IS GEOPOLYMER CONCRETE A SUITABLE ALTERNATIVE TO TRADITIONAL CONCRETE?

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Abstract *Geopolymer concrete is the result of the reaction of materials containing aluminosilicate with concentrated alkaline solution to produce an inorganic polymer binder. While it has a history starting in the 1940's and has attracted significant academic research, geopolymer concrete has yet to enter the mainstream of concrete construction. Most applications to date have been in the precast industry using accelerated curing. However, the use of geopolymer concrete in ready mixed applications is increasing; building on the information currently available and motivated by the considerable sustainability benefits of using a binder system composed almost entirely of recycled materials.*

A wide range of different geopolymer binder systems are available and discussed in the literature. This creates a potential problem of the satisfactory performance of particular proprietary geopolymers being used to support the use of unproven products under the generic label of geopolymer concrete.

Wagners in Australia is supplying a proprietary geopolymer concrete for both precast and in-situ applications. This paper presents data on the engineering properties of this concrete and examples of its application. The paper demonstrates that this particular geopolymer concrete complies with the relevant performance requirements of the Australian Standards and thus provides the Engineer with a viable alternative to Portland cement based concrete allowing greatly reduced the embodied energy and carbon dioxide footprint.

1 INTRODUCTION

The term 'geopolymer' was used by Davidovits[1] to describe the inorganic aluminosilicate polymeric gel resulting from reaction of amorphous aluminosilicates with alkali hydroxide and silicate solutions. Duxson et al.[2] has identified many other names in the literature, such as alkali-activated cement, inorganic polymer concrete and geocement, which have been used to describe materials synthesised using the same chemistry.

Synthesis of a geopolymer usually involves mixing materials containing aluminosilicates, such as metakaolin, fly ash, slag with alkali hydroxide, and alkali silicate solution, sometimes sodium carbonate in slag based systems[3]. There are numerous publications discussing different properties of geopolymer synthesised from different raw materials and activators. Therefore the term "geopolymer" covers a bewildering range of potential binders that those interested in this technology must navigate. Product data sheets, and even technical papers, on "geopolymers" may "cherry pick" data obtained from different binder chemistries giving the misleading impression that a specific material has been comprehensively tested when it has not. Papers may also focus on a particular material with poor performance to negatively characterise geopolymers. For example, the geopolymer concrete considered by Turner and Collins[4] contained very high activator levels and required steam curing so that the product had relatively high embodied energy and emissions leading to the conclusion that there was little benefit in terms of carbon footprint compared to OPC concrete.

One area where reference to generic geopolymer data is helpful is durability. For geopolymer concrete to be considered a suitable alternative to Portland cement based concrete, the basic geopolymeric gel must be durable. This can only be established over time. Xu et al.[5] investigated activated slag concretes from the former Soviet Union. The slag had been activated by carbonates and by carbonate/hydroxide mixtures. The research found high compressive strengths that were significantly higher than when initially cast and excellent durability over a service life of up to 35 years. Xu et al.[5] and Shi et al.[3] report that the carbonation depths were relatively low for their age and no microcracks were observed after prolonged service. While the performance of each proprietary geopolymer concrete needs to be established by comprehensive assessment, it is comforting to know that the basic geopolymer matrix appears to be durable and the reaction products appear stable over time.

Until recently, geopolymers have been found in niche applications, including fire resistant materials, coatings, adhesives and immobilisation of toxic waste[6]. However, the main potential application for geopolymers has been in the construction industry as an environmentally friendly concrete with reduced embodied energy and CO_2 footprint[7,8] compared to the traditional Portland cement based concrete.

2 MECHANICAL PROPERTIES

This geopolymer has been used on a number of different projects in Australia and a total volume of over 3000 m³ has been poured to date. It is not "labcrete"! Test specimens have been taken during actual production and a summary of the average mechanical properties are given in Table 1.

