

NEW INSULATING PRECAST CONCRETE PANELS

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ABSTRACT

Conventional concrete is a poor insulating material but has good thermal mass while lightweight concrete provides good insulation at the price of thermal mass. Precast concrete walls systems have not been widely used in residential homes due to poor thermal and acoustic performance. Precast concrete can however provide high quality products and are easy to construct. Bellamy and McSaveney proposed the concept of a panel produced from a single concrete mix that combined insulation and thermal mass. This was accomplished with a lightweight insulating top (outside) layer and a heavy/normal weight material dense bottom (inside) layer.

These layers were gained by controlled segregation or stratification. The stratification was achieved by vibration using aggregates of different density and a moderately sticky paste. Trial panels were made using waste materials such as fly ash, slag and expanded glass beads together with either Portland cement or inorganic polymer cements.

Research shows promising potential of producing variable density concrete panels. These panels can be manufactured with a simple and energy efficient processes using mostly recycled materials. As well as being simple in construction they are also energy saving during the life time of the building by having good thermal properties.

KEYWORDS:

Heavy/normal/lightweight concrete; stratification; insulating; energy saving; recycled materials

INTRODUCTION

Heating residential houses and other buildings is essential in cold countries. In hot countries the buildings need to be able to retain the heat of the day and release it again at night time. Buildings in these countries should therefore have suitable thermal insulating properties to save heating energy and thermal capacity to stabilize the internal temperature (Bobrowski, 1978).

Energy is becoming more expensive and people are realizing that saving energy is important. All over the world we are trying to save long term energy efficient options, from hybrid cars to energy-saving light bulbs. Nevertheless badly insulated houses are still being built. These houses use a lot of energy for heating during winter and cooling during summer. There is increasing pressure from governments and the public to produce more energy efficient buildings; and regulations are being tightened in many countries.

In this paper a new type of insulating precast concrete wall panels is introduced. These panels combine the properties of lightweight insulating and heavy/normalweight concrete. Research on these panels show promising results and some full scale panels will be cast later in the year.

INSULATING CONCRETE PANELS

Thermal properties of concrete

Traditional concrete is considered a poor insulator with good thermal mass, or fabric energy storage. Thermal mass is the ability of material to absorb and store thermal energy with its mass. The theory is simple: the concrete will absorb thermal energy, store it, and release it when the internal temperature drops below that of the concrete. Due to thermal mass, solid construction buildings usually feel cooler

during summer and warmer during winter. That is; temperature fluctuations are reduced and a more comfortable home is the result (Cement and Concrete Association of Australia, 2005). Products such as insulating concrete forms have greatly improved insulation but these products prevent the full thermal mass of concrete being utilized.

Lightweight concrete can be produced by using lightweight aggregate or by aeration. One of the advantages of lightweight concrete is a good thermal insulating property, but other equally important properties are for example reduced mass while maintaining adequate strength, good durability and good sound insulation (Babu et al, 2006). The use of lightweight concrete is energy saving in many ways: for example, less energy is required for heating over the lifetime of the building and reduced weight reduces the energy demand during construction. The greater the density of lightweight aggregate concrete the higher the thermal conductivity and strength but lower thermal insulation is provided by the concrete.

Lighter aggregates produce concrete with low thermal conductivity whereas higher density aggregates provide good thermal mass. Other material and environmental factors that influence the thermal conductivity of concrete are for example (Mackechnie et al, 2007c):

- The density of the concrete – low density gives low thermal conductivity
- The binder type used – inorganic polymer gives lower thermal conductivity than similar Portland cement binder
- The moisture content – long term drying reduces the thermal conductivity

Conventional concrete typically has thermal conductivity between 1.5 and 2.5 W/mK. Lightweight concrete has much lower thermal conductivity but it is difficult to get the thermal conductivity value below 0.2 W/mK.

