

ENVIRONMENT DESIGN GUIDE

SUSTAINABLE HOUSING USING LIGHTWEIGHT CELLULAR CONCRETE

Swee Mak, Seongwon Seo, Michael Ambrose, Leigh Gesthuizen

Summary of

Actions Towards Sustainable Outcomes

Environmental Issues/Principal Impacts

- With an estimated 130,000 new dwellings built per year in Australia, employing low-emission materials can make a significant impact.
- Concrete is the highest volume construction material used worldwide, and can contribute up to 20 per cent of the embodied energy of building materials used.
- Embodied energy may be up to 60 per cent of the overall life-cycle energy of buildings, and materials substitution may provide up to 20 per cent reduction in total energy over a 50-year building life-cycle.

Basic Strategies

In many design situations, boundaries and constraints limit the application of cutting EDGe actions. In these circumstances, designers should at least consider the following:

- Structural lightweight cellular materials such as Load-Bearing Cellular Mortar (LBCM) can be manufactured as precast panels for use in domestic construction, and has better insulative properties than normal concrete.
- Based on comparisons with some conventional wall systems, the use of LBCM may result in a two to six-fold reduction in both gross energy and GHG emissions, as well as a reduction in embodied water.
- In housing construction, lightweight cellular concrete can reduce construction time and cost because of easier lifting and transportation of the prefabricated panels.

Cutting EDGe Strategies

- To capitalise on the environmental potential of using LBCM in residential construction new technologies are needed to enhance current materials and research alternative materials, manufacturing and design processes.
- Collaboration with industry, regulatory and research authorities is needed to ensure future needs and trends can be achieved.
- For overall evaluation, however, a wide range of other considerations are necessary including unit product cost, cost of installation, fit with functional requirements, compliance with building regulations and supply chain issues associated with materials, manufacturing and transportation.

Synergies and References

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Using lightweight technologies, such as precast cellular concrete wall panels, provides an opportunity to reduce the environmental footprint of construction materials, through the general reduction in materials usage, reduced transportation and lifting energy, potential improvements of in-service energy efficiency and improved recyclability. This paper presents the results of an environmental analysis of a new load-bearing cellular concrete system and more traditional wall systems such as brick veneer, double brick and autoclaved aerated concrete. The results show that for residential buildings, the precast cellular concrete wall panel system has superior environmental performance in terms of reduced embodied energy, embodied water and greenhouse gas emissions when compared to traditional systems. This suggests that such building systems may play a crucial role in the future development of sustainable and environmentally friendly housing.

Keywords:

sustainability, housing, lightweight, cellular, concrete, embodied energy, greenhouse gas, precast, water, panels



Figure 1 Precast LBCM panels being lifted and propped in test house at, CSIRO Highett, Melbourne

(Source: CSIRO, 2007)

1.0 INTRODUCTION

Concrete is the dominant material used in the construction of many buildings, which depending on building type, may account for 20 percent of the embodied energy of building materials. In the context of climate change impacts and the fact that concrete is the highest volume construction material used worldwide (Metha and Meryman, 2009), there is a

strong incentive to evaluate alternative technologies that may meaningfully reduce the environmental impacts of concrete use. This paper reports on an environmental analysis of a Load-Bearing Cellular Mortar (LBCM)-based precast lightweight cellular concrete system in comparison with a conventional precast concrete and various wall systems commonly used for residential applications in Australia.

Thermal factors

Improving the energy efficiency of buildings could be a relatively effective and low-cost global greenhouse gas (GHG) abatement strategy (Enkvist et al. 2007). For instance, improving building insulation reduces the operational energy demands for heating and cooling, therefore building materials with good insulative properties will play an increasingly important role in assisting with global carbon abatement.