While the most common concrete grades used are 32 and 40 MPa (equivalent to f'_{cu} of 40 and 50 MPa), cylinder strengths up to 70 MPa have been measured. Since the geopolymer binder consists entirely of fly ash and GGBS, there has been a common perception that geopolymer concrete would develop its strength very slowly or require heat curing. Portland cement systems containing high volume replacement of fly ash or GGBS and many geopolymer binders do develop compressive strength slowly. However, this particular geopolymer concrete develops its strength quite rapidly with design strength typically achieved after 7 days under laboratory conditions as seen in Figure 1. Strength development at early age (up to 3 days) is sensitive to ambient temperature but adequate early strength would be expected if the concrete temperature is above approximately 20°C.

Mix	Compressive Strength (MPa)	Std Deviation	Tensile Strength (MPa)	Flexural Strength (MPa)	Shrinkage (microstrain)	Elastic Modulus (GPa)	Poisson's ratio
32 MPa	38.1	3.7	4.5	6.2	300	31.8	0.20
40 MPa	55.6	4.3	6.0	6.6	230	38.5	0.24

Table 1: Mechanical properties of geopolymer production concrete

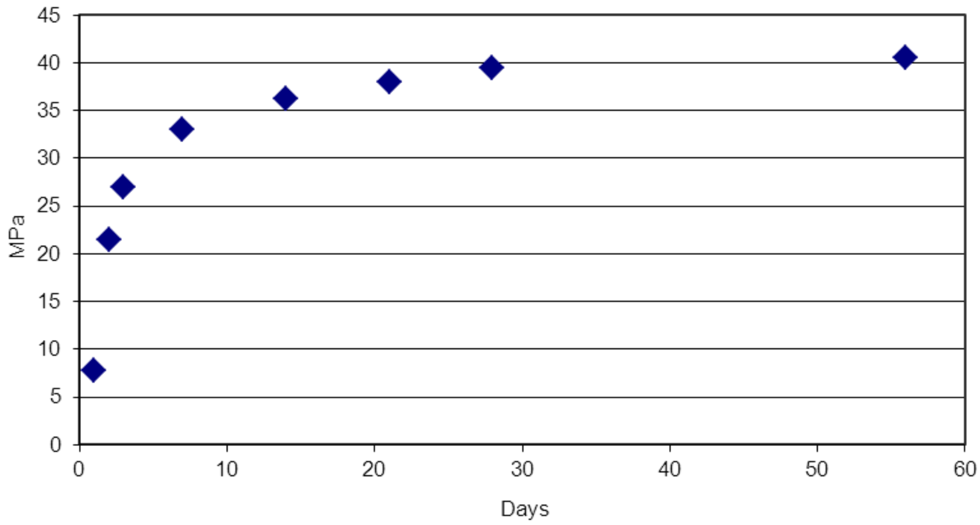

Figure 1: Compressive strength development of S32 EFC under laboratory curing.

The data available suggest that geopolymer concretes in general including this particular geopolymer tend to have higher tensile and flexural strength relative to the compressive strength than Portland cement based concrete. This appears due to the strong bond of the geopolymer gel to the aggregate particles[9] and would be expected to improve crack resistance of geopolymer concrete.

Several researchers have reported a significantly lower elastic modulus for geopolymer concrete than for comparable OPC concrete. For example, Pan et al.[10] found the reduction was about 23% for typical strength grade compared to the equations given in AS 3600. Accordingly those geopolymer concretes were outside guidelines given in Australian Standard AS 3600 and ACI Committee 363. However, the elastic modulus of this proprietary geopolymer concrete has been found to be comparable to Portland cement based concrete as shown in Table 1. The Poisson's ratio has been found to range between 0.19 and 0.24 which is slightly higher than would be expected for Portland cement based systems.

3 OTHER SIGNIFICANT PROPERTIES

The drying shrinkage of this geopolymer concrete is much lower than for Portland cement based concrete with typical 56 day values of approximately 300 microstrain or less. The drying shrinkage will normally be less than that achieved for a Portland cement based concrete even incorporating a shrinkage reducing admixture as shown in Figure 2. The product also has a very low heat of hydration as seen in Figure 3. The limited thermal and drying shrinkage makes it well suited for thick and heavily restrained concrete elements and should enable a significant reduction in the quantity of crack control reinforcement.

