Engineering Properties of a Proprietary Premixed Geopolymer Concrete

James M Aldred
Technical Director, AECOM

Abstract: Geopolymer concrete is the result of the reaction of materials containing aluminosilicate with concentrated alkaline solution to produce an inorganic polymer binder. Initial research began in the 1940's and there has been significant academic work since then. However, geopolymer concrete has yet to enter the mainstream of concrete construction. Most applications so far have been in the precast industry using accelerated curing but the use of geopolymer concrete in ready mixed applications is increasing. This has been based on the encouraging data currently available and motivated by the considerable sustainability benefits of using a binder system composed almost entirely of recycled materials.

Many 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 promote unproven products under the generic label of geopolymer concrete.

One supplier in Queensland is supplying a proprietary geopolymer concrete for a range of precast and in-situ applications. This paper presents data on the engineering properties of this concrete which demonstrate that this particular geopolymer concrete complies with the relevant performance requirements of the Australian Standards. Therefore the product appears to provide the Engineer with a viable alternative to Portland cement based concrete allowing greatly reduced embodied energy and carbon dioxide footprint as well as several significant technical advantages.

Keywords: geopolymer, strength, modulus, shrinkage, deflection, durability.

1. Introduction

The term 'geopolymer' was used by Davidovits (1) to describe inorganic aluminosilicate polymer products from reaction of amorphous aluminosilicate containing materials and alkali hydroxide and silicate solutions. Duxson et al. (2) has identified many other names in the literature (e.g. alkali-activated cement, inorganic polymer concrete, geocement) that have been used to describe materials synthesised using the same chemistry.

Geopolymer concrete has been extensively studied by various universities and is starting to gain traction in a range of different applications. There are many publications discussing different properties of geopolymer synthesised from different raw materials and activators. Product information sheets, and even technical papers, may present positive data obtained from different binder chemistries giving the misleading impression that a specific proprietary material has been comprehensively tested when it has not. Alternatively papers may also focus on a particular material with poor performance to negatively characterise geopolymers.

One common concern raised by designers regarding the use of innovative materials, such as geopolymer concrete, is compliance with the relevant Australian Standards. Standards necessarily develop from the established construction materials and practices which can inhibit the use of innovative materials and procedures. While the Australian Standard for Concrete Structures (AS 3600) is obviously based on Portland cement based concrete, the materials components of the Standard are primarily performance based. Therefore, it is possible to compare the performance of a specific proprietary geopolymer concrete with the expected performance from a Portland cement based concrete with regard to the engineering, durability and other significant properties listed in the Standard. This approach provides an objective basis to assess any concerns with using a non-traditional concrete such as a geopolymer.

This paper discusses the engineering properties of a proprietary geopolymer concrete which is produced in Queensland. This material has been used in a range of precast and in-situ applications. A total quantity of approximately 5000 cubic metres has been poured to date. It is certainly not "labcrete"! Much of the data presented in this paper is taken from the Grade 40 geopolymer production concrete used in precast floor panels for the Global Change Institute (GCI) project at the University of Queensland which was cast from April to October 2012.

2. Mechanical Properties

Compressive strength

This proprietary geopolymer concrete has been supplied at compressive strength grades of 25, 32, 40 and 50 MPa for both precast and in-situ applications. As the binder consists entirely of supplementary cementing materials, there is a common expectation that strength development would be very slow. However, this particular geopolymer generally achieves over 80% of the 28 day strength in 7 days under ambient curing conditions.

Over the six months of suppy to the GCI project, the average 7 and 28 day strengths were 42.3 and 51.7 MPa respectively. The basic standard deviations were 3.3 and 3.9 MPa. No single 28 day result fell below the specified requirement of 40 MPa.

Tensile Strength

AS 3600 allows uniaxial tensile strength to be calculated based on either 60% of the flexural strength or 90% of the indirect tensile. For the GCI project, the mean flexural strength for the Grade 40 concrete was 6.4 MPa which is equivalent to 3.8 MPa uniaxial tensile strength. The corresponding mean indirect tensile strength was 4.8 MPa which is equivalent to 4.3 MPa uniaxial tensile strength according to the Standard conversion.