The thermal performance of buildings is often assessed by using the R-value or thermal resistance. The R-value is a measure of product's insulating ability (R-value = thickness/thermal conductivity). A building product with high R-value has more resistance to heat loss in winter and heat gain in summer than a product with low R-value. New Zealand is divided into three climate zones with different R-values requirements:

- Zone 1 – Auckland and Northland with minimum R-value of $0.6m^2K/W$
- Zone 2 – Remainder of the North Island with minimum R-value of $0.6m^2K/W$
- Zone 3 – South Island and Central North Island with minimum R-value of $1m^2K/W$

The R-values requirements are also dependent on the building component, but the R-values listed above are the minimum requirements for a wall in a solid construction (NZS 4218, 2004).

Precast wall panels

The use of precast panel systems for walls in residential homes offers the opportunity to control the quality of the end product to a very high degree. This is because the panels are supplied from specialized precasting factories and therefore cast in controlled environment. The precast concrete is then transported to the construction site and lifted into place. The construction time needed, is reduced due to the fact that large forms are not constructed on site and it does not become essential to wait for the curing of the concrete. Construction periods in residential communities should be as short as possible so that disturbances to neighbouring houses are kept to a minimum. The fact that no large forms are being build also means less scrap being brought into the neighbourhood.

To some degree, precast concrete is though not suitable for residential construction due to its poor thermal and acoustic performance. Currently there are several concrete wall systems manufactured with higher insulation values, achieved by the use of various insulating mediums. The most common medium is polystyrene sheeting which is attached to the interior or exterior face of the panel or located within the panel ("sandwich panel construction"). These products however prevent the full thermal mass of concrete being utilized (CCANZ, 2007). These insulation forms are also not ideal in terms of energy efficiency, cost and labour requirements. Precast panels made of lightweight concrete are usually reinforced with fibres rather than conventional steel reinforcing and can have a variety of finishes applied or cast integrally on the surface.

Insulating precast wall panels

Trying to combine good thermal storage, insulation and high quality end product Bellamy and McSaveney proposed the concept of the variable density concrete panel. The variable density concrete panel, Figure 1, is produced from a single concrete mix which is vibrated to achieve:

- Lightweight insulating top (outside) layer with low thermal conductivity providing good insulation
- Heavy/normal weight material, dense bottom (inside) layer with high specific heat to provide thermal mass and sufficient strength for construction handling and to withstand service loads

On top of the lightweight layer a wearing or surface coat will be placed to protect the lightweight concrete and to have better appearance, this coat is not shown on Figure 1.

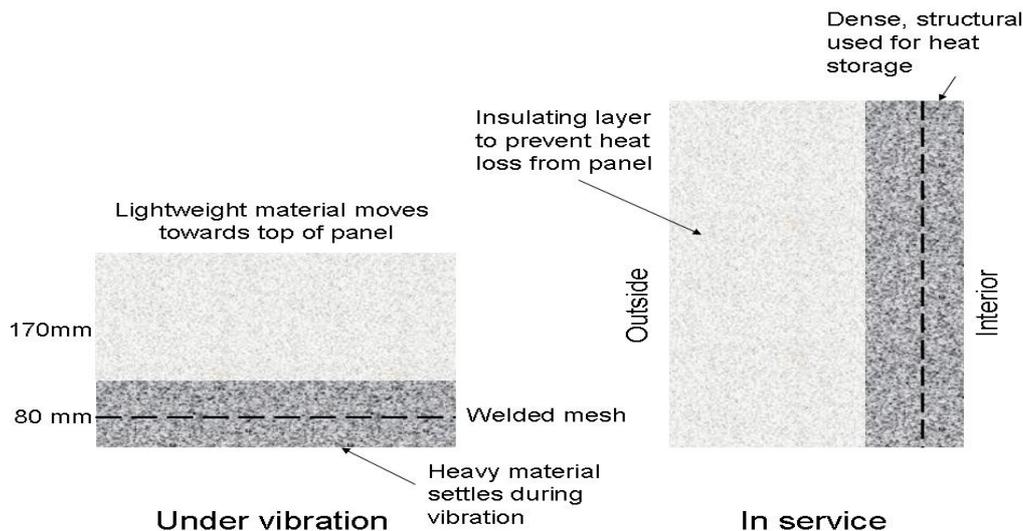


Figure 1 - Illustration of variable density concrete panel (Mackechnie et al, 2007b)

To achieve this, aggregates of different densities were used which segregated under vibration, if provided a moderately sticky paste. That is; controlled stratification was needed to get different layers within the panel from a single batch of concrete. The top layer mainly contains lightweight material with low thermal conductivity to provide good thermal insulation, while the bottom is mainly the heavier material with high specific heat to provide good thermal mass. The heavier layer also gives the panel sufficient strength for handling and to withstand service loads (Mackechnie et al, 2007b).