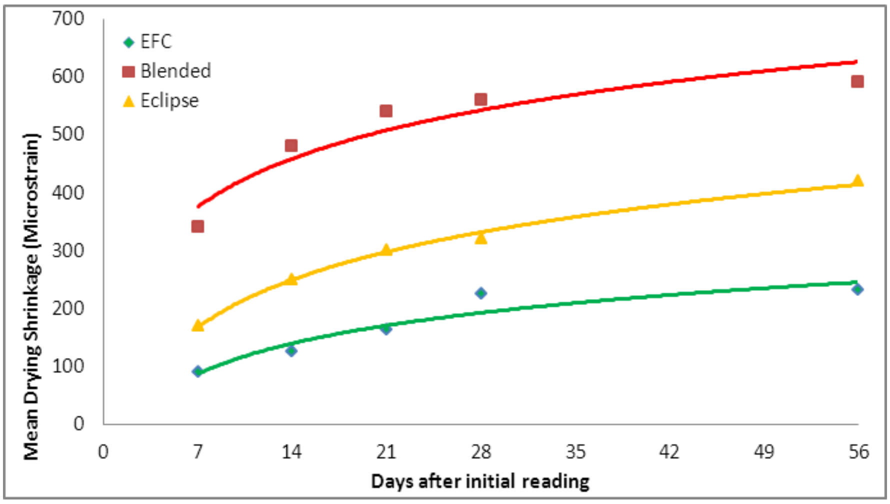

Figure 2: Drying shrinkage of geopolymer, 30% fly ash and shrinkage reduced concretes

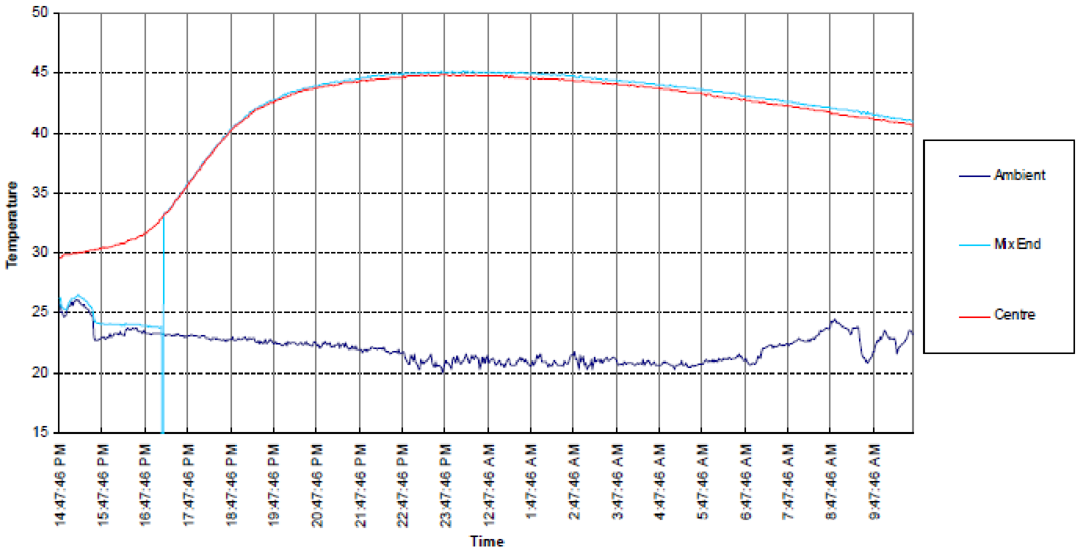

Figure 3: Temperature rise in insulated 1 m^3 block (Wagners' data)

While creep has not been directly measured, prestressed girders were cast using this proprietary geopolymer concrete in 2011. The prestress was transferred after 3 days. The girders were left unloaded for 100 days. The girders were loaded with W80 wheel load (8 tonnes) in accordance with the Australian bridge standard (AS 5100) and continuously measured for deflections over the subsequent 15 months period as shown in Figure 4a. The hogging prior to load and deflection under sustained load were monitored using embedded vibrating wire strain gauges and the results are shown in Figure 4b. The structural behaviour in the girders was consistent with the compressive strength and modulus indicating no unusual deformation properties.

