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CRC

Installation of Geopolymer Concrete Pavement at Wyndham Street for City of Sydney: Interim Report

Project: RP1020u3



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Title	Installation of Geopolymer Concrete Pavement at Wyndham Street for City of Sydney: Interim Report
ISBN	
Date	28/06/19
Keywords	Carbon emissions, Geopolymer concrete, Pavements
Publisher	Cooperative Research Centre for Low Carbon Living
Preferred citation	Foster, S.J., Shen, J.X., Parvez, A., Aldred, J., Heidrich, C., Doraiswamy, A., and Glasby, T. (2019). <i>Installation of Geopolymer Concrete Pavement at Wyndham Street for City of Sydney: Interim Report</i> . CRC for Low Carbon Living, Sydney.



Australian Government
Department of Industry,
Innovation and Science

Business
Cooperative Research
Centres Programme



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Acknowledgements

This research was funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative.

The experimental work was carried out in the Materials and Structures Laboratory at the School of Civil and Environmental Engineering, UNSW Sydney, Australia. The project could not have been undertaken without the strong and valued contribution of our many industry partners: City of Sydney, Australasian (iron & steel) Slag Association (ASA) and Ash Development Association of Australia (ADAA), Wagners and Sydney Civil. The strong support of each is acknowledged with thanks.

We specially acknowledge the contributions of Ahmad Mourad and Srdjan Djukic of Sydney Civil and their excellent crew for the construction work, David Eckstein and Andrew Christie of City of Sydney and Stephen Summerhayes of the CRC-LCLC for their vision in getting this project underway and John Day and Russell Genrich of Wagners for their highly-valued contributions and expertise in the manufacture of the low-carbon geopolymer concrete.

Thankyou

At this final stage of our seven-year adventure with CRC for Low Carbon Living we acknowledge the great support of our many industry partners (see acknowledgements), without the support of whom such innovative projects would not be possible. Two partners require a special thankyou; the Australasian (iron & steel) Slag Association (ASA) and Ash Development Association of Australia (ADAA), who's vision ensured these works happen and shared our journey beginning to end.

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and provided constructive feedback which was considered and addressed by the author(s).

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Acronyms

GHG Greenhouse gas

GPC Geopolymer concrete

OPC Ordinary Portland Cement

Executive Summary

It has been calculated that cement production is responsible for about six percent of total greenhouse gas (GHG) emissions and, while considerable effort has been undertaken by Australian industry to reduce emissions due to the energy input, which is considerable, process emissions represent about 56 per cent of the total. To date, schemes such as carbon-capture-storage-utilisation have yet to make significant inroads into reducing the release of these process emissions with environmentally harmful gasses released to the atmosphere.

This project represents the third and final stage of a seven-year program by the CRC for Low Carbon Living for the mainstreaming of non-traditional concrete and its delivery to practice; more specifically Geopolymer concrete (GPC). It was identified in the first stage of this project that although research in Australia on GPC began almost three decades ago, a lack of codes of practice and design and construction specifications have led to significant roadblocks in transference from university and industry research laboratories to practice. This was addressed in stage two, which continues, with the development of "Handbook for Design of Geopolymer and Alkali Activated Binder Concrete Structures", by the CRC and Standards Australia.

This third, and final, stage of the CRC low carbon materials project is the transfer the work undertaken in earlier projects to reality and to deliver the CRCs goal of moving GPC from a specialised product to mainstream construction.

GPC addresses two major issues of our time – climate change and the sustainable use of resources. GPC uses blended fly ash and GGBFS (slag) as the binder; all of which are by-products of industry. The development and use of "*no-cement*" concrete is one of several initiatives in the construction sector to a reduce its the carbon footprint.

In Australia alone, more than 30 million cubic meters of concrete is placed annually and is estimated to release between 8 and 12 million tonnes of CO₂-e emissions. Whether 8 million or 12 million tonnes, the contribution to Australian environmental CO₂ emissions released to the atmosphere by concrete is considerable and cannot be ignored if the goal is to reduce such emissions.

Pavements, slabs on ground and mass concrete elements represent about 70 per cent of all concrete supplied to end users and, thus, are a large component of the embedded carbon in concrete construction. A successful, monitored, demonstration of

GPC pavement under high volume traffic loads provides councils, government, business enterprises, public utility companies, owners and architects, as well as suppliers and specifiers, confidence in product delivery and placement, as well as its long-term performance. It is the aim of this study to provide the evidence needed for designers and specifiers to build pavements of non-traditional concrete and for stepped change in the concrete supply industry.

The field trail in this study took place on Wyndham Street, near the junction of Bourke Road, Alexandria, in the City of Sydney. City of Sydney constructs many thousands of square metres of pavement each year and, with a zero emissions goal, led the project in the planning and identifying the site, in providing the needed approvals to close the roadway for a 45-hour period and in contracting of the construction crew. UNSW, the Ash Development Association of Australia (ADAA) and Australasian (iron & steel) Slag Association provided the technical expertise for the project and Wagners provided the Geopolymer concrete. Both the Geopolymer and OPC concrete roadways were constructed by contractors Sydney Civil, with the Geopolymer concrete pavement constructed first and the OPC concrete pavement one week later.

Two sections of road were placed (each 3m x 15m), one of GPC and one of conventional concrete. The pavements are located one after the other and subjected to the same, high-volume, traffic conditions. Due to the high-traffic volumes and importance of the road to the local traffic network, construction was undertaken on Saturday and the pavement opened 5:00 am Monday morning, just 37 hours after the completion of works.