The relationship between compressive strength and splitting tensile strength for normal Portland cement based concretes by a range of researchers is shown in Figure 1 (Oluokun (3)). The mean values for this geopolymer virtually fall on the line of best fit showing that the relationship between these parameters is very similar to that expected for Portland cement based concrete.

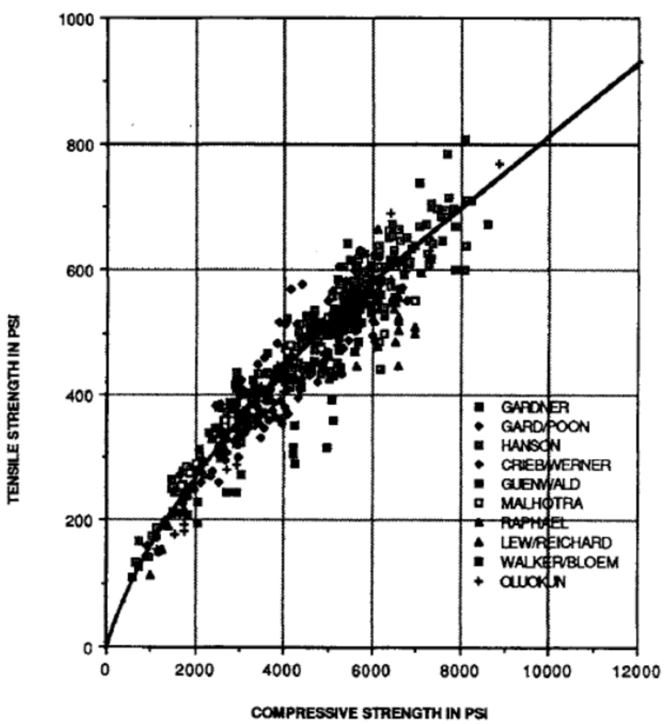

Figure 1: Indirect tensile strength compared to compressive strength (After Oluokun, 3)

Modulus of Elasticity

Several researchers have reported significantly lower elastic modulus for some geopolymer concretes compared to Portland cement based concrete (eg 4, 5). AS 3600 gives equations to estimate elastic modulus from compressive strength. Based on an average compressive strength of 51.7 MPa and a density of 2500 kg/m³, the formula given in AS 3600 estimates an elastic modulus of 36.5 GPa for the GCI concrete. The measured mean elastic modulus was 39 GPa. These data suggest that, unlike some other geopolymers, this proprietary geopolymer has an elastic modulus comparable to Portland cement based concretes.

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Stress Strain Curve

AS 3600 Clause 3.1.4 states that; "The stress-strain curve for concrete shall be either (a) assumed to be of curvilinear form defined by recognized simplified equations; or (b) determined from suitable test data. Figure 2 shows a curvilinear stress strain curve in testing conducted by Cardno. This appears consistent with recognized simplified equations for stress-strain .