After some initial trials a set of technical objectives was developed which can be viewed in Table 1.

Table 1 – Technical objectives for stratified concrete (Mackechnie et al, 2007c)

Material Property	Top Layer	Bottom Layer
Thickness [mm]	170	80
Density [kg/m^3]	1000	2250
Compressive Strength [MPa]	2-5	25-35
Thermal Conductivity [W/mK]	<0.25	1.00-1.25
Specific Heat [MJ/m^3K]	0.75-1.25	2.00-3.00
R-value panel [m^2K/W]	0.8-1.0	

The thickness of the top and bottom layer was estimated to get the optimum thermal performance from the panel. It was estimated that roughly two thirds of the depth should be lightweight insulating concrete and one third normal/heavy weight thermal storage concrete to achieve the best thermal performance from the panel. As well as providing thermal storage, the bottom layer had to be thick enough to provide reasonable cover and bond to a light welded mesh within the layer (Mackechnie et al, 2007b). As mentioned before the bottom layer also had to be thick enough to provide sufficient strength for service loads and handling.

Despite obvious benefits in thermal performance of the panels and being easy to manufacture, there are several major technical concerns that need further investigation (Mackechnie et al, 2007c):

- Control the segregation; that is allow the concrete mix to stratify during moderate levels of vibration, but remain fairly homogenous during mixing and handling
- Control the potential of the panels to warp and bend due to differences in shrinkage and stiffness across its depth
- Provide sufficient strength without excessively compromising the thermal performance
- Ensure that the materials used were sufficiently durable and serviceable to provide satisfactory long-term service of the panels
- Achieve satisfactory surface finish that requires minimal further treatment on site
- Provide a robust mix design and process system that will tolerate minor variations in batching, casting and compaction

After a series of laboratory trial concrete mixes, these concerns are not believed to be major but still need to be further investigated on full scale panels outside of the controlled environment within the laboratory. A series of full-scale trial panels are planned to be cast in collaboration with a precast concrete company.

Casting the variable density panel is slightly more expensive than casting a conventional concrete panel. This is mainly due to more expensive material being used in the variable panel. The excessive cost of making the panels will be saved over the lifetime of the building due to better insulation.

MATERIALS AND MIX DESIGN

Using recycled materials and byproducts from other industries is becoming more important. This is especially the case in developed countries which produce a lot of waste that needs to go into landfills. In these countries there is increasing landfill cost and areas for landfills are becoming hard to find.

After some material inspections and initial trials it was decided to carry on with two different mixes.

- Pumice and perlite as lightweight materials and greywacke chips (greywacke sandstone) as normalweight material. This mix was designed due the fact that these materials can be found in New Zealand, but are unfortunately not recycled
- Expanded glass beads and perlite as lightweight materials and slag as heavyweight material, due to the fact that these materials are found in Europe
 - Expanded glass beads are made from recycled glass that cannot be used by the glass industry to manufacture new glass products (Poraver, 2007)
 - Slag is a byproduct from smelting iron ore at Glenbrook

After working with these mixes for a while it was noticed that the pumice and perlite used were not consistent enough to guarantee the quality of the mix and proper stratification. It was therefore decided to develop the third mix which included:

- Expanded glass beads as lightweight material and slag as heavyweight material

As well as using different materials within the mixes, two binder systems were also used:

- Portland cement, general purpose cement from New Zealand
 - Cement production is a high energy process, with embodied energy between 1470 and 1110kWhr/tonne and embodied CO₂ between 1090 and 870kg/tonne. Where embodied energy is the total energy used in production and embodied CO₂ is the total amount of carbon dioxide produced. (Mackechnie, 2007a). Cement is made by grinding calcined limestone and clay to a fine powder
- Inorganic polymers, made with fly ash and/or slag, activated with alkali and sodium silicate solutions and thermal curing (Mackechnie et al, 2007b)
 - Fly ash is a mineral residue from coal combustion in electric generating plants. In the past fly ash was taken up by flue gases and dispersed into the atmosphere. Today some of the fly ash is recycled or reused but worldwide more than 65% of fly ash produced is disposed into landfills (Wikipedia, 2007)

In the end 6 different mix types were therefore used and is work currently being carried out on the two grade glass beads mix.

