bottles had a moderate U-Value of 2.94 W/m^2K, however, its compressive strength makes it more attractive. The U-value may not be the most important parameter for thermal performance, especially in low cost buildings in developing countries where poorly built or damaged building envelopes are common. Therefore, other parameters such as thermal mass should be investigated.

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