Figure 4a: Loading of prestressed geopolymer girder

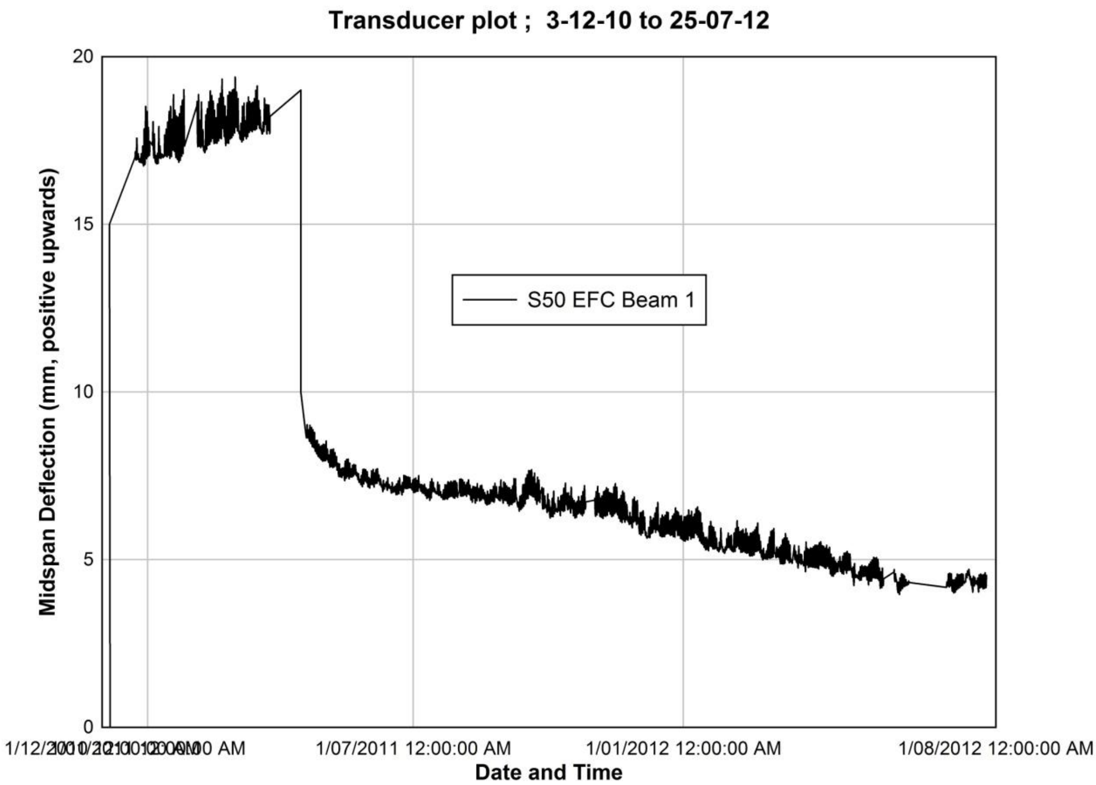

Figure 4b: Initial hogging and loaded deflection of prestressed geopolymer girders

Precast reinforced beams were cast for the Global Change Institute at the University of Queensland. AECOM modelled the beam in RAPT based on an uncracked condition under self-weight and the measured mechanical properties. The expected deflection under the test load of 5x2 tonne blocks equally spaced was calculated to be 3.0 mm (Figure 5a). The actual maximum deflection was 2.85 mm (Figure 5b) indicating that the structural behaviour of the beam closely followed the prediction.

Figure 5a: Load testing of a 10 metre precast geopolymer beam.