FRESH PROPERTIES

After some development work finding the right mixes, it was noticed that the degree of stratification was highly related on many things such as:

- Frequency of vibration
- Duration of vibration
- Rheological properties of the mix

Quality of the outer surface and the interface between the structural and insulating layer were affected by excessive vibration. Restricted vibration on the other hand led to bad stratification of the mix. Rheology is the science of deformation and flow of matter and is used to understand the fresh properties of concrete (Mackechnie et al, 2007b). Stratified concrete requires defined rheological properties, so three broad rheological ranges were defined (JR Mackechnie et al, 2007c):

- Having moderate to low flow and moderate to high viscosity the concrete can be too stiff and/or sticky to stratify adequately under vibration
- Having good flow and low viscosity the concrete would segregate during handling and produce uneven layers during vibration. When vibrated these mixes are more likely to delaminate
- Having good flow and moderate viscosity the concrete would be relatively homogenous during mixing and handling and stratify under moderate levels of vibration



Figure 2 - Degree of stratification of concrete (increasing from left to right)

HARDENED PROPERTIES

To estimate the behaviour of the stratified panel, different properties of the heavier thermal storage zone and the lightweight thermal insulating zone were checked. Cylinders and prism cast from the stratified concrete were tested in accordance with NZS 3112 (NZS 3112. 1986) and AS 1012 (AS 1012. 1992), Table 2. The major difference in hardened properties between the top and bottom layer are that the lightweight concrete has lower strength and elastic modulus and higher drying shrinkage than the normal/heavyweight concrete in the bottom layer. The normal/heavyweight concrete has similar hardened properties as conventional concrete. The geopolymer concrete seems to have lower strength, elastic modulus and drying shrinkage than the Portland cement concrete. The strength of conventional concrete for residential houses is usually between 17.5 and 30MPa. The bottom structural layer is within this range when using Portland cement as a binder whereas the geopolymer concrete has a slightly lower strength, Table 2. There is some ongoing work being done to improve the strength of the geopolymer mix.

The hardened properties of these mixes, viewed in Table 2, are slightly different to what was aimed for after some initial trials, Table 1. The density and strength of the lightweight insulating layer is slightly higher and the structural bottom layer has lower density and strength than what was expected. This could be related to the fact that there is always a bit of trapped material that gets stuck within the wrong layer.

Table 2 – Material properties of the panel mixes at 28days and the 56days drying shrinkage

MIX	Measured Density [kg/m ³]	Strength [MPa]	Modulus of Elasticity [GPa]	Shrinkage 28 days [micro-strain]	Shrinkage 56 days [micro-strain]
Cement glass/perlite					
TOP	1404	8.8	6.4	1331	1724
BOTTOM	2388	22.4	20.7	643	891
Cement pumice/perlite					
TOP	1680	10.5	8.4	1345	1453
BOTTOM	2169	19.6	18.1	776	900
Geopolymer glass/perlite					
TOP	1280	9.5	4.5	607	863
BOTTOM	2095	14.0	8.0	331	429
Geopolymer pumice/perlite					
TOP	1230	7.5	5.5	455	647
BOTTOM	2100	15.0	11.0	343	445

Half-scale panels were cast to check the structural and serviceability performance of the panels. A total of seven panels were cast, four of which were left exposed outside for 5 months and the remaining three were cured in the laboratory. The laboratory cured panels were vibrated for a short, moderate and long time to gain different stratification. Different properties could then be estimated dependent on the amount of stratification.