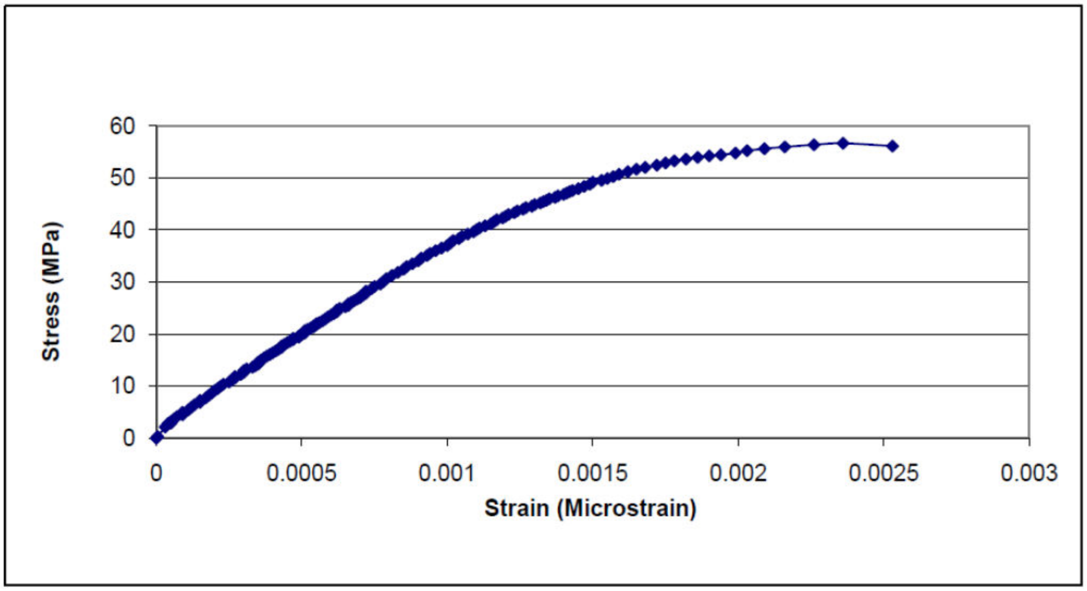

Figure 2: Stress-strain behavior of Grade 40 geopolymer concrete

AECOM modelled the GCI 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. The actual maximum deflection was 2.85 mm as shown in Figure 3 indicating that the structural behaviour of the beam closely followed the prediction.

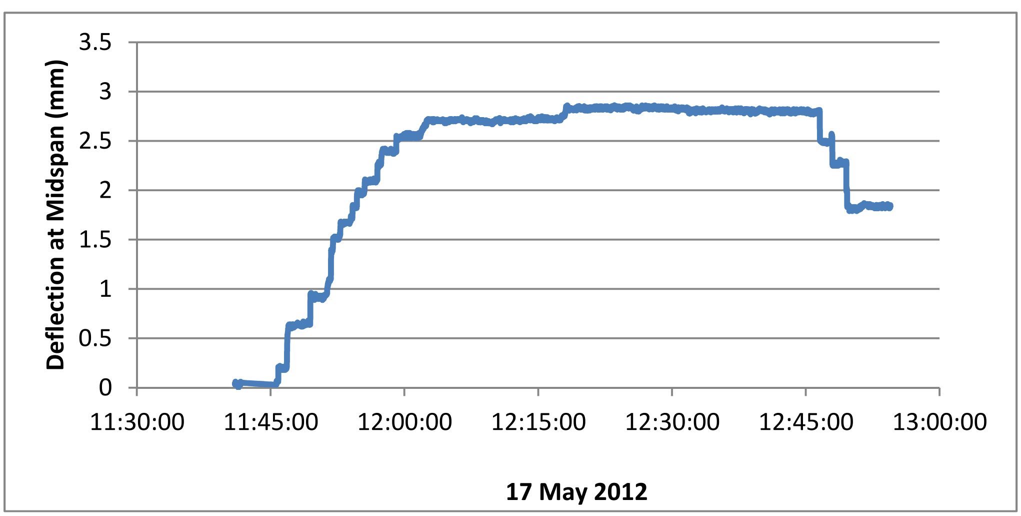

Figure 3: Deflection of precast proprietary geopolymer beam under test load.

Poisson's Ratio

AS 3600 states that the Poisson's ratio can either be taken as equal to 0.2 or determined by test. The mean Poisson's ratio for the Grade 40 geopolymer concrete was 0.23 within a range from 0.21 to 0.25. Neville (6) states the Poisson's ratio of Portland cement based concrete lies generally in the range of 0.15 to 0.22. Therefore this geopolymer appears to have a slightly higher Poisson's ratio than reported for Portland cement based concrete. This is not considered to have any significant effect on structural performance.

3. Deformation Properties

Drying Shrinkage

The mean 56 day shrinkage for GCI project concrete was 317 microstrain. Figure 4 shows the drying shrinkage results for concretes containing similar aggregates with a fly ash blended cement with and without a shrinkage reducing admixture and this geopolymer. The significantly reduced drying shrinkage of this geopolymer concrete is an important technical benefit.