The project showcases the potential for green construction materials through delivery by a major Australian Council, and Industry Partner the City of Sydney, in the adoption of Geopolymer concrete as "*conventional*" practice. The project further demonstrates the capacity to deliver on the council's stated objectives for the use of "*Sustainable Materials in Concrete*".

This interim report details the installation of the pavements, the GPC materials properties, the installation of gauges and initial surface scanning undertaken for monitoring of long-term performance. The project will be on-going over the next five and more years to evaluate performance under high volume and heavy vehicle traffic loading.

1 Introduction

Building and construction materials contribute one third of the planet's greenhouse gas (GHG) emissions, with cement production alone responsible for approximately 5-7% of these (Chen et al, 2010). According to the IEA (2007) report on tracking of industrial CO₂ emissions, the country average CO₂ intensity for cement manufacture is 0.65~0.92 tonnes per tonne of cement produced, with an internationally weighted average of 0.83 tonnes per tonne. In Australia various estimates are available for the CO₂ emissions produced from OPC production; the industry's peak body provides a figure less than the world average at about 0.73 tonnes per tonne of cement produced, or 0.7 tonnes per tonne for total cementitious sales (CIF, 2013), whereas the report by Life Cycle Strategies Pty Ltd has the figure at 1.00 tonnes per tonne of cement produced (Grant, 2015). While the Australian cement industry continues to drive down its carbon footprint through more efficient and greener sources for energy production, approximately 50% of the total CO₂ emitted in cement manufacture derive from process emissions that arise from the chemical transformation of the limestone.

According to the Concrete Industry Federation (CIF, 2019), total CO₂ emissions in Australia from cement in the year 2016-17 was about 5.2 million tonnes. One way to reduce emissions in concrete is by using less cement per unit volume; this can be done either through optimisation (i.e. increasing performance with less cement) or by utilising high volume or full cement replacement using supplementary cementitious materials such as Fly Ash (FA) and Granulated Ground Blast Furnace Slag (GGBFS). For concrete, the results of the recent study of Teh, et al. (2017) are worth examining; this study uses an input output-based hybrid analysis (hLCA), rather than the more simplistic process-based life-cycle analysis (LCA), to determine economy wide cradle to gate carbon emissions. This study puts a 50 MPa ordinary Portland cement (OPC) concrete without supplementary cementitious materials (SCMs) at about 510 kg CO₂-e per cubic metre of concrete, and a 40 MPa concrete with 30% of fly ash at about 430 kg CO₂-e per cubic metre of concrete.

The increasing attention on threats to the environment imposed by CO₂ emissions have

promoted alternatives; one such alternative being the development and use of inorganic polymer binders such as geopolymer and alkaline activated binders, which involve the reaction between solid aluminosilicate materials with alkaline solutions. Sources of aluminosilicates include fly ash, blast furnace slag and metakaolin. Geopolymer concrete (GPC) offers potential benefits in reducing the GHGE associated with conventional concrete derived from OPC, aggregates, water, SCMs and various chemical admixtures.

Duxson et al. (2007) reports that geopolymer binders are capable of achieving a 65 to 95 per cent carbon emission reduction over OPC binders, depending on the type and volume of activators used, with a typical value for the reduction at about 80 per cent. Noting that the binder represents the most intensive CO₂-e component of concrete. For a typical 40~50 MPa concrete, the research of Teh et al. (2017) gives the binder as representing 75 to 80 per cent of total emissions. Assuming all non-binder components are approximately equal in their total emissions for GPC and OPC (aggregate, water, transport, etc.), this equates to a 60~65 per cent reduction in CO₂-e emissions for a GPC binder concrete in comparison to OPC binder concrete of similar performance.

In the hLCA model of Teh et al. (2017), as noted above, a 50 MPa OPC concrete gives emissions of 510 kg CO₂-e per cubic metre of concrete, whereas Mohammadi and South (2017) give a figure of 383 kg CO₂-e per cubic metre for a similar performance concrete using LCA. This demonstrates the importance of using a single methodology when comparing the performance of each, and the danger of comparing numbers across different research studies. For a 90 per cent GGBFS, 50 MPa, GPC concrete, Teh et al. (2017) give 290 kg CO₂-e per cubic metre of concrete for emissions; this represents a 40 per cent reduction in CO₂-e emissions for a similar strength OPC concrete analysed in their study.

It is concluded that with current mix designs, using a GGBFS GPC mix of 40~50 MPa strength approximately halves the CO₂-e values of concrete and, thus, a clear potential is identified for Geopolymer and Alkaline Activated Binder technologies to considerably

lower construction industry GHG emissions from the use of concrete.

With respect to the above discussion, conventional concrete is a long-established material entrenched in the construction industry and the use of alternatives, such as GPC, face many obstacles to large scale implementation. One component of the CRC research is to identify pathways for commercialisation of low CO₂ emission concrete and contribute to reduction of emissions in the built environment.

Berndt et al. (2013) conducted a detail study to identify the barriers to widespread adoption of GPC. An industry survey was also performed to better understand barriers particular to GPC in Australia and to identify potential pathways to overcoming these barriers. Highest priority activities were identified as: (i) development of a Handbook through Standards Australia specific to GPC that include performance requirements and provision for use of in state and local specifications and (ii) independent research on GPC engineering properties, durability and field performance.

Ng et al. (2013) determined that the widespread utilisation of GPC in the industry is the most promising pathway to increase the rate of fly ash and GGBFS utilisation and reduce the embodied carbon of construction materials. To this end, Foster et al. (2018) conducted extensive research to cover many gaps in understanding the mechanical and serviceability performance of GPC structures for designers to specify GPC with confidence of its properties and longevity. This project addresses one of the key remaining barriers of supply chain, confidence of product delivery and specification, and large-scale demonstration projects that monitor performance over a reasonable time period.