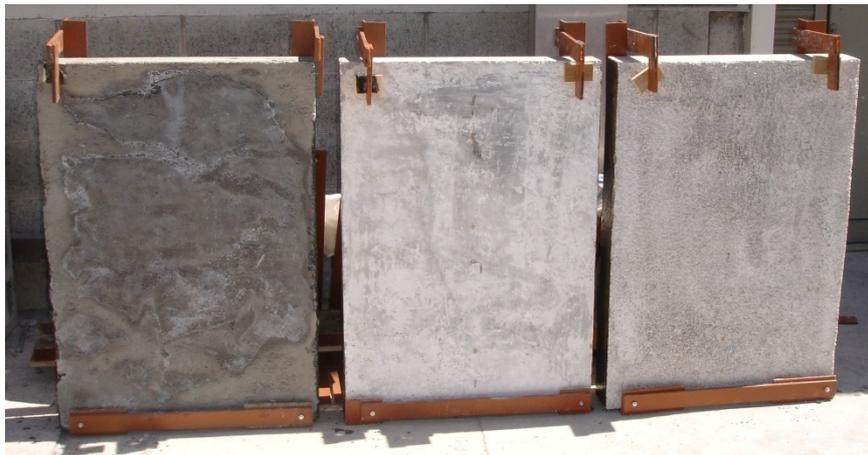


Figure 3 – Panels left exposed in outdoor conditions for 5 months

The panels were cut into 150mm strips and tested for axial compression strength and flexural tensile strength. The stratification of the samples varied:

- The exposed cement based panels were not properly stratified
- The exposed geopolymer panels were well stratified or almost over stratified
- The panel vibrated for a short time was moderately stratified
- The panel vibrated for a moderate time was well stratified
- The panel vibrated for a long time was almost over stratified

The strips were able to sustain reasonable stresses in compression and bending with typical results:

- 7 – 19MPa in compression
- 4.2 – 4.9MPa in ultimate flexure strength
- 1.6 – 4.5MPa in flexural strength when first cracking

Axial compression strength

The axial compression strength is generally lower than 17.5MPa which is the lower strength limit of conventional concrete for residential purposes. There are some potential for increasing the strength. By increasing the strength some thermal properties can though be lost. Reasonable thickness (250mm) of the panels is going to help carry the load. A large proportion of lightweight material is also going to reduce the load the panels need to carry, when compared to conventional concrete.

The compressive strength capacity was influenced by the degree of stratification of concrete, with well stratified material having lower compressive strength than more homogenous specimens. The strips did not show any signs of buckling but generally failed at the interface between the structural and insulating layers, Figure 4.

The compression strength of the strips was generally higher than the strength of the lightweight top cylinders but considerably lower than the compression strength of the bottom cylinders. There are many reasons for the reduced strength in the strips compared to the top and bottom cylinders such as:

- The interface layer in the strips is much weaker than a cylinder with even contribution of material and no interface layers
- In the heavy weight material layer there is a higher proportion of trapped lightweight material in the panels than in the cylinders
- When the panels are over vibrated the lightweight layer tends to lose paste that binds the lightweight particles together. These panels also seem to have three layers instead of two



Figure 4 – Failure modes of stratified concrete loaded in compression

Flexural tensile strength

The flexural strength of the concrete itself is estimated by the load when the first crack in the strip appears. This is done due to the fact that there is a steel mesh in the strips that starts contributing in load bearing when the concrete cracks.

The strength decreases with better stratification. The flexural tensile strength for the concrete, when the strips first crack, is higher for the laboratory cured strips than the exposed ones. This could be related to some longer term effects and drying stresses. It is believed that the lightweight layer creeps to follow the deformations that occur in the structural layer. This should decrease the strength of the concrete.



Figure 5 – Testing machine used to get the flexural tensile strength and displacement of the strips

Warping

One of the main issues that were expected in the panels was related to differential shrinkage within the member causing curling (warping) of the panel. Different shrinkage within a member can be caused because of various reasons but the most common ones are different temperature, moisture, stiffness (elastic modulus) or strength (Mailvaganam et al, 2000). As can be seen on Figure 6 and in Table 2, all these situations can be expected within the panel. The top layer shrinks more than the bottom one as well as having lower strength and stiffness. The potential for warping in service is increased even further by the fact that the outside, top layer is exposed to more severe drying than the interior bottom layer.