One class of materials that may potentially play such a role is cellular concretes with densities ranging from 500 to 1500 kg/m³ as compared to 2300–2500 kg/m³ for conventional concrete. Cellular concretes are lightweight concretes with a Portland cement base containing many small air cells uniformly distributed throughout the concrete. These materials may be manufactured in various elemental forms from blocks to large precast panels with compressive strengths of 3–25 MPa, providing a range of functional benefits, from non-load-bearing to fully structural load-bearing applications. Since the porosity of such materials increases when density decreases, low-density materials typically exhibit relatively lower thermal conductivity, and hence better insulative properties when compared to materials of relatively higher density. Therefore, products at the low-density end of the range may provide useful insulative properties in their own right, whereas materials at the higher density end need to be combined with other materials to provide adequate insulation.

Energy factors

Apart from the potential to provide improved building insulation, there may be a wider range of environmental benefits arising from the increased use of lightweight building materials such as cellular concrete. These may range from reduced materials usage to reduced transportation energy, both of which contribute directly to the embodied energy of a building. The lifecycle environmental impacts of using a particular material or design should not be overgeneralised on the basis of relatively rudimentary analyses of embodied energy. However, such analyses provide a useful starting point when considering alternative materials or building systems on the basis of environmental performance. In some office buildings, the embodied energy may be as high as 20 times the annual operational energy (Ballinger et al., 1995). Depending on the type of construction and design, various studies have shown that external walls contribute 10–20 per cent of the total embodied energy of a building (Pullen, 1995; Treloar, 1996, Treloar and Fay, 1998). Other studies have suggested that the embodied energy may be up to 60 per cent of the overall lifecycle energy of buildings, and that materials substitution may provide up to 20 per cent reduction in total energy over a 50-year lifecycle (Huberman and Pearlmuter, 2008).

Strength factors

In recent years, there has been significant progress in the development of structural lightweight cellular materials for use in both commercial and residential construction. One such development is a Load-Bearing Cellular Mortar (LBCM) manufactured as large precast panels (Mak et al., 2005). LBCM is basically a mixture of cementitious material, sand and water that is aerated. Apart from a direct weight reduction, which enables reduced structural member sizes and foundations, the LBCM panels may also provide further advantages in faster and cleaner construction with reduced on-site trades and waste generation. The proportional relationship between strength and density, in which strength decreases as density decreases, is well known. Therefore, the key challenge with lightweight cementitious products is to achieve the highest strength possible for a particular density. Strength not only provides load-bearing capability, but it also contributes to a wide range of other functions such as reducing breakage, and improving impact resistance and durability.

Other considerations

Whilst strength is of primary importance, an effective lightweight technology also needs to fulfil a range of common functions and performance requirements. In the case of wall panel elements used in above ground construction, these would include durability, shrinkage, impact resistance, thermal resistance and fire resistance. While the combination of a 40–50 per cent weight reduction (compared to normal weight concrete) with structural load bearing capacity is a compelling incentive to use such materials instead of traditional building materials, increasingly the reason for choosing them may hinge on environmental performance.

2.0 DEFINING LIGHTWEIGHT CELLULAR CONCRETES

Normal grade concretes typically have densities of 2300–2500 kg/m³, while cementitious products termed 'lightweight' may have densities of 300–2000 kg/m³. However, as there is no universally accepted definition of distinct classes of lightweight materials, it is important that the term 'lightweight concrete' is not overgeneralised, since there may be many very different materials with widely varying properties within a certain density range.

Lower density products are typically used as insulation, toppings or non-load-bearing infills. Load-bearing lightweight concretes typically have densities of 1000–2000 kg/m³. Many so called 'lightweight concretes' are in fact not concrete in the traditional sense, since they do not contain aggregates, but are aerated mortars produced either by gassing reactions or the use of preformed foams. Alternatively, many such cellular concretes are cementitious mortars containing lightweight fillers such as polystyrene beads, vermiculite or perlite, and these concretes typically have densities of 300–1200 kg/m³. On the other hand, Lightweight Aggregate Concretes (LWACs) normally incorporate

either naturally occurring porous stones such as scoria, or artificial aggregates such as sintered fly ash or ceramics. LWACs typically have densities of 1500-2000 kg/m³ and can be produced with compressive strength of 40-50 MPa.

