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An experimental assessment of the energy performance of novel concrete walls embedded with mini solar collectors

Larry A. Bellamy[a]*

[a]RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia

Abstract

Experimental measurements from a twelve-month trial are used to assess the energy performance of a solar-heated stratified concrete wall panel. The panel comprises an interior layer of high thermal mass concrete and an exterior layer of insulating concrete that is embedded with a solar thermal collector covering 10% of the panel's face. Results indicate that the collector improves the energy performance of stratified concrete panels by more than 15%.

Keywords: Concrete wall; solar collector; energy performance

1. Introduction

Ordinary concrete walls are typically unsuitable for use in the thermal envelopes of conditioned buildings, due to their poor energy performance. Developing cost-competitive and affordable solutions for improving the performance of these walls is a challenge, especially in the current environment where building regulations are becoming increasingly stringent.

One solution for improving the energy performance of concrete walls is to use lightweight aggregates in the concrete mix instead of normal-weight aggregates. It is not too difficult to produce lightweight concrete wall panels with densities less than 1000 kg/m^3 and thermal conductivities less than 0.2 W/mK [1], however panels with these properties have low structural strength and may need to be thick (>400 mm) in order to satisfy U-factor requirements in building regulations. In addition, while lightweight concrete improves the insulation properties of a panel it is a poor thermal mass material compared with

* Corresponding author. Tel.: +61-3-9925-3907; fax: +61-3-9925-1939.
E-mail address: larry.bellamy@rmit.edu.au

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ordinary concrete, which is a disadvantage because thermal mass can provide significant energy benefits, especially in temperate climates [2].

1.1. Solar heated stratified concrete wall panels

The objective of this paper is to use experimental measurements to assess the energy performance of a solar heated stratified concrete (SHSC) wall panel. This new type of panel has been devised to address the problems with insulating concrete, identified above. The panel is formed with bonded layers of normal-weight and lightweight concrete [1], and has mini solar collectors embedded in the lightweight concrete layer (Fig. 1). The normal-weight concrete layer adds strength and thermal mass to the panel while the collectors are designed to improve the panel's energy performance and/or act as a substitute for wall insulation.

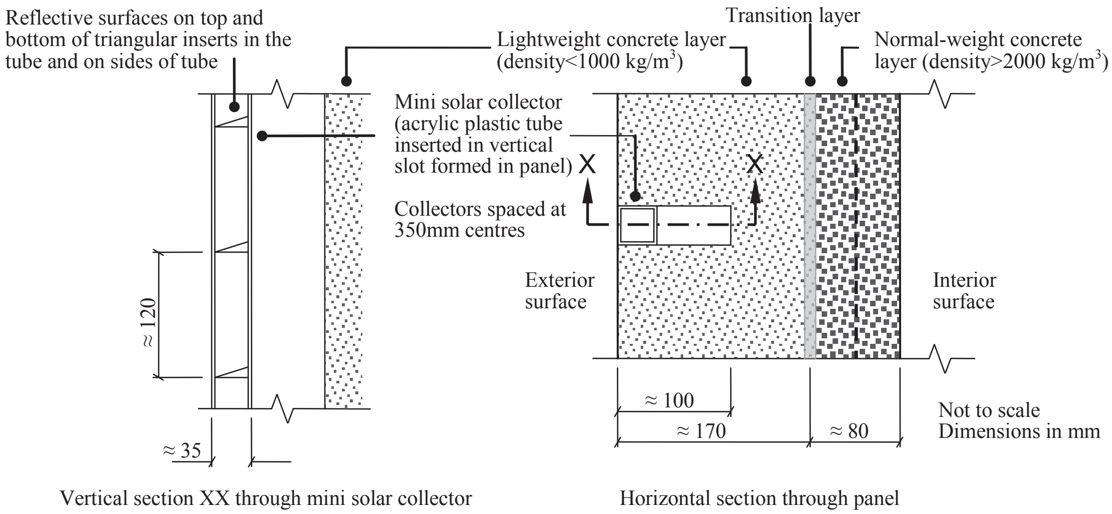

Fig. 1. 250 mm thick solar heated stratified concrete (SHSC) wall panel

2. Mini solar collector development

Like other walls with integrated solar collectors, the SHSC panel is designed to utilise solar radiation incident on the external walls of buildings more effectively. Unlike other solar walls, the collectors in a SHSC panel cover a small fraction of the wall's area – only 10% in the case of the prototype panel tested in this paper. Another difference is that solar radiation is absorbed at, or near, the exterior surfaces of other solar walls, whereas it is absorbed within the fabric of the SHSC panel – a strategy designed to improve the efficiency of solar energy collection and utilisation.

Previous research [3] established the technical feasibility of using mini solar collectors to improve the energy performance of stratified concrete panels. However, while the simple collector designs tested in [3] improved panel heating performance they had a negative effect on panel cooling performance, due to unwanted solar heat gains from the collectors during the summer.