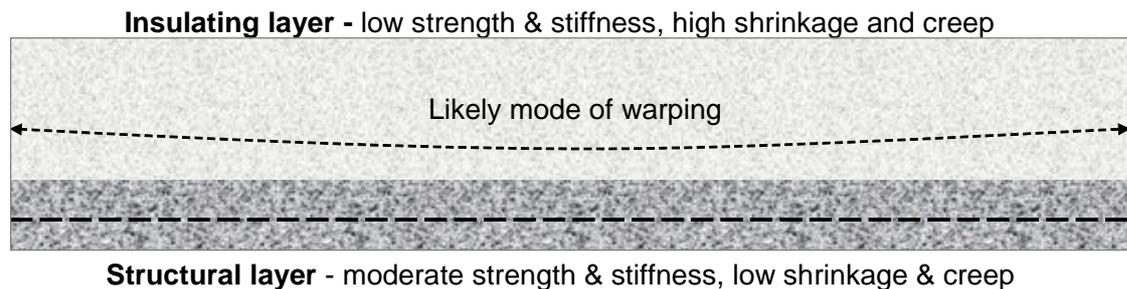


Figure 6 – Potential for warping of stratified concrete (Mackechnie et al, 2007c)

The strips dried within the laboratory showed signs that with more stratification less difference in deflection occurred, Figure 7. Another interesting trend experienced was the fact that the difference in deflection increased in the short and moderate vibration time strips with time whereas the opposite happened in the long vibration time strips. This could be related to more stress and strain release in the lightweight material section when not interfered with stronger particles. The lightweight section is so much weaker than the structural layer that it creeps to follows the structural section. The fact that the deflection is decreasing on the long vibration time strips supports this theory.

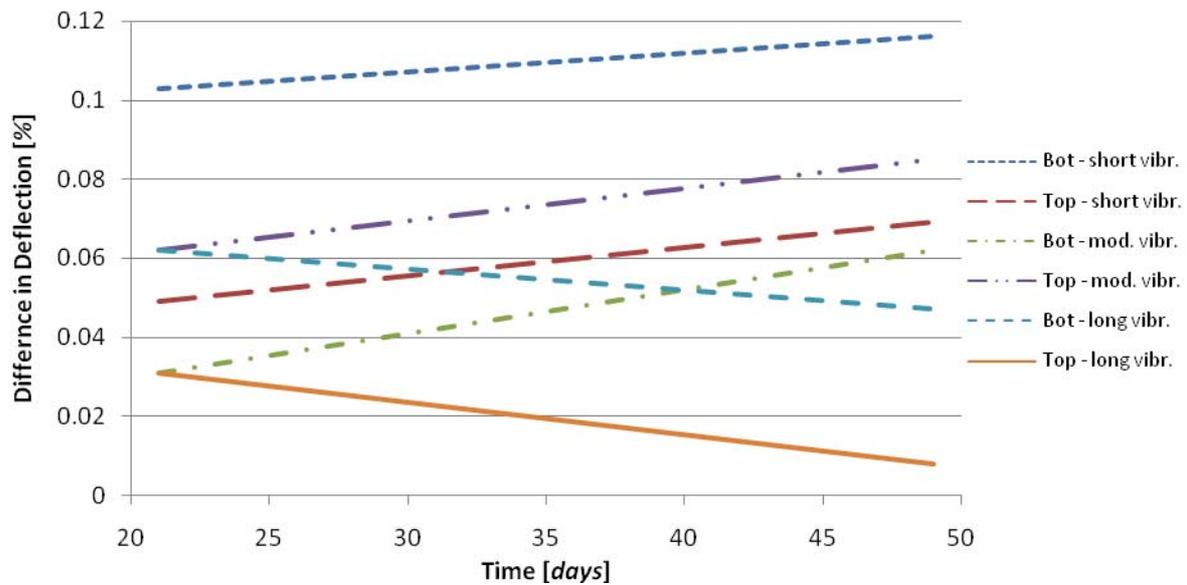


Figure 7 – The difference in deflection is different depending on the stratification of the strips