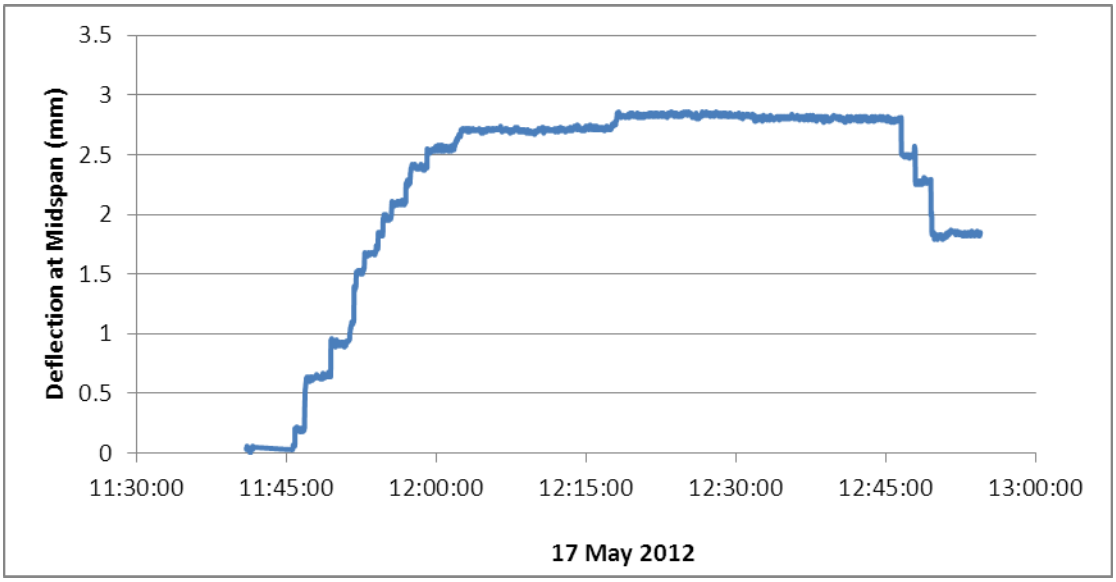

Figure 5b: Deflection of 10 metre precast geopolymer beam under test load.

The fire resistance of this proprietary geopolymer concrete has been tested according to the Standard Time-Temperature Curve (STTC) heating profile specified in the ISO 834 Standard for a cellulose fire. A structural panel (3m x 4.7m x 0.17m) was installed into a specially designed furnace at the CSIRO Materials Science and Engineering Test Facility in Sydney. For the two hour test duration, it was exposed to a superimposed dead load of 5.5 kPa. The test showed this geopolymer concrete performed considerably better than would be expected for an OPC based concrete when exposed to the equivalent of a cellulose fire. The element satisfied the requirements of AS 1530 in spite of being exposed to full design load.