The final stage of the CRC low carbon materials project is to transfer the work undertaken in earlier projects to reality and deliver the CRCs goal of moving GPC from a specialised product to mainstream construction, delivering on a lower-carbon future in building materials.

2 Research Significance

GPC addresses two major issues of our time – climate change and the sustainable use of resources. GPC uses blended fly ash and GGBFS

(slag) as the binder; all of which are by-products of respective industries. Use of no cement in the concrete combined with less material is an effort to a reduced carbon footprint associated with cement production. Australia generates 14 million tonnes of fly ash (from coal fired power generation) and three million tonnes of various metallurgical slags (from steel manufacture) as industrial by-products, which have considerable potential for full utilisation within a circular economy (Mahmood et al., 2018).

In Australia alone, more than 30 million cubic meters of concrete was placed in 2017 (CCAA, 2018), and, based on an average 400 kg of CO₂-e per cubic metre of product (estimated from the Teh et al, 2019, hLCA modelling), gives about 12 million tonnes annually of CO₂-e emissions. The estimated value of CO₂-e emissions is slightly less at 8.3 million tonnes annually if the LCA model of Mohammadi and South (2017) is used (based an average concrete strength of 32 MPa giving 278 kg CO₂-e per cubic metre of concrete). Whether 8 million or 12 million tonnes, the contribution to Australian environmental CO₂ emissions released to the atmosphere by concrete is considerable, and cannot be ignored if the goal is to reduce such emissions.

Pavements, slabs on ground and mass concrete elements represent about 70 per cent of all concrete supplied to end users and, hence, represent a large component of the embedded carbon in concrete construction. A successful demonstration of GPC pavement will provide councils, government, business enterprises, public utility companies, owners and architects, as well as suppliers and specifiers, confidence in product delivery and placement, as well as its long-term performance.

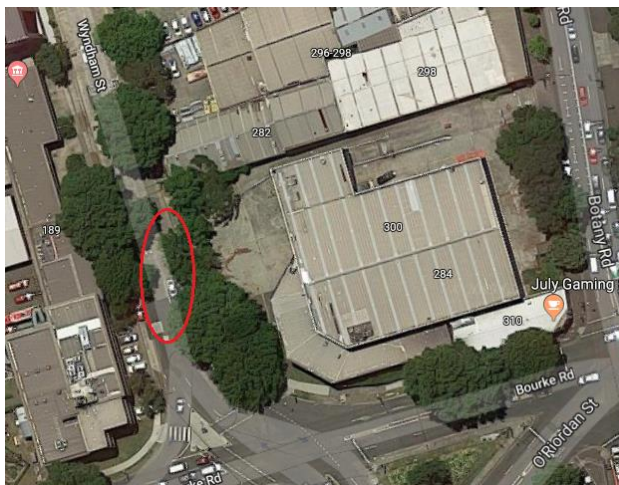
3 Field Trial

3.1 General

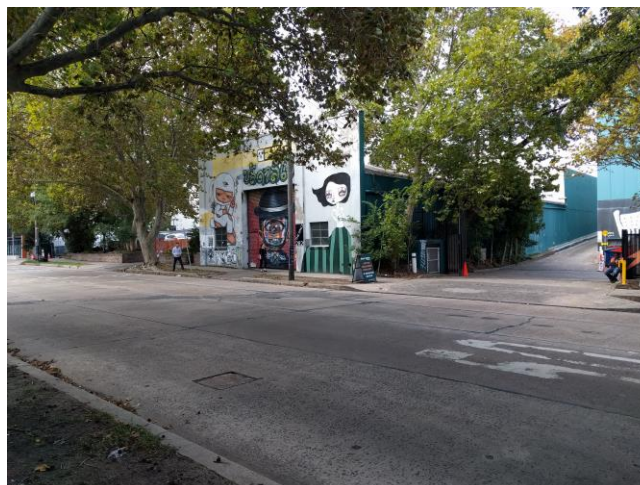
The field trail took place on Wyndham Street, near the junction of Bourke Road, Alexandria, in the City of Sydney. City of Sydney constructs many thousands of square metres of pavement each year and, with a zero emissions goal, led the project in the planning and identifying the site, in providing the needed approvals to close the roadway for a 45-hour period and in

contracting of the construction crew. UNSW, the Ash Development Association of Australia (ADAA) and Australasian (iron & steel) Slag Association provided the technical expertise for the project and Wagners provided the Geopolymer concrete. Both the Geopolymer and OPC concrete roadways were constructed by contractors Sydney Civil, with the Geopolymer concrete pavement constructed first and the OPC concrete pavement one week later.

Two sections of pavement (each 3m x 15m) located one after the other and subjected to the same traffic conditions were selected i.e. one section for GPC and the other one for OPC concrete. This allows monitoring and direct performance comparisons between GPC and OPC pavement under the similar traffic condition. The site location is shown in Figure 1.



(a)



(b)

Figure 1. Site location - Wyndham St, Alexandria, Sydney (a) Google maps (b) site picture.

3.2 Project plan

Sydney roads experience high traffic volumes most of each day. To avoid traffic disruption usually the road construction and maintenance are undertaken over a short time period on weekends, noting that with residential considerations construction noise is also an issue with work not being able to begin before 7:00 am. The construction of trial GPC and OPC concrete pavements was planned for Saturday, 30 March and 6 April, respectively. Road and Maritime Service's (RMS) strict requirement was the road must open to traffic on the following Monday at 5 am.