Table 3 – Deflection in panels (1000x700x120mm) after being exposed for 5 months

Max deflection [%]	Short direction	Long direction	Diagonal
Cement glass/perlite	0.061	0.135	0.074
Cement pumice/perlite	0.114	0.072	0.098
Geopolymer glass/perlite	0.114	0.075	0.059
Geopolymer pumice/perlite	0.094	0.130	0.070

The percent of deflection was found by:

$$\frac{\text{max deflection on the panel surface}}{\text{length in the direction of the deflection}} \times 100 = \text{maximum deflection [\%]}$$

As a general rule it is often assumed that the deflection of a member should not exceed 1/500 or 0.2%. All the deflections found in Table 3 are well within these requirements.

These results indicate that the level of stratification, the material and binder used does not affect the amount of warping. The fact that the level of stratification did not seem to affect the amount of warping is surprising when looking at Figure 7. It is possible that the creep process of badly stratified panels simply takes longer time but in the end they all look for the same equilibrium.

Warping of the panels was less than what was expected. This is most likely related to the low stiffness and high creep potential of the outer, lightweight layer. This theory is currently being investigated and full-scale panels have yet to be assessed for serviceability.

THERMAL PERFORMANCE

The thermal properties of concrete vary dependent on the materials used. Higher density concrete has higher thermal conductivity and inorganic polymer concrete seems to have lower thermal conductivity compared to Portland cement concrete, Figure 8. Heavier materials have higher specific heat and therefore provide better thermal mass. The specific heat did not seem to change by using different binder type.

The thermal performance of the stratified concrete was assessed by measuring the thermal conductivity and the specific heat of the top and the bottom layer. From these parameters the R-value could be calculated over a 250mm thick stratified wall panel. The panels were found to have relatively good thermal properties and suitable for moderate climates such as the Mediterranean. Typical thermal properties were (Mackechnie et al, 2007b):

- thermal conductivity values in the insulating top layer of between 0.2 – 0.3W/mK, with IP concrete tending to have slightly lower results

- specific heat values in the structural layer of between $1.3 - 2.5 \text{ MJ/m}^3 \text{ K}$
- R-values for 250 mm thick walls being between $0.6 - 0.8 \text{ m}^2 \text{ K/W}$ for Portland cement concrete and up to $1.0 \text{ m}^2 \text{ K/W}$ for inorganic polymer concrete.

These R-values do not include the surface resistances, which are approximately 0.12 and $0.03 \text{ m}^2 \text{ K/W}$ for the inside and outside surfaces respectively. The thermal properties have not been fully examined as well as optimised but the thermal values that were aimed for in the beginning should be reached, Table 1. As well as optimising the mix some further testing of the thermal performance of walls in service will shortly be undertaken to assess the composite performance under changing weather conditions.

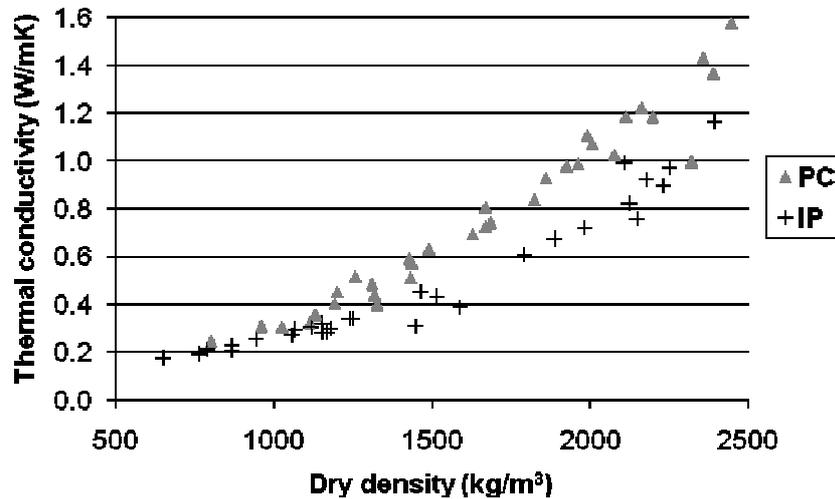


Figure 8 – Thermal conductivity versus density of concrete (Mackechnie et al, 2007c)