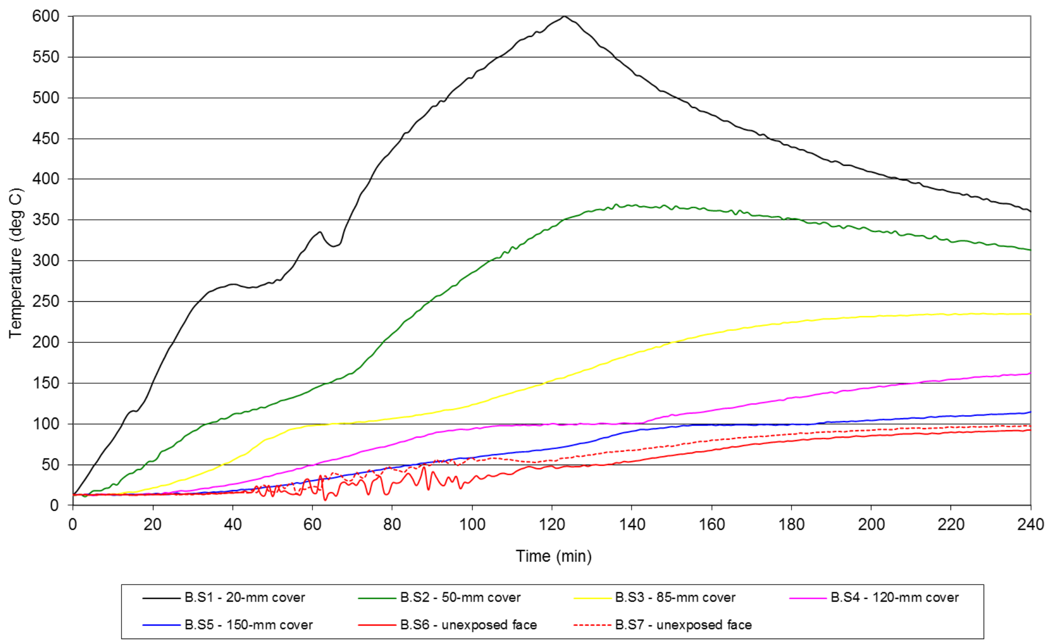

Figure 6: Geopolymer exposed to standard fire for 120 minutes

One point of concern that has been raised regarding the use of Portland cement free concrete is the potential for carbonation. Accelerated carbonation tests were conducted on a standard 40 MPa geopolymer concrete by RMIT. These tests showed that the depth of carbonation was higher than for an OPC concrete but was comparable to a 50 MPa concrete with 70% GGBS replacement.

The basic chemistry of this geopolymer concrete would be expected to provide good resistance to chloride and other aggressive chemicals. This has not been tested as yet. Samples were tested according to ASTM C1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration" and found to have "very low" chloride ion penetrability according to the guidelines (130 - 230 coulombs). RMIT have placed samples of this particular geopolymer at marine exposure sites in Fremantle, Portland and MacKay covering temperature and tropical exposure conditions.

4. STANDARDS

Waste materials, such as fly ash and GGBS, are ideal to produce environmentally friendly geopolymer concrete. Fly ash and GGBS have been used with Portland cement in blended cement to reduce heat of hydration and improve other fresh and hardened properties. Their use in low heat cement application have been standardised for use by Australian Standards Committee[11] and International Standards Committee[12,13]. The content of blended minerals usually vary greatly depending on the proposed use, EN 197 CEM III/C cement allows up to 95% GGBS with 5% clinker. Many standards and specifications, such as EN 197, place limits on the alkali content of cement, fly ash and GGBS which, without qualification, may limit the acceptance of geopolymer based products. As discussed by Shi et al.[3], except in some former Soviet Union countries, there appear to have been no international standards or specifications for alkali activated geopolymer concrete. In November 2010, the road regulator in the state of Victoria (VicRoads) revised their specifications on "General Concrete Paving"[14]. The introduction now states that; "In the context of general concrete paving, portland cement concrete and geopolymer binder concrete are equivalent products." This is a significant step for a major regulator in Australia and shows that VicRoads consider the data available on geopolymer concrete is sufficient to allow its use. The Concrete Institute of Australia [9] published a Current Practice Note on geopolymer concrete in 2011 which may also help in the more widespread acceptance of this technology.

Standards have necessarily been developed from the prevalent construction practices. Indeed, the time taken to develop standards means that they are often based on recent construction practices rather than current ones. This can be a serious impediment to the promotion and use of innovative materials and procedures. The author Dr Aldred was involved in preparing a state of the art report for this proprietary geopolymer concrete in Australia. While the standard is obviously based on Portland cement based concrete, the materials components of the AS 3600 for Concrete Structures are essentially performance based. The format of the report followed the engineering, durability and other significant properties listed in the Standard and compared the performance of the geopolymer concrete with the expected performance from a Portland cement based concrete. This approach has been quite successful in helping designers understand the performance properties of a novel material. This geopolymer concrete has now been used in a range of different applications. Designers have requested independent verification of the use of the product to help mitigate any possible risks with using a non-traditional concrete. This has been an excellent system for introducing innovative sustainable concrete materials in actual structures, as opposed to relying solely on laboratory specimens, to build confidence in new technology.

National Standards and Codes which are more prescriptive in nature and explicitly limit concrete to a Portland cement based binder are an impediment to non-Portland based binders being accepted in the industry. While SS 206-2009 (similar to EN 206) includes an equivalent performance concept, there is a restriction that potential binders should comply with EN 197 and therefore would technically exclude geopolymers which do not contain Portland cement clinker.