Type of concrete	Approximate density
Normal grade	2300-2500 kg/m ³
Lightweight Aggregate Concretes (LWACs)	1500-2000 kg/m ³
Load-bearing lightweight concretes	1000-2000 kg/m ³
Lightweight 'concretes' (often aerated mortars)	300-2000 kg/m ³
Cellular concretes (often mortars containing lightweight fillers)	300-1200 kg/m ³

Table 1 Concrete Densities

3.0 METHODOLOGY

The use of lightweight building products has the potential to significantly reduce the environmental impacts of construction through reductions in, for example, bulk materials usage, and transportation and construction energy.

The results discussed in this paper focus on the embodied energy, GHG emissions (shown for CO₂ equivalent gasses) and embodied water in a range of commonly used wall systems compared to a new lightweight precast LBCM system. A 'cradle-to-grave' (from the elemental extraction of source materials through the life of the product to disposal at end of use) methodology was adopted, utilising embodied energy and GHG emission values through Boustead modelling, which is a computer modelling tool for life cycle inventory calculation. In addition, a 'gate-to-site' (from manufacturer to building site) transport value was also calculated to compare the transportation energy of different products over a distance of 40 km, based on a typical truckload of each product.

Wall Systems

The LBCM used in the analysis is a relatively high strength cellular mortar manufactured as large precast structural panels in two density grades, i.e. 1000 kg/m³ (H1000) and 1500 kg/m³ (H1500). The cellular structure is created by gas aeration of a relatively high strength cementitious mixture of Portland cement and various supplementary cementitious materials such as fly ash or silica fume. The product is precast in panel sizes up to 18 m² (e.g. 3m x 6m) on steel formwork, then heat cured to achieve sufficient early-age strength before being demoulded from the formwork. To improve handling, structural performance and shrinkage control, the panels are reinforced with

various grades of steel mesh. The compressive strengths of the cellular material used for the H1000 and H1500 products are 8 and 20 MPa respectively. As walling systems, these cellular concrete panels can be installed with a thin concrete render, or they can be combined with insulative materials and linings to provide the required thermal insulation performance.

Thermal performance

One of the key underlying environmental performance requirements for a wall system is its thermal rating, often expressed simply in terms of its thermal resistance or R-value. For residential construction, the recommended R-value for walls typically ranges between R1.5 and R2, depending on geographic location. This basic requirement provides guidance on the comparison of wall systems in this paper. The key property underpinning the R-value is the thermal conductivity of a material, which for concrete and many other materials is related to density, whereby as density reduces so does thermal conductivity. This is shown in Figure 2 where Normal density Concrete (NC) is compared with medium density LBCM and a relatively lower density Autoclaved Aerated Concrete (AAC). In turn, this implies that the R-value will increase as density decreases, and thus lower density cellular concretes will exhibit relatively higher R-values compared to normal density concretes. However, when used in the normal thickness range of 100-150 mm, cellular concretes generally do not meet the thermal rating requirements for wall construction unless additional insulation is provided. For instance, the dry-state thermal conductivity of AAC ranges from 0.12-0.14 in the density range of 510-580 kg/m³. The corresponding R-value of a 150 mm thick AAC element with a density of 550 kg/m³ ranges R0.9-1.1, depending on the moisture content (CSR Hebel Technical Manual, 2006). The dry-state thermal conductivity of the H1000 LBCM is 0.35, implying that the insulative value of a 150 mm thick element is R0.45. For the same thickness of normal density concrete, the insulative value would be only R0.12. However, when used as part of a wall system, the required R-value can be easily achieved by any of these concretes through, for instance, the addition of air gaps, fibreglass insulation batts, polystyrene sheets or reflective foil liners.