CONCLUSION

Sustainability is becoming more important, with nations setting high goals in becoming more sustainable. If these goals are to be reached it is required to adopt a multi disciplinary approach, covering a number of features such as: energy saving, improved use of material, reuse and recycling and emissions control (Asif, 2007). By using the variable density panels we are getting closer in becoming sustainable due to the facts that:

- Energy is saved over the lifetime of the building, by using less energy in heating
- By using the concrete itself as the insulating material, we are improving the use of the material. This would also save the use of other insulating mediums that are not ideal in terms of energy efficiency and prevent the full thermal mass of concrete being utilized
- These panels have been designed using recycled materials or by-products from other industries. The concept is therefore to build from our waste instead of putting it into landfills
- Portland cement production is a high energy process that could be replaced by using inorganic polymer binder instead of Portland cement. This would prevent a large value of CO_2 emission to be released

Further research is being carried out but it shows promising potential of producing the variable density concrete panels. These panels are going to be manufactured with a simple and energy efficient processes using mostly recycled materials. As well as being simple in construction they are also energy saving during the life time of the building by providing good insulation and thermal mass.

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REFERENCES

- Asif, M.; Muneer, T. & Kelley, R. 2007. "Life cycle assessment: A case study of a dwelling home in Scotland". *Building and Environment* 42:1391-1394.
- Australian Standard. 1992. "AS 1012, *Methods of testing concrete*". Standards Australia, Canberra, Australia.
- Babu, Daneti Saradhi; Babu, K. Ganesh; Tiong-Huan, Wee. 2006. "Effect of polystyrene aggregate size on strength and moisture migration characteristics of lightweight concrete." *Cement & Concrete Composites* 28:520-527.
- Bellamy, L.A. & McSaveney, L.G. 2003. "FRST – *Future Building Systems Research Proposal*", University of Canterbury, Christchurch, New Zealand.
- Bobrowski, Jan. 1978. *FIP State of Art Report: Principles of thermal insulation with respect to lightweight concrete*. Cement and Concrete Association, Wexham Springs, Brittan.
- CCANZ, Cement & Concrete Association of New Zealand. 2007, 20th of January. *Residential Precast Concrete Systems*. Web site: <http://www.cca.org.nz>.
- CCANZ, Cement & Concrete Association of New Zealand. 1999. "Thermal performance - putting the heat on residential housing standards: the challenge for concrete." *Concrete: Journal of the Cement & Concrete Association of New Zealand* 43 (3):16-19.
- Cement and Concrete Association of Australia. 2005. *Thermal benefits of 'solid' construction*. Australia.
- Mackechnie, J.R. 2007a. Lecture notes in ENCI 621, *Concrete Materials and Practice*, 2nd of August. University of Canterbury, Christchurch. Notes: Þorbjörg Sævarsdóttir.
- Mackechnie, J.R.; Park, Y.S.; Saevarsdottir, T & Bellamy, L. 2007b. *Variable Density Precast Concrete Panel Development*. Unpublished paper. University of Canterbury, New Zealand.
- Mackechnie, J.R.; Saevarsdottir, T. & Bellamy, L.A. 2007c. "Stratified Precast Concrete Panels for Buildings." *Concrete Plant International*, July 2007.
- Mailvaganam, N.; Springfield, J.; repetto, W. & Taylor, D. 2000. *Curling of Concrete Slabs on Grade*. Construction Technology Update No. 44. National Research Council Canada. Web site: http://irc.nrc-cnrc.gc.ca/pubs/ctus/44_e.html.
- NZS, New Zealand Standard. 2004. "NZS 4218: *Energy Efficiency – Small Building Envelope*". NZS, New Zealand Standard, Wellington, New Zealand.
- NZS, New Zealand Standard. 1986. "NZS 3112: *Method of Testing Concrete*". NZS, New Zealand Standard, Wellington, New Zealand.
- Poraver. 2007, 20th of February. Web site: <http://www.poraver.com/>.
- Wikipedia. 2007, 20th July. *Fly Ash*. Web site: http://en.wikipedia.org/wiki/Fly_ash