GPC develop compressive strengths depending on the heat curing regime, noting that it is important reasonable heat be maintained in the slab during the curing period. This was achieved by providing a GPC mix with 75 per cent slag and 25 per cent fly ash and controlling the water volume. The target was to achieve about 20 MPa of strength at the time of opening

of the roadway, with a 28-day strength of 40 MPa.

To meet RMS's strict timeline all concerned, that is City of Sydney, Sydney Civil, Wagners and UNSW researchers, developed the target time plan given in Table 1. However, with adverse weather conditions the start of the project was delayed 3 hours and with each following stage similarly delayed. This gave additional challenges by reducing the radiant heat provided to the pavement before sunset and ensuring good heat is maintained overnight.

3.3 Site preparation and pavement construction

The weather on the day of GPC pavement casting (30 March) was unfavourable. It was raining heavily in the morning. The work at site was jeopardised and delayed by 3 hours from the schedule in Table 1. Civil Contractor Sydney Civil started demolishing work from 10 am. They cleared the demolition waste, levelled the

Table 1. Original work plan for GPC pavement casting (30 March)

Stage	Scope of Work	Responsibility
Stage 1 (7am – 11 am)	- Road closing to traffic at 7 am - Demolition and excavation of old pavement - Site levelling - Laying out of reinforcement	Sydney Civil
Stage 2 (11 am – 12 pm)	- Installing strain gauges	UNSW
Stage 3 (12 pm – 1 pm)	- Pouring of geopolymer concrete	Sydney Civil and Wagner
Saturday 1 pm to Monday 5 am	- Traffic control during ambient curing period	Sydney Civil

base and laid reinforcement meshes. To monitor the pavement performance under temperature change and long-term loading, UNSW research team installed strain gauges on the reinforcing bars.

The site was then ready for concrete pouring. The trucks from Wagners discharged the GPC into the prepared site and the fresh concrete was vibrated for consolidation. Two trucks with 10 m³ of concrete were poured. The pavement was levelled immediately. After completion of pouring and levelling an alcohol based curing compound was sprayed on the surface to minimise moisture loss; the afternoon wind was

relatively strong (gusting to approx. 25 knots) and the relative humidity had dropped to 40 per cent. Work was completed at about 4:00 pm, giving two further hours of shaded light on the pavement surface before sunset. The following two nights (Saturday and Sunday) were relatively cool. The weather data for successive three days for the GPC pour is given in Table 2. The sequence of work is given in Figures 2 and 3.

The pavement surface was provided with a broom finish for enhanced tyre traction on the surface (Figure 4).

Table 2. Sydney daily weather observation (Bureau of Metrology)

Date	Day	Temps °C		Rain mm	9am		3pm	
		Min	Max		Temp °C	RH%	Temp °C	RH%
30/3	Sa	18.1	26.5	30.8	18.7	88	25.1	40
31/3	Su	12.5	22.5	0.2	15.2	42	21.4	26
1/4	Mo	13.1	20.8	0	16.0	57	20.1	64

4 Geopolymer Concrete

4.1. Batching

Wagners contractors drove two dry-batched trucks from Toowoomba, Queensland, to Sydney each with 5 m³ of dry GPC mix. The activators were added at the Sydney Civil yards (about 5 km from the site) using a mobile mixer about 1 hour before placement. The Wagners team prepared the activator solution by adding the prescribed amount of water and dry chemicals to the chemical mixer.

A shear pump attached to the mixer was run for three minutes to fully mix the chemicals into activator solution. The solution was made one load at a time. Then activator solution was pumped directly into agitator of the truck. The agitator was rotated at high speed for six to ten minutes before the truck was dispatched to the site for placement of the GPC (Figure 5).



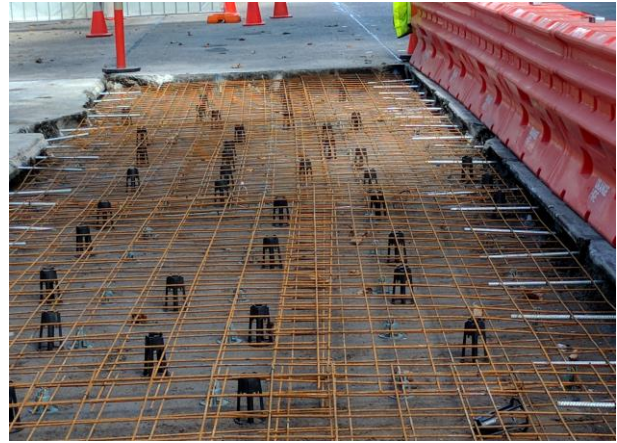
(a)



(b)



(c)



(d)



(e)



(f)

Figure 2. Sequence or work for GPC pavement preparation: (a) wet existing pavement; (b) pavement demolition; (c) levelling the base; (d) placement of mesh reinforcement; (e) vibration strain gauges; and (f) resistance strain gauges.



(a)



(b)



(c)



(d)

Figure 3. Sequence of work – GPC pavement placement: (a) pouring; (b) levelling; (c) completed surface at 4 pm Saturday; (d) traffic over pavement on Monday.

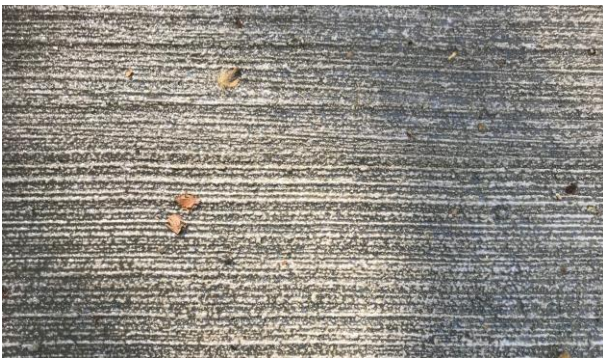


Figure 4. Broom finished surface of GPC pavement.