However, the BCA Green Mark System does strongly encourage the use of recycled materials and particularly innovation, Therefore there is good reason for Singaporean developers to look into this technology.

5. FIELD APPLICATIONS

5.1 Pavements

A typical light pavement, 900 metres long by 5.5 metres wide as shown in Figure 7, was cast using Grades 25 MPa and 40 MPa. A variety of construction procedures were used to assess pump compared with chute placement, saw cutting compared with wet formed tooled joints, manual compared with power troweling. A noticeable difference to GP concrete is that the geopolymer concrete had no available bleed water rising to the surface. To maintain adequate surface moisture for screeding, floating and troweling operations as well as provide protection against drying, an aliphatic alcohol based surface spray was used throughout the entire placement period (Figure 8).

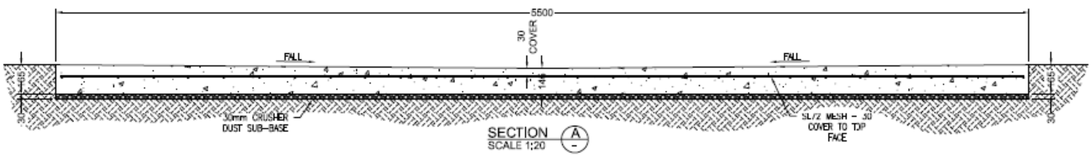

Figure 7: Light pavement incorporating geopolymer concrete.

Figure 8: Placing of pavement using geopolymer concrete.

The pavement slab for a weighbridge at the Port of Brisbane was cast in November 2010 using Grade 32 MPa geopolymer concrete. Geopolymer has also been used in footpath applications by various local councils.

Figure 9: Placing of pavement for weighbridge using geopolymer concrete.

5.2 Retaining Wall

A total of over fifty 40 MPa geopolymer precast panels were used a retaining wall for a private residence. The panels were up to 6 metres long by 2.4 metres wide and were designed to retain earth pressure of 3 metres. The precast panels were cast in Toowoomba and cured under ambient conditions before being sent to site for installation (Figure 10).

Figure 10: Precast geopolymer retaining walls for a private residence.

5.3 Water Tank

Two water tanks (10 m diameter x 2.4 m high) were cast in March 2011 as seen in Figure 11. The first water tank was constructed using a Grade 32 MPa concrete with a maximum aggregate size of 10 mm with blended cement consisting of 80% Portland cement and 20% flyash. The second tank is constructed with a Grade 32 MPa geopolymer concrete also with a 10 mm maximum aggregate.

One reason was to investigate the autogenous healing behaviour of this geopolymer concrete. Autogenous healing in Portland cement based concrete is primarily due to the deposition of calcium hydroxide. As there is very little calcium hydroxide present in the geopolymer mix, the performance of geopolymer concrete in a water retaining application is of considerable interest.

Nominal leaking through cracks in the geopolymer tank did heal relatively rapidly. Ahn and Kishi[15] suggest that geomaterials may be able to autogeneously heal due to a gel swelling mechanism.

Figure 11: In-situ water tanks cast with blended cement concrete (left) and geopolymer concrete (right).

Figure 12: A gauge to measure any crack movement in the geopolymer concrete after healing

5.4 Boat Ramp

An extremely innovative application made possible under an R&D project by QLD Transport and Main Roads, Department of Maritime Safety. The existing in-situ concrete boat ramp at Rocky Point, Bundaberg was due for replacement due to severe deterioration. Wagners were awarded an R&D tender to replace the ramp using an entirely novel form of construction material - precast concrete boat plank units made from Grade 40 geopolymer concrete and reinforced with Glass Fibre Reinforced Polymer (GFRP) reinforcing bar. The approach slab on ground to the ramp was made from site cast geopolymer and similarly reinforced with GFRP. The project was successfully completed during November - December 2011 as seen in Figure 13. The precast ramp units were manufactured at Wagners precast facility in Toowoomba, while the site cast geopolymer for the approach slab was batched in Toowoomba, trucked to site with a 6.5 hour transit time and then activated with the chemical activators on site. A unique feature of this particular geopolymer is that the entire batch constituents can be mixed in a truck bowl and remain completely dormant until the activator chemicals are added.