The mini solar collector shown in Fig. 1 was devised to reduce unwanted solar heat gains during summer. The collector is made with an acrylic plastic tube that is inserted into a slot formed in the lightweight concrete layer of the panel. Triangular inserts divide the plastic tube into discrete cells to reduce heat loss from the collector. The surfaces of the triangular inserts and the sides of the plastic tube are reflective to aid rejection of solar radiation from the collector during the summer months.

3. Energy performance trial

A 250 mm (approx.) thick solar heated stratified concrete panel (SHSC) was mounted for testing in the north wall of a solar laboratory in Christchurch (43.5^{0}S), New Zealand, approximately two years after it was cast. The panel was tested over a period of twelve months, from February 2009 to January 2010. Light was excluded from the interior of the laboratory and its air temperature was maintained at approximately 20^{o}C throughout the trial. The exterior surface of the panel was exposed to ambient conditions and essentially unshaded. Conduction at the panel's interior surface was measured with a Hukseflux HFP01 thermal sensor and a Campbell Scientific CR7X datalogger. Indoor and outdoor air temperatures and exterior solar radiation on a vertical surface were also measured.

Two other panels were tested with the SHSC panel. A stratified concrete panel without a solar collector (SC) was cast from the same Portland cement-based concrete mix used to produce the SHSC panel. Measurements from this panel enable the effectiveness of the mini solar collector to be determined. A lightweight polystyrene sandwich panel was also tested, in order to assess the effect of thermal mass on wall energy performance and to act as a control for the test. The panels were painted the same colour.

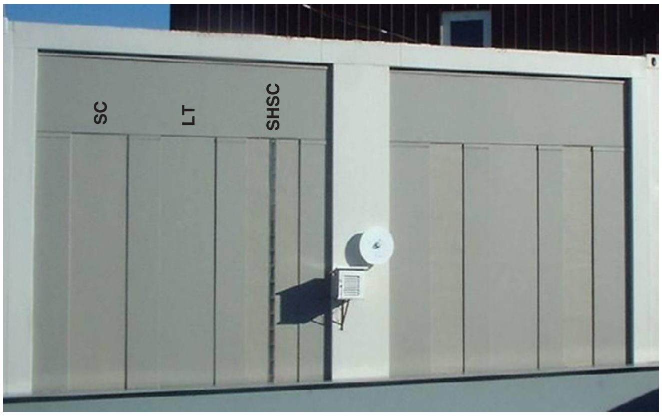

Fig. 2. Solar heated stratified concrete (SHSC), stratified concrete (SC) and lightweight polystyrene (LT) test panels in the north wall of a solar laboratory at Christchurch (43.5^{o}S)

4. Results

4.1. Interior surface conduction

Monthly mean hourly conduction (+ve towards the outdoors) at the interior surfaces of the panels are shown in Fig. 3 for February, May, August and November. Conduction in the SHSC panel is almost always less than conduction in the SC panel. So the solar collector improves panel heating performance, since it reduces the annual thermal load the panel imposes on building heating equipment, but it also reduces panel cooling performance.

The largest differences in conduction between the two concrete panels occur from mid-morning to midnight, when solar heat is being collected, stored and released. It appears that the heat produced by the collector reduces conduction too early in the day and does not persist long into the night, which indicates the collector's design is not optimal.

Fig. 3 also shows that conduction in the concrete panels is low or negative during the night and greater during the day. This type of profile is well-suited to buildings that require both heating and cooling, and is in stark contrast to the lightweight panel, which has the opposite type of profile.

An indication of the heating performances of the panels (i.e. the annual loads they impose on heating equipment) in real buildings may be got by treating the solar laboratory as a building space that needs auxiliary heating when the hourly mean ambient air temperature is less than either 10°C or 15°C. Mean conduction when the ambient air temperature is less than 10°C equals 5.84 W/m^2, 4.99 W/m^2 and 5.87 W/m^2 for the LT, SHSC and SC panels, respectively. The SHSC panel has the best heating performance of the three panels and the solar collector improves performance by 15%. Mean conduction when the ambient air temperature is less than 15°C equals 3.69 W/m^2, 3.88 W/m^2 and 4.99 W/m^2 for the LT, SHSC and SC panels, respectively. In this case the LT and SHSC panels have near-equal performance and the solar collector improves performance by 22%.

Likewise, the panels' cooling performances (i.e. the annual loads they impose on mechanical cooling equipment) may be assessed by treating the solar laboratory as a building space that needs mechanical