Type of concrete wall panel (150mm thick)	Approximate insulative value
Autoclaved Aerated Concrete (AAC) (with density of 550 kg/m ³)	R 0.9-1.1
LBCM (1000 kg/m ³ or H1000)	R 0.45
Normal density Concrete (NC)	R 0.12

Table 2 Insulative value of concrete panels

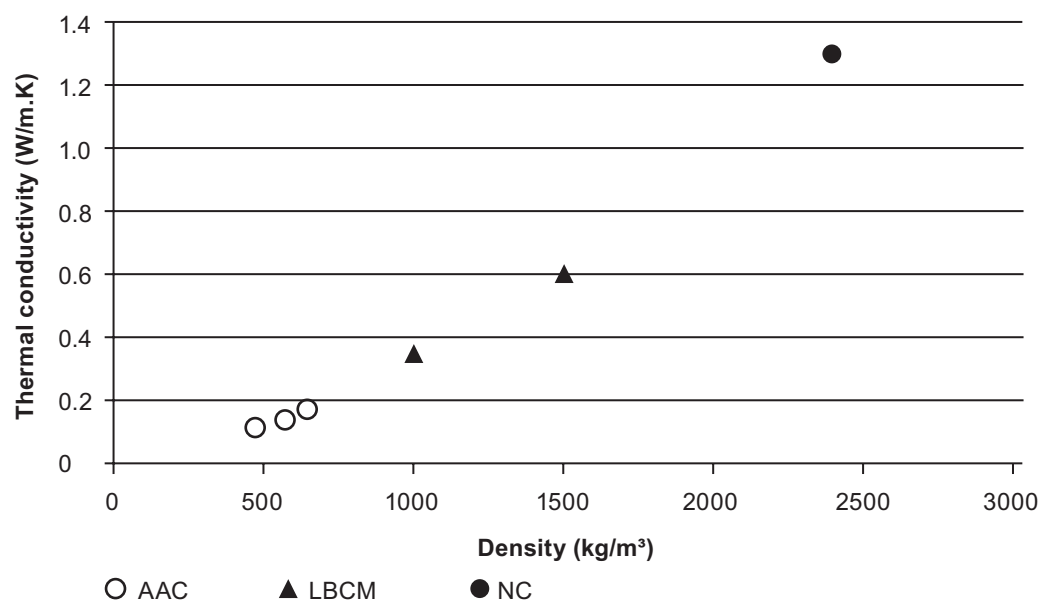


Figure 2 Thermal conductivity of normal and low-density concretes

(Source data for AAC, GFC Concrete Ltd, 2006)

Therefore, it is important that environmental analyses of embodied energy are carried out for entire wall systems that meet a minimum performance requirement, rather than the primary wall material itself. From this perspective, the discussion in this paper is focused primarily on the H1000 LBCM used as 100mm thick panels, this being the product intended for use in residential construction. Some reference

will be made for comparative purposes to the H1500 LBCM and a range of wall systems commonly used in Australian residential construction. A description of the generic wall systems studied in this investigation is given in 3. These include brick veneer, double brick and concrete block walls, all rendered externally and lined internally with plasterboard.

Wall system Code	Primary material	Cladding and lining materials
PC40	40 MPa precast concrete	None
BV	Brick veneer	15mm external concrete render timber studs R1.5 insulating batts plasterboard lining
CB	Concrete block	15mm external concrete render timber studs R1.5 insulating batts plasterboard lining
DB	Double brick wall	15mm external concrete render timber battens plasterboard lining
AAC	Autoclaved aerated concrete	15mm external concrete render timber studs plasterboard lining
H1000 / H1500	LBCM	5mm external concrete render
H1000P / H1500P	LBCM	5mm external concrete render 65mm polystyrene insulation plasterboard lining
H1000B / H1500B	LBCM	5mm external concrete render timber battens R1.5 insulating batts plasterboard lining