Figure 5. Casting of Geopolymer concrete.

4.2 Control specimen preparation, curing and testing

To determine the mechanical properties of GPC 100 x 200 mm concrete cylinders and dog-bones for direct tension measurements were cast on site according to AS 1012.8.1. The specimens were left on site overnight and transported to laboratory the following day for later testing. The specimens were demoulded, sealed and stored in a temperature and humidity controlled environmental room at a temperature of 23 °C and relative humidity of 50% until the day of testing (Figure 6). The specimens were tested for compressive strength, compressive stress-strain, split tensile strength and direct tensile strength.



(a)



(b)

Figure 6. Control specimens (a) on site (b) sealed for ambient curing.

5 Results and Discussion

5.1 Assessment of 24-hour compressive strength and at roadway opening

It was found that the cylinders left overnight at the site and tested the next day had not achieved any significant strength gain; this was attributed the cold overnight on-site conditions together with the small size of the cylinders not allowing for any heat to be captured from the chemical reactions – contrary to that of the, larger, pavement cast on ground, which is able to maintain the heat provided by on-going chemical reactions. Rebound hammer testing undertaken on the pavement (Figure 7) confirmed the strength gain of the slab with an initial estimated strength 16 MPa at 27 hours and 19 MPa immediately prior to the road opening (36 hours). These estimates were later corrected to 19 MPa and 22 MPa, respectively, when the 30-day data became available (with the rebound hammer data being calibrated to the results obtained from the compression testing machine).

It is concluded that cylinder strength is not a reliable predictor of in-situ strength at early ages due to the significantly different curing environments.

5.2 Compressive strength

For the 30-day strength, the control cured 100 mm diameter by 200 mm high cylinders

were unsealed prior to testing and both ends were ground flat. The compressive strength was measured in accordance with Australian Standards AS 1012.9–1999. The average compressive strengths measured from three cylinders at 30 days was 40.7 MPa and from two cylinders tested at 115 days was 49.7 MPa.

The in situ compressive strength of the GPC pavement was measured by Schmidt rebound hammer at 27 and 36 hours and 7 and 30 days after casting. The estimated compressive strengths were then calibrated with the 30 days cylinder strength measured in the laboratory. The data is given in Table 3 and Figure 8.



Figure 7. Rebound hammer testing at 27 hours.

Table 3. Compressive strength gain of Geopolymer concrete.

Test	27 Hours	36 Hours	7 Days	30 days	115 days
Average of rebound Hammer measurements (reading)	23	25	31.8	36.7	–
Estimated concrete strength (MPa)	16	19	27	–	–
Corrected estimated based on 30 Days cylinder strength (MPa)	19	22	32	40.7*	49.7*

*GPC compressive strength measured from cylinder tests at 30 and 115 days.

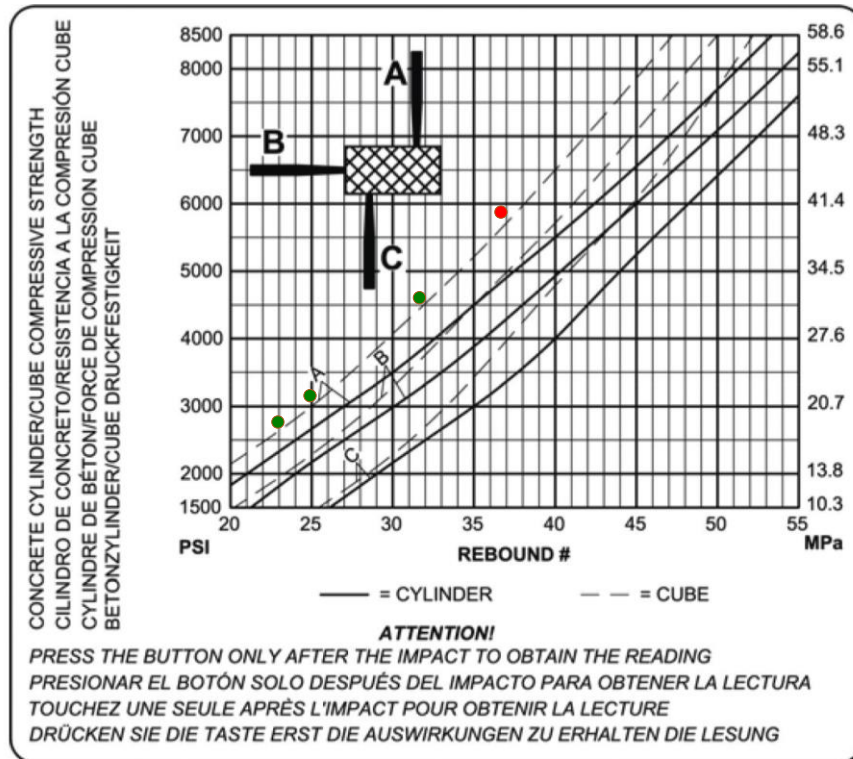


Figure 8. Correlation curve for rebound hammer reading – initial estimate based on curve “A”. Green markers indicate corrected rebound hammer results based on 30-day test calibrated curve. Red marker correlated measured 30-day compression strength with rebound hammer reading.