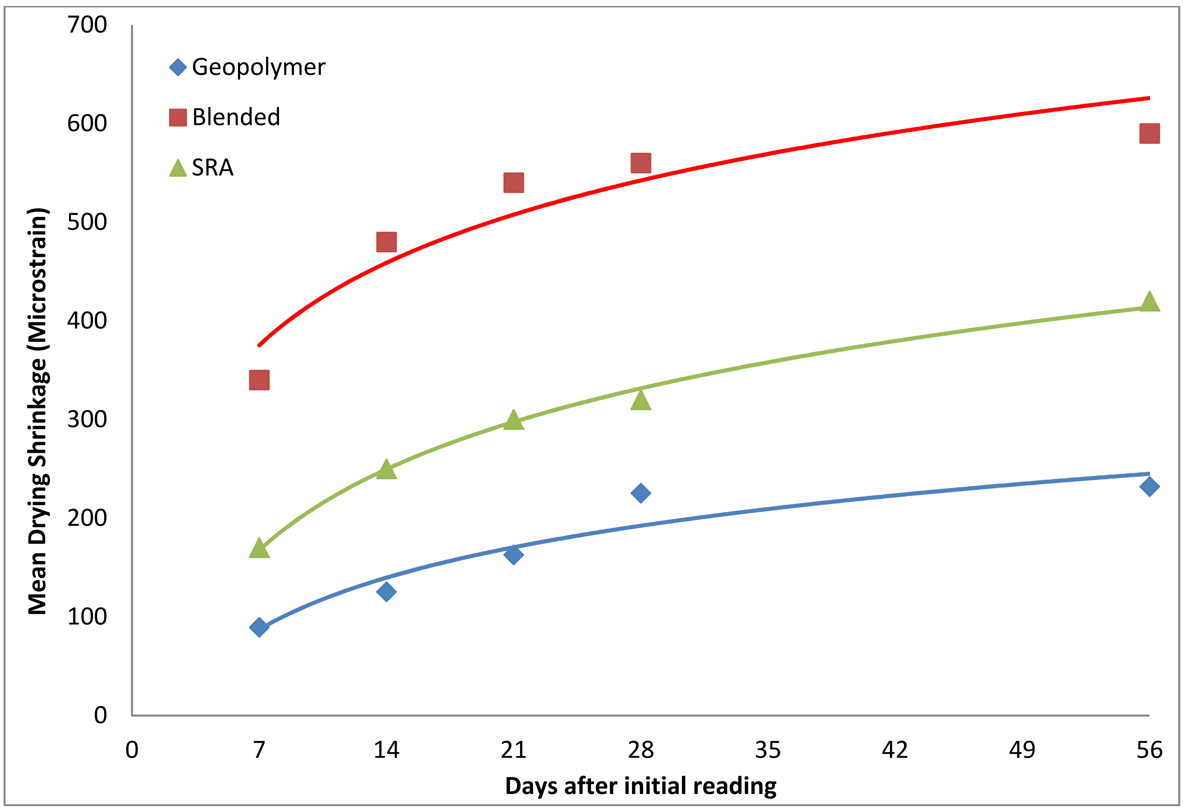

Figure 4: Comparison of drying shrinkage results for concretes with similar aggregates.

Creep

While creep was not 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 24 months period. 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 5. The structural behaviour in the girders was consistent with the compressive strength and modulus indicating no unusual deformation properties. There was very limited creep in the girder beyond 17 months.