Table 3 Wall systems investigated

4.0 RESULTS AND DISCUSSION

4.1 Gross Embodied Energy

The direct relationship between bulk density and unit materials usage implies a potential to reduce embodied energy through the lower rate of materials usage in lightweight materials. However, normal density concrete is a composite material consisting of a cementitious binder and inert fillers such as sand or coarse aggregates. The relative unit contribution of

compared to normal grade concretes on a volumetric basis. Therefore, a lightweight cellular material may not always provide an obvious reduction in embodied energy when compared to a normal density concrete even though the amount of materials used is relatively lower. This is evident in Table 4 where two grades of LBCM (H1000 and H1500) are compared with a conventional 40 MPa precast concrete (PC40). On a volumetric basis, the gross energy of H1000 is 17 per cent lower than that of PC40, but that of H1500 is 17 per cent higher because of its relatively higher cement

Concrete	1m³ of product	1m² of panel including reinforcement	
		150 mm thick	100 mm thick
PC40	3269 MJ	563 MJ	399 MJ
H1500 LBCM	3834 MJ	631 MJ	439 MJ
H1000 LBCM	2722 MJ	465 MJ	328 MJ

Table 4 Gross energy of various concrete panels

these materials to the total embodied energy may vary greatly, with the gross unit energy of cement being 75-100 times higher than that of aggregates on a tonnage basis.

The major volumetric constituents of cellular concrete are cement and sand, with coarse aggregates omitted. However, cellular concretes may contain more cement

content. When the panel products are compared on a surface area basis, and including steel reinforcements, the gross energy of the 100 mm thick H1000 panel is 18 per cent lower than for PC40. By contrast, the gross energy of the H1500 panel of similar thickness is 10 per cent higher than that of the precast concrete. The gap in embodied energy between H1500 and PC40 has, in this case, narrowed due to the relatively lower quantity of steel mesh needed in the LBCM panel.

The results in Table 4 imply that the use of H1000 LBCM in residential construction, for example, may potentially reduce the gross energy content of a wall system by more than 15 per cent when compared to precast concrete. However, the differences between LBCM and precast concrete are relatively small, particularly when compared to other conventional wall systems. For instance, the results in Figure 3 show that the gross embodied energy of the H1000B system is more than six times lower than that of the double brick wall and almost four times lower than that of either the brick veneer or concrete block walls. When compared to the particular AAC wall system analysed here, the gross energy of the H1000B wall was 70 per cent lower. The addition of insulation to achieve the required R-values in the LBCM increases the gross embodied energy of the wall system. This is evident from Figure 3 where the addition of R1.5 insulating batts increased the gross energy from 328 to 531 MJ/m². However, the choice of insulation in this instance did not influence the gross embodied energy of the LBCM wall systems.

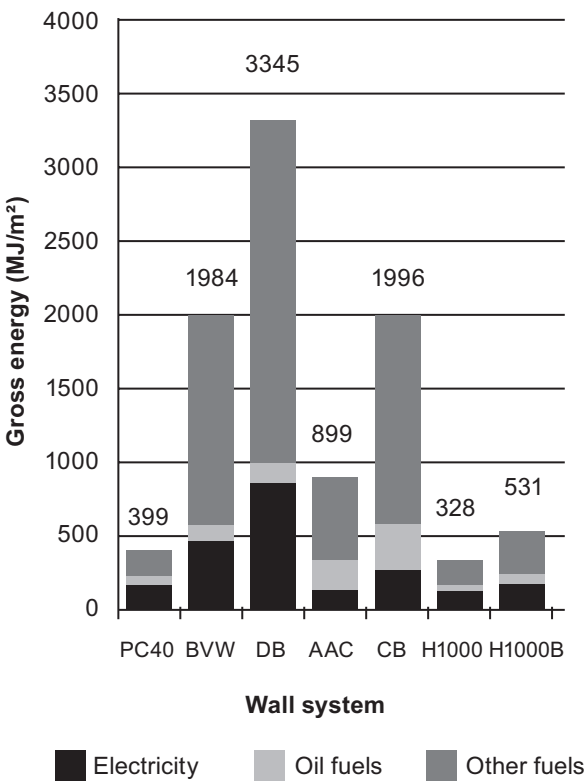


Figure 3 Gross embodied energy comparison of 100mm wall systems

See Table 3 for a description of wall systems

4.2 Greenhouse Gas Emissions

In Australia, GHG emissions generally follow a similar profile to embodied energy values, due to the dominance of coal-fired power stations and the usually large flow of electricity used throughout manufacturing processes. However, concrete-based products can

alter this profile due to the fact that CO₂ is released during the cement manufacturing process. It has been discussed above that the cement content will dominate the gross energy of a product. This is even more so when it comes to GHG emissions.