Figure 13: Boat ramp constructed with both precast and in-situ geopolymer concrete.

5.5 Precast Bridge Decks

One of the earliest fully structural applications of this geopolymer was the Murrarie Plant site bridge. This is a composite bridge structure made from pultruded fibreglass girders acting compositely with a Grade 40 geopolymer bridge deck. The bridge was prefabricated at Wagners Toowoomba CFT factory and brought to site for installation in 2009 as seen in Figure 14. The bridge has been successfully in service since that date with continual concrete agitator truck loadings and no signs of distress.

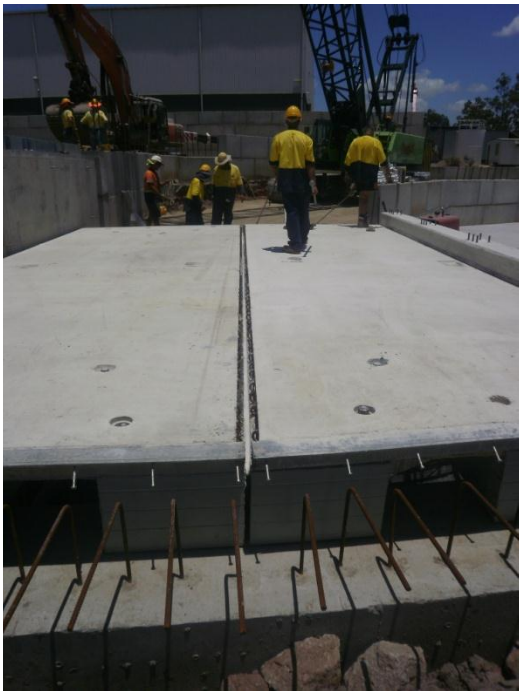

Figure 14: Installation of prefabricated bridge at Murrarie concrete batching plant.

The Bundaleer Road Bridge, West Moggill, Brisbane was constructed and installed during May-June 2012 as shown in Figure 15. This project is another example of a composite pultruded girder and Grade 40 geopolymer deck bridge structure. The geopolymer concrete deck acts as the compression flange to the bridge as well as providing a serviceable wearing deck. The client was the Brisbane City Council and the certifying engineer i-cubed Pty Ltd.

Figure 15: Composite pultruded girder and Grade 40 geopolymer deck bridge in Brisbane.

5.6 Precast Beams

The supply of Grade 40 geopolymer to produce 33 x precast floor beam-slab elements marks a significant milestone in modern geopolymer concrete. Believed to be the first application of modern geopolymer concrete into the structure of a multi-storey building, these precast floor beams form three suspended floor levels of the very innovative GCI building, which is a showcase for next generation sustainable building technologies. There are 2 sizes of beams which span 10.8 m (x 2.4 m wide) and 9.6 m (x 2.4 m wide) respectively. Apart from being a structural floor element, the beams also are a major architectural feature, having an arched curved soffit and being specified as off form class 2 with a light white colour as seen being lifted into place in Figure 16. The beams will also play a major part in low energy space heating with water pipes being placed inside them for temperature controlled hydronic heating of the building spaces above and below. A rendering of the finished building is shown in Figure 17.

The Project partners are the Principal - University of QLD, Architect - Hassell group, Project Engineer - Bligh Tanner, Geopolymer Certifying Engineer - AECOM, Builder - McNab, precast manufacture - Precast Concrete Pty Ltd.

Figure 16: 10.8 metre geopolymer beam with vaulted soffit being craned into position.

Figure 17: The Global Change Institute which will be a showcase of sustainable construction.

CONCLUSIONS

Geopolymer binders cover a wide range of possible source materials and activators. Some binders within this generic group are not viable alternatives to traditional Portland cement based concrete. The particular geopolymer considered in this paper does appear to provide a suitable alternative and has been used in a number of applications in Australia. The low shrinkage and heat of hydration as well as the high tensile strength means that the material may have technical advantages over traditional concrete, particularly in structural elements subject to external restraint.

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