5.3 Compressive stress- strain

The stress-strain curve for the concrete was obtained by testing two of the cylinders according to AS 1012.17; the results are shown in Figure 9 (both tests gave similar results). The behaviour of the GPC in compression is comparable to that of OPC concrete.

The secant elastic modulus determined at the point corresponding to 40% of the maximum stress 33.0 GPa (average of two tests). The elastic modulus is consistent with that predicted by models of AS3600–2018 for the strength achieved.

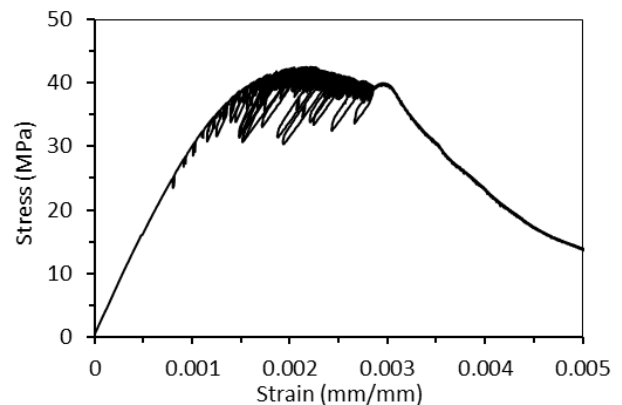


Figure 9. Compressive stress – strain.

5.4 Tensile strength

The indirect tensile strength (f_{sp}) was determined from by undertaking Brazil tests on two specimens at age 51 days. The average strength was determined as $f_{sp} = 3.9$ MPa.

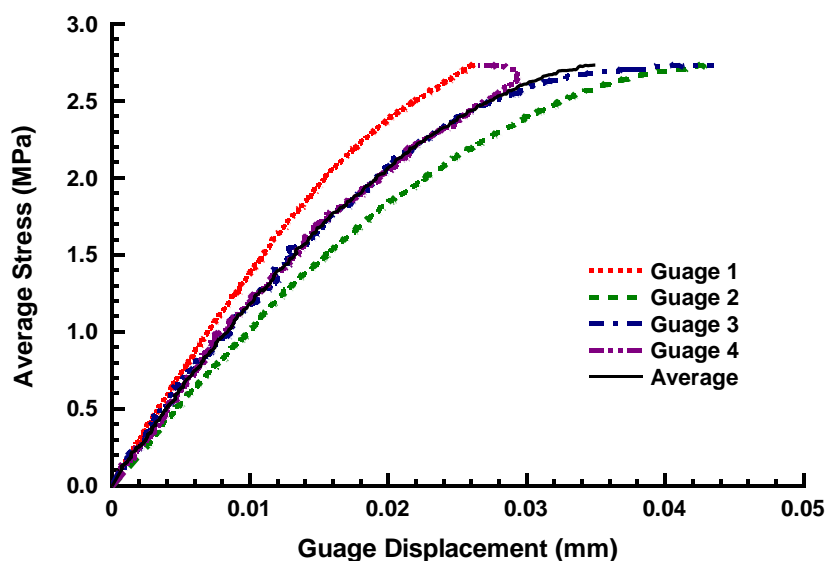
In addition to indirect tension, a direct tension test was undertaken at age 51 days on a dog-bone shaped specimen (the shape of the specimen is as for that for steel fibre reinforced concrete testing in Appendix C of AS3600–2018). The specimen was gauged on each of its four sides for displacement, with a gauge length of

230 mm. At the critical section the width of the specimen was measured as 132.2 mm and the thickness was 124.7 mm.

At the failure load of the direct tensile test the average tensile strength across the section was 2.7 MPa. A closer examination of the individual gauge results allows for correction against the accidental bending that is induced by the loading set-up; the corrected direct tensile strength was determined as $f_{ct} = 4.3$ MPa. The applied load versus displacement gauge readings are given in Figure 10.



(a)



(b)

Figure 10. Direct tensile test: (a) dog-bone specimen; (b) tensile stress versus gauge displacements.

5.5 Other observations

The workability of GPC is somewhat different to that of OPC concrete. GPC can be “sticky” in nature. It was observed that workers on ground found it difficult in terms of handling and leveling and further work is needed in the development of superplasticiser technology for manual handling. GPC appears on the surface to harden quickly but with renewed vibration the concrete, even after considerable time has elapsed, again becomes liquefied (not unlike that observe in liquefaction of soils).

Training of the workforce on the nuances of GPC, and differences with conventional concrete in placement and compaction is needed.

As noted above, further work on the development of superplasticizers is needed for ease of placement, compaction and workability for GPC and the industry would benefit greatly from such research.

6 Surface Scans and Monitoring

Two surface scanning techniques have been implemented in this project to capture the conditions of concrete pavement in fine detail: (1) 2D photogrammetry; and (2) 3D laser scanning, as shown in Figure 11. The initial imaging was conducted on 7 April 2019 for both Geopolymer and OPC concrete pavements; the

day after the OPC concrete placement and eight days after the GPC concrete. The scanning results were recorded as the initial status of the concrete surface. Scans are to be repeated at regular intervals to monitor changes of the concrete surfaces over the time, to determine wear (abrasion), cracking and other performance indicators.



(a)



(b)

Figure 11. Experimental setup for concrete surface scanning: (a) 2D photogrammetry, and (b) 3D laser scanning.

A single high-resolution imagery of each pavement was produced through 2D photogrammetry (Figure 12). A Sony Alpha 5100 (24.3 megapixel APS-C CMOS sensor (with 16 mm wide-angle lens) was used to capture individual images along the concrete pavement; the image resolution is 6,000 x 4,000 pixels). Thirty-one images were taken for the GPC pavement, and 32 for the OPC pavement, which were then stitched together into one single image for

each. During the field trial, surveying measurement tapes and photogrammetry targets were placed along the concrete pavement as spatial references (Figure 13).