As shown in Figure 4, in terms of GHG emissions, there was little difference between the H1000 LBCM and PC40. However, when compared to other conventional residential wall systems, the GHG emissions of the LBCM were significantly lower. Again, the double brick wall system produced the highest GHG emissions, being just under six times that of the H1000B wall system with batts. The brick veneer wall and the concrete block wall systems both benefit from a biomass credit in the GHG analysis, but still show higher GHG emissions compared to the LBCM system. Biomass credits are obtained from cradle to gate of each product. The standard AAC block wall system also benefits from a biomass credit, which results in this system having the lowest GHG emissions of all systems analysed.

4.3 Embodied Water

The consumption of water during product manufacturing processes has gained increasing attention in recent years in Australia, mainly as a result of the prolonged drought conditions being experienced here. Embodied water calculations are utilised to determine the total water consumption through a manufacturing process in much the same way as embodied energy tracks energy use through a manufacturing process.

An embodied water analysis shown in Figure 5 illustrates that the production of LBCM panels uses significantly less water than any other wall system investigated. The water consumption of a plain H1000 wall was only a quarter that of PC40, whilst that of the insulated H1000B wall system was over 60 per cent lower than PC40, equating to a saving of more than 100 litres per square metre of panel. When compared to other wall systems such as concrete block, the use of the LBCM system produced savings of almost 160 L/m².

Previous discussion suggested that the choice of insulation to provide similar total R-values did not affect the gross embodied energy of the LBCM wall systems. By contrast, the embodied water content is significantly affected by the choice of added insulation material. Due to the relatively high embodied water content in manufacturing polystyrene sheets, the use of 65mm polystyrene sheets as added insulation in the LBCM walls increased their embodied water content by more than three times when compared to a system that was insulated using fibreglass insulating batts.

5.0 IMPLICATIONS FOR SUSTAINABLE HOUSING

This environmental analysis has shown that wall systems built with prefabricated cellular concretes have the potential to reduce the gross embodied energy, GHG emissions and embodied water content in residential construction. Based on comparisons with some conventional wall systems, the use of LBCM may result in a two to six-fold reduction in both gross energy and GHG emissions. Adding further