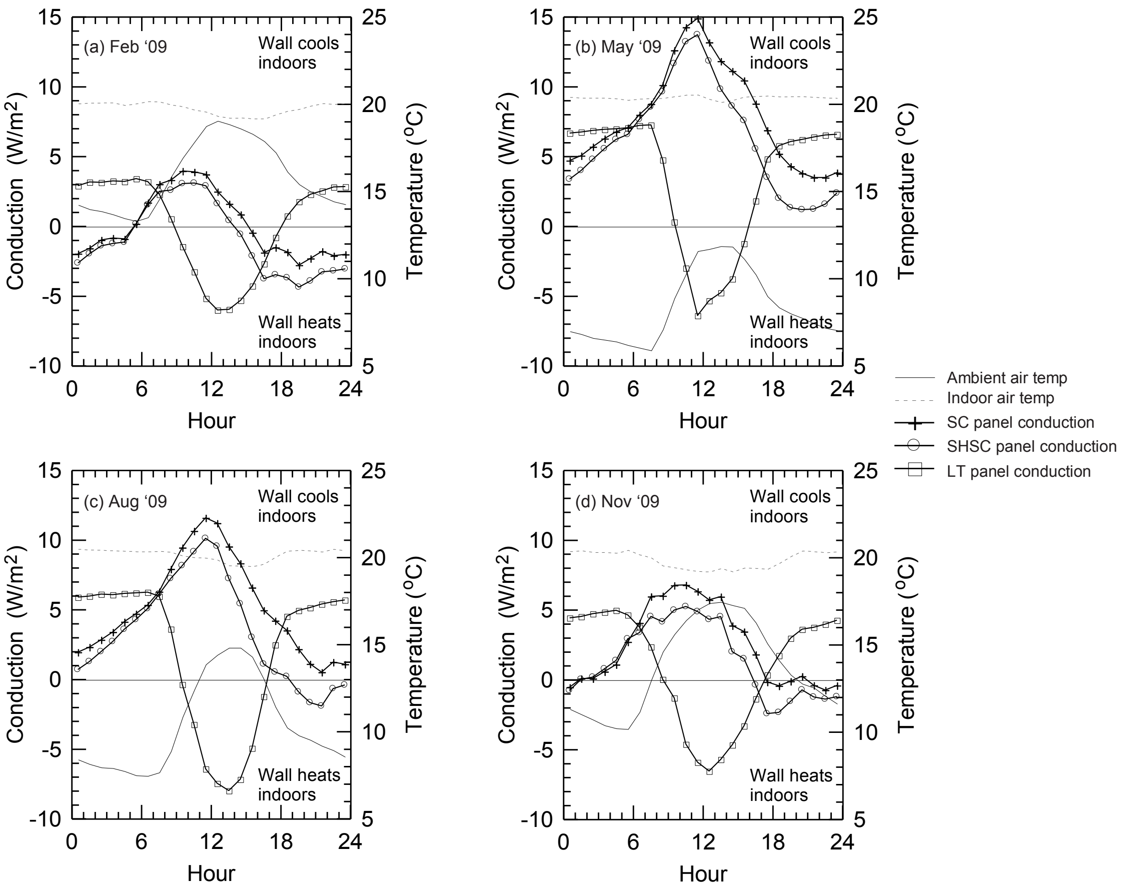

Fig. 3. Monthly mean hourly conduction (+ve towards outdoors) at the interior surfaces of solar heated stratified concrete (SHSC), stratified concrete (SC) and lightweight polystyrene (LT) test panels in the north wall of a solar laboratory at Christchurch (43.5°S)

cooling when the ambient air temperature exceeds 22°C. Mean conduction for these hours equals -8.74 W/m^2, -0.07 W/m^2 and 2.70 W/m^2 for the LT, SHSC and SC panels respectively. While the cooling performance of the SHSC panel is inferior to that of the SC panel, it is far superior to that of the lightweight panel.

4.2. U-factor

The U-factor of the solar heated stratified concrete panel (≅ 1.15 W/m^{2}K) was found from conduction measurements to be slightly greater than the U-factor of the stratified concrete panel (≅ 1.10 W/m^{2}K). The collector slightly compromised the insulation provided by the lightweight concrete layer.

The equivalent U-factor is usually a better indicator of a wall's overall energy performance than the U-factor [4]. The equivalent U-factor is the apparent U-factor when the adjacent building space requires auxiliary heating or mechanical cooling. Equivalent U-factors (Table 1) were determined for the panels, using conduction and air temperature measurements from the trial and treating the solar laboratory as a building space that needs auxiliary heating when the ambient air temperature is less than 15°C and mechanical cooling when the ambient air temperature exceeds 22°C. The values in Table 1 show that the SHSC panel has the best overall energy performance and the mini solar collector improves energy performance by more than 20%.

Table 1. U-factors of the test panels

Panel	U-factor (W/m^2K)	Equivalent U-factor (W/m^2K)
Stratified concrete (SC)	1.10	0.38
Solar-heated stratified concrete (SHSC)	1.15	0.29
Lightweight polystyrene (LT)	0.48	0.36

5. Conclusions

The solar heated stratified concrete panel tested in this paper has a relatively high U-factor and an embedded mini solar collector that covers only 10% of the panels face. And yet its energy performance is better than that of a lightweight panel with more than double the amount of insulation. The concrete panel's superior performance can largely be attributed to its thermal mass. However, the mini solar collector embedded in the panel made a significant contribution to its performance.

There is scope to improve the performance of the collector. It still produces unwanted solar heat during the summer and delivers solar heat to the interior surface of the wall panel too early in the day. Optimising the collector's geometry should produce significant performance gains.

This paper has not considered the aesthetics and economic feasibility of solar heated stratified concrete panels. Clearly these have to be considered in the future developments of this technology.

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