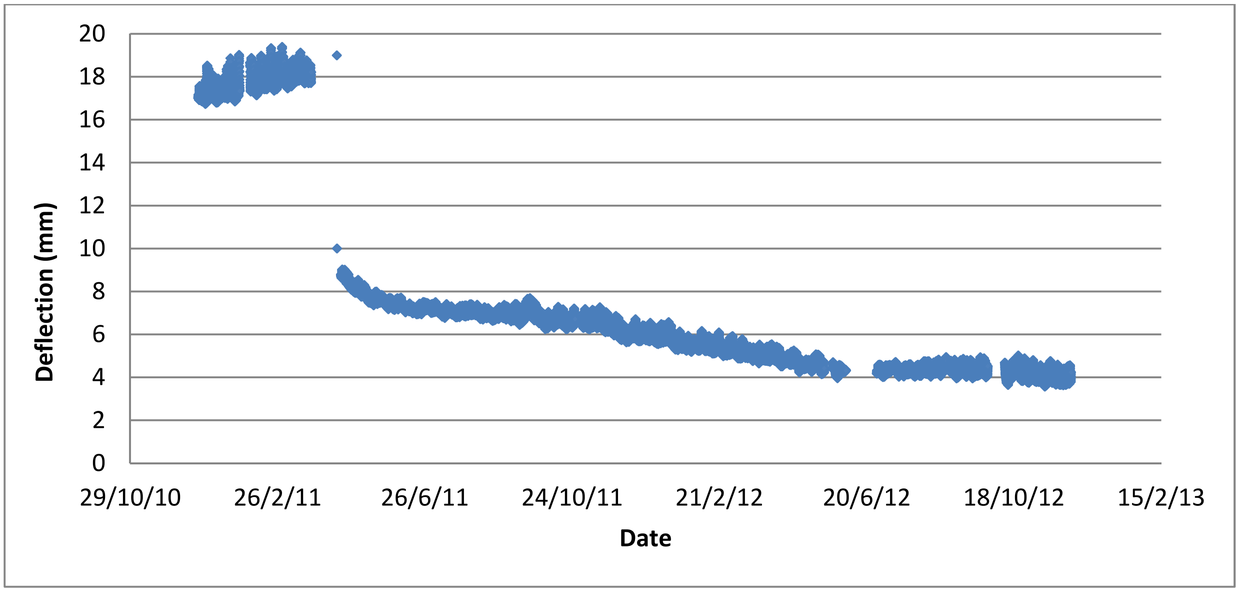

Figure 5: Deflection of prestressed girders after transfer and loading,

4. Durability Properties

Chloride and Sulfate content

AS 1379 specifies that the acid soluble chloride and sulfate contents should not exceed 0.8 kg/m³ and 50g/kg of cement respectively. For the GCI project, the chloride content was less than the limit of reporting (100mg/kg) which is equivalent to a maximum chloride content of 0.254 kg/m³.The sulfate content was less than the limit of reporting (1000mg/kg) which is equivalent to a sulfate content of 7.6 g/kg.

Chloride Penetration

The Royal Melbourne Institute of Technology (RMIT) is conducting exposure trials on panels of this geopolymer concrete in three maritime sites around Australia. RMIT conducted 90 day ponding tests as described in AASHTO T259. The results for the 400 kg/m³ binder content showed virtually no chloride penetration from 0-50 mm depth (less than 0.017%). McGrath and Hooton (6) reported that concretes with a w/cm ratio of 0.4 and 25% fly ash or 8% silica fume replacement had a chloride concentration of 0.1% (ie. over 30 times greater than the maximum measured for this geopolymer concrete over the outer 50 mm) to a depth of 12.3 mm and 7.7 mm respectively. The calculated chloride diffusion coefficients for these Portland cement based concretes with much higher chloride penetration was 7.65 and 1.68 x 10^{-12} m²/s respectively. The corresponding values to ASTM C1202 were 2056 and 316 coulombs. Testing to ASTM C1202 by Queensland TMR showed a value of 229 coulombs for the geopolymer sample.

Therefore the chloride penetrability of this proprietary geopolymer concrete appears to be extremely low with effectively no chloride penetration after 90 days ponding. The effective chloride diffusion coefficient should be established by independent testing but I would expect it to be significantly less than 1 x 10^{-12} m²/s.