Figure 12. High resolution photogrammetry of (a) GPC and (b) OPC concrete pavement slabs.



Figure 13. Surveying measurement tapes and photogrammetry targets.



Figure 14. Solar powered data logger installation.

A Leica BLK360 imaging laser scanner was also employed to capture 3D coloured point clouds of the entire site (Figure 11b). Highly accurate spatial information (around 5 mm accuracy) have been registered, including road surface, trees, buildings and traffic signs. The data will be further processed to generate a 3D model and digital twins of the project in the future.

7 Embedded Sensors

Both the GPC and OPC concrete pavements were instrumented with vibrating wire (VW) and embedded resistance foil (RF) strain gauges to monitor the performances due to temperature changes and real time traffic (shown in Figures 2(e) and (f), respectively). The wiring was passed through the pavement and connected to solar powered data loggers placed in a weatherproof housing located adjacent to the roadside (Figure 14). A GSV-8DS SubD15HD logger manufactured by GSV for the RF strain

gauges and DT85GM logger, manufactured by DataTaker, for VW strain gauges). The data loggers for the GPC slab were installed on the site on 17 July 2019.

Initial readings obtained from the embedded resistance (RF) strain gauges placed in the GPC pavement, are shown in Figure 15 for change of strain ($\Delta\varepsilon$) versus time. The measurements were taken at a sample rate of 500 Hz for a period of 60 seconds. The results are processed to remove measurement noise that occurs around zero (typically ± 30 microstrain), while maintaining spikes that result from vehicle axle loading. Spikes separated by more than approximately 1 second represent individual vehicles travelling at speed across the pavement.

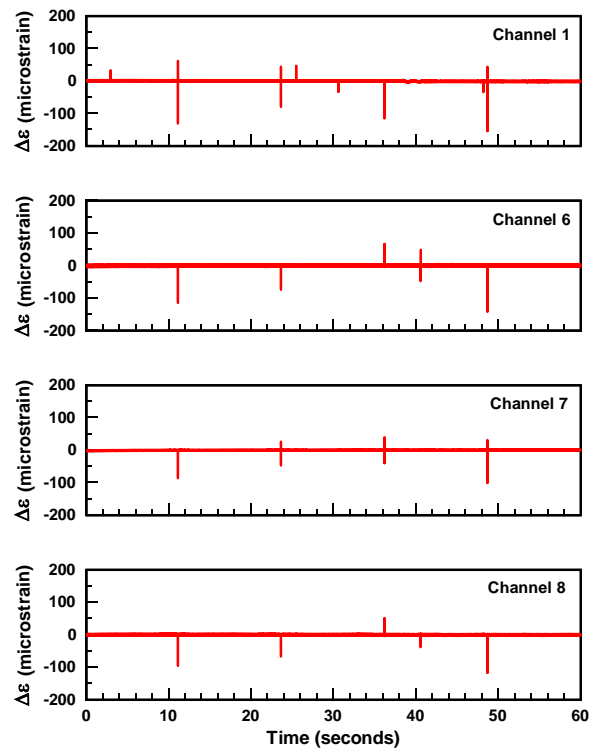


Figure 15. Strain measurements from RF strain gauge in the GPC pavement.

8 Conclusions

Adoption of new or different materials for construction has been examined by several authors who highlight technical, regulatory, economic and supply chain barriers specific to widespread commercialisation of geopolymer concrete. This last barrier is addressed in this study through example of a large-scale

demonstration project in a highly visible location. The literature indicated that geopolymer concrete can provide about a 50 per cent reduction in carbon emissions compared to current conventional OPC concrete mix designs and thus, if proven to be durable, may be an important construction materials technology for lowering the GHG emission footprint of the construction industry.

In this study, a Geopolymer concrete road pavement was constructed at Wyndham Street, Alexandria, Sydney within the Council boundary area of City of Sydney; the objective being to move Geopolymer concrete from a specialised product to that of a mainstream construction material for road pavements and other slab on-ground applications.

Despite unfavourable weather at the day of casting of the GPC road pavement, a three metre wide by 15 metre long concrete road pavement has been replaced by Geopolymer concrete in construction time of 5 hours; this included the time for installing the embedded gauges used for monitoring of concrete strains.

In addition of other mainstreaming projects in Australia that have used geopolymer concrete such as the Global Change Institute building and other applications (Aldred and Day, 2012), it was demonstrated that Geopolymer concrete can be manufactured and be delivered to a busy city site with reasonable workability and

the Sydney Civil workforce demonstrated that Geopolymer concrete can be handled effectively. This said, further research is needed in the development of the next generation of chemical admixtures to further improve the flowability of GPC for improved handling. The City of Sydney slab is the first of its kind to be constructed in a high traffic volume location.

The Geopolymer concrete pavement gained good strength with time, with an estimated strength of 22 MPa at the time of road re-opening, just 36 hours after finishing of the last concrete.

This project showcases the potential for green construction materials through delivery by a major Australian Council, and Industry Partner the City of Sydney, in the adoption of Geopolymer concrete as “*conventional*” practice is a viable option for cement-based pavements. The project further demonstrates the capacity to deliver on the council’s stated objectives for the use of “*Sustainable Materials in Concrete*”.

In addition to the installation of a GPC slab and conventional OPC concrete slab was cast the following week immediately following the GPC slab. This allows for the performance of the GPC and OPC concrete slabs to be monitored over time and directly compared in their performance. The data collected will be used to inform design engineers and Australian standards.