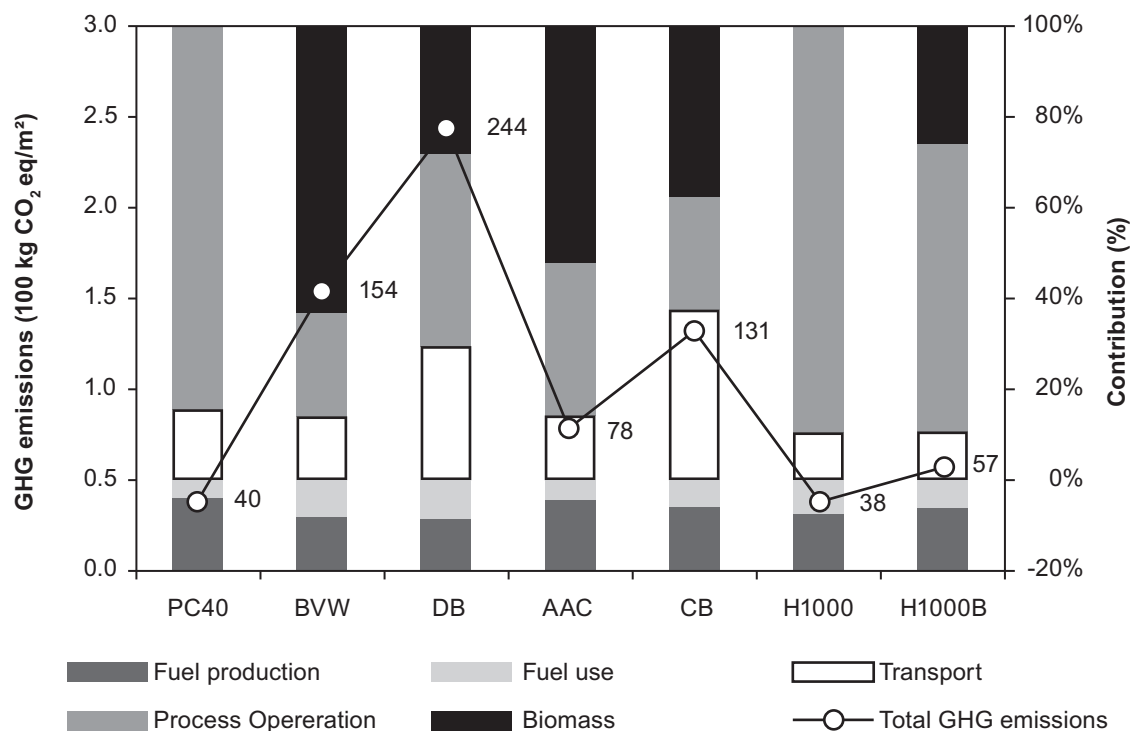


Figure 4 GHG emissions of various wall systems from cradle to gate by production energy input

See Table 3 for a description of wall systems

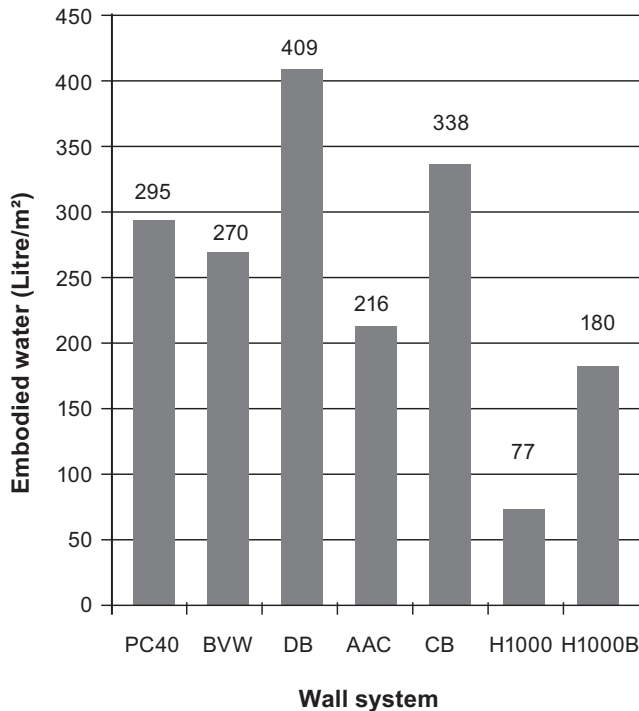


Figure 5 Embodied water used in manufacturing various wall systems

See Table 3 for a description of wall systems

to potential improvements in sustainability is the reduction in embodied water used in manufacturing, and the feasibility of producing wall systems with the required thermal ratings by coupling LBCM with a range of insulation materials. However, it is important that environmental performance analyses of different wall systems are conducted on the basis of some common functional requirements, such as equivalent thermal rating. Ultimately, it is necessary to obtain an objective comparison in whole building performance from either actual measurements or experimentally validated methods of calculating thermal performance (Heathcote, 2008).