Ongoing field exposure trials are being conducted by RMIT at various sites around Australia. The current density and corrosion penetration values after roughly 1 year's exposure demonstrate that the reinforcement at 30 mm cover would be considered passive or undergoing very low corrosion according to RMIT's criteria. It is still early but the results are promising.

Sulfate Resistance

RMIT measured length change in prisms immersed in sodium and magnesium sulfate solutions at 500, 5000 and 50000 ppm. Figures 6 and 7 shows the length change for geopolymer concrete with a binder content of 400 kg/m³ compared with a reference concrete with 30% fly ash immersed in sodium sulfate and magnesium sulfate respectively. The geopolymer concrete had significantly reduced length change in both sulfate solutions compared to a concrete which would be considered to have reasonable sulfate resistance according to BRE Special Digest (7).

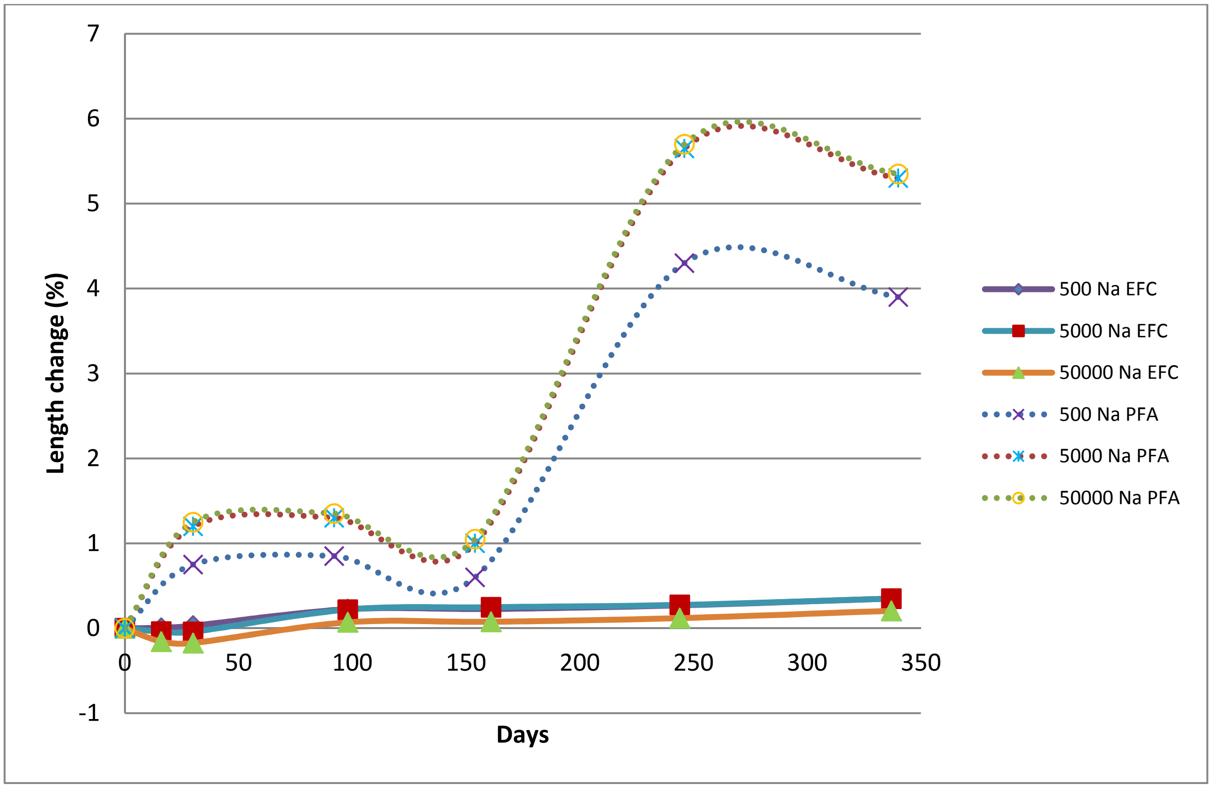

Figure 6: Length change vs time in sodium sulfate solutions for geopolymer and fly ash concrete (After RMIT)