References

Aldred, J., and Day, J. 2012. "Is Geopolymer Concrete a Suitable Alternative to Traditional Concrete?", 37th Conference on Our World in Concrete & Structures, 29-31 August 2012, Singapore, 14 pp.

AS3600-2018. Concrete structures. Standards Australia.

Australian Bureau of Statistics, Monthly Manufacturing Production Commodities, Pre-mixed Concrete, <http://www.abs.gov.au/ausstats/abs@.nsf/mf/8301.0> (accessed 21 January, 2017).

Berndt ML, Sanjayan J, Foster SJ, Castel A. Pathways for overcoming barriers to implementation of low CO₂ Concrete. CRC for Low Carbon Living, 2013, Contract No.: RP1004-1.

CCAA 2018, Australia's Concrete Industry Reports Record Production Year, November 27, 2018, https://www.ccaa.com.au/imis_prod/documents/271118_nat_figures_reveal_big_boom_in_heavy_materials.pdf (accessed 2 July 2019)

Chen, C., Habert, G., Bouzidi, Y. and Jullien, A. 2010. Environmental Impact of Cement Production: Detail of the Different Processes and Cement Plant Variability Evaluation, *Journal of Cleaner Production*, Vol. 18, No. 5, pp. 478-485.

CIF 2013, Cement Industry Federation Industry Report ,2013, 18pp.

CIF 2019, Cement Industry Federation, <http://www.cement.org.au/Home.aspx> (accessed 1 July, 2019).

Duxson, P., Provis, J.L., Lukey, G.C., van Deventer, J.S.J., "The role of inorganic polymer technology in the development of 'green concrete'", *Cement and Concrete Research*, 37 (12), Dec 2007, pp. 1590-1597.

Flower D.J.M., Sanjayan J. G., "Green House Gas Emissions due to Concrete Manufacture", *The International Journal of Life Cycle Assessment*, Volume 12, No. 5, July 2007, pp. 282-288.

Grant T.F. 2015. Life Cycle Inventory of Cement & Concrete produced in Australia. Life Cycle Strategies Pty Ltd, Melbourne, Australia.

IEA, 2007, International Energy Agency, Tracking Industrial Energy, 321 pp.

Efficiency and CO₂ Emissions. Paris, France

Khan, M. S. H., Castel, A., Akbarnezhad, A., Foster, S. J. & Smith, M. Utilisation of steel furnace slag coarse aggregate in a low calcium fly ash geopolymer concrete. *Cement and Concrete Research* 89, 220-229, doi: <http://dx.doi.org/10.1016/j.cemconres.2016.09.001> (2016).

Mahmood, A.H., Foster, S.J., Castel. A., Modra, B., Heidrich, C., Tory, G., Genrich, R., Engelen, P., 2018, Development of Development of High-Density Geopolymer Concrete for Breakwater Armour Units for Port Kembla Harbour, *Concrete in Australia* 44(4).

Mohammadi, J., and South, W., Life cycle assessment (LCA) of benchmark concrete products in Australia, *International Journal of Life Cycle Assessment*, 2017, Vol. 22, pp. 1588–1608.

Ng, T.S., Foster, S.J., Castel, A., Sanjayan, J., Berndt, M., Heidrich, C., Smith, M., Butcher, R., and Sagoe-Crentsil, K. (2013). "State of Practice: High Volume Applications of Fly Ash and Barriers to Commercialisation", CRC-LCL Research Project: RP1004-II.

Noushini, A., Aslani, F., Castel, A., RI Gilbert, R.I., Uy, B., Foster, S.J. 2016. Compressive stress-strain model for low-calcium fly ash-based geopolymer and heat-cured Portland cement concrete. *Cement and Concrete Composites* 73, 136-146.

Noushini, A., Castel, A. 2016. The effect of heat-curing on transport properties of low-calcium fly ash-based geopolymer concrete. *Construction and Building Materials* 112, 464-477

Rangan, B. V. Low-calcium fly ash-based geopolymer concrete. E. G. Nawy (Ed.) edn, (CRC Press, 2007).

Robati, M., Oldfield, P., Akbar Nezhad, A. & Carmichael, D. 2018. Embodied Carbon and Capital Cost Impact of Current Value Engineering Practices: A Case Study. CRC for Low Carbon Living, Sydney.

Teh, S.H., 2018. "Integrated Carbon Metrics and Assessment for the Built Environment". PhD Thesis, UNSW Sydney.

Teh, S. H., Wiedmann, T., Castel, A., de Burgh, J., 2017a. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. *Journal of Cleaner Production*, 152, 312-320.

Teh, S. H., Wiedmann, T., Schinabeck, J., Moore, S., 2017b. Replacement scenarios for construction materials based on economy-wide hybrid LCA. *Procedia Engineering*, 180, 179-189.

Teh, S. H., Wiedmann, T., Moore, S., 2018. Mixed-unit hybrid life cycle assessment applied to the recycling of construction materials. *Journal of Economic Structures*, 7(1), 13.

Teh, S. H., Wiedmann, T., 2018. Decomposition of integrated hybrid life cycle inventories by origin and final-stage inputs. *Journal of Economic Structures*, 7(1), 15.

Yang, K. & Song, J. Workability Loss and Compressive Strength Development of Cementless Mortars Activated by Combination of Sodium Silicate and Sodium Hydroxide. *Journal of Materials in Civil Engineering* 21, 119-127, doi:10.1061/(ASCE)0899-1561(2009)21:3(119) (2009).