Test Cell

A single-storey model building with a floorspace of 25m² was designed and constructed to demonstrate proof of concept for both the manufacturing process and the method of construction using this LBCM panel technology. For construction of this demonstration building, approximately thirty 100 mm thick panels with standard dimensions of 900 x 2700mm were manufactured. All panels were reinforced with one layer of mesh placed centrally, and some panels included cast in conduits for electrical services. Figure 1 shows these precast panels being lifted into place and propped, as is normal practice for erecting precast concrete walls. The entire wall structure was completed in less than one working day. A number of joint preparation and surface finishing methods were used to assess the long-term weathering and shrinkage properties of the wall system. The completed building is shown in Figure 6. The knowledge gained from the construction of this



Figure 6 The completed test house at CSIRO Highett, Melbourne

This cell was built by CSIRO for evaluating the manufacturing and construction process

(Source: CSIRO, 2007)



Figure 7 Precast LBCM panel house, Werribee, Victoria

(Source: HySSIL, 2009)

test house has since been used to develop larger precast panels of between 8-9m² which were used in the construction of a fully operating residence in Werribee outside of Melbourne (Figure 7). The first demonstration home was built with a Melbourne based housing company in a new residential estate in Werribee, Victoria. The project was completed in early 2009.

6.0 CONCLUSION

With Australia's housing stock increasing by an estimated 130,000 dwellings per year, the potential for reducing environmental impacts through the use of relatively low-emission materials to provide improved thermal performance, will add to the impact of other abatement strategies employed throughout the economy. The overall feasibility of using such new materials would obviously be based on a wide range of other considerations, such as unit product cost, cost of installation, fit with functional requirements, compliance with building regulations and supply chain issues associated with materials, manufacturing and transportation.

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The papers included in the World SB08 Proceedings, Volume 2, have been reviewed in entirety and deemed to be worthy of inclusion in the conference program and proceedings by at least two, and in many cases three, independent and qualified experts drawn from Australia and internationally, including members of the International Scientific Committee. These reviews were not 'blind' however.

BIOGRAPHIES

Dr Swee Mak is Deputy Chief (Industry) of CSIRO Materials Science and Engineering where he is responsible for the effective delivery of research to industry from a large R&D portfolio that focuses on sustainable, advanced materials and manufacturing processes. He obtained both his undergraduate and PhD degrees in civil engineering from Monash University, an MBA from the Australian Graduate School of Management and is a member of the Australian Institute of Company Directors. Dr Mak has provided expert advice and R&D services to many companies in Australia and overseas, and was also a Director of the Concrete Institute of Australia and ex-President of its Victorian Branch.

Swee.Mak@csiro.au

Dr Seongwon Seo is a senior research scientist at CSIRO Division of Sustainable Ecosystems. Dr Seo has completed research and demonstration projects for sustainable infrastructure in university and governmental research institutes in various countries. His research interests are in developing methodologies and tools for environmental and economic analysis of urban infrastructure systems, primarily for the construction industry and the built environment. His research is currently focussed on the measurement of building environmental performance, sustainable construction, building assessment tools, and life cycle modelling for urban infrastructure systems.

Seongwon.Seo@csiro.au

Mr Michael Ambrose is an environmental scientist with CSIRO's division of Sustainable Ecosystems. His background is in architecture and building and his research work has focused on the environmental impacts of the built environment, especially residential buildings and neighbourhoods. Recent projects have included developing the Your Development web portal to provide sustainability information to land developers, local council and planning authorities. Currently, he is developing Australia's first zero emission house aimed at the mass housing market.

Michael.Ambrose@csiro.au

Mr Leigh Gesthuizen is the General Manager of HySSIL Pty Ltd. Mr Gesthuizen has built a strong portfolio of regulatory compliance and business management. Well experienced in Regulatory Compliance of Building Regulations in addition to extensive experience in Australia and Asia managing large concrete laboratories, concrete manufacturing facilities and road transport businesses for a major Australian Blue Chip organisation, he graduated in Building Surveying, Project Management and is currently undertaking a Masters in Entrepreneurship and Innovation at Swinburne University.

leighgesthuizen@hyssil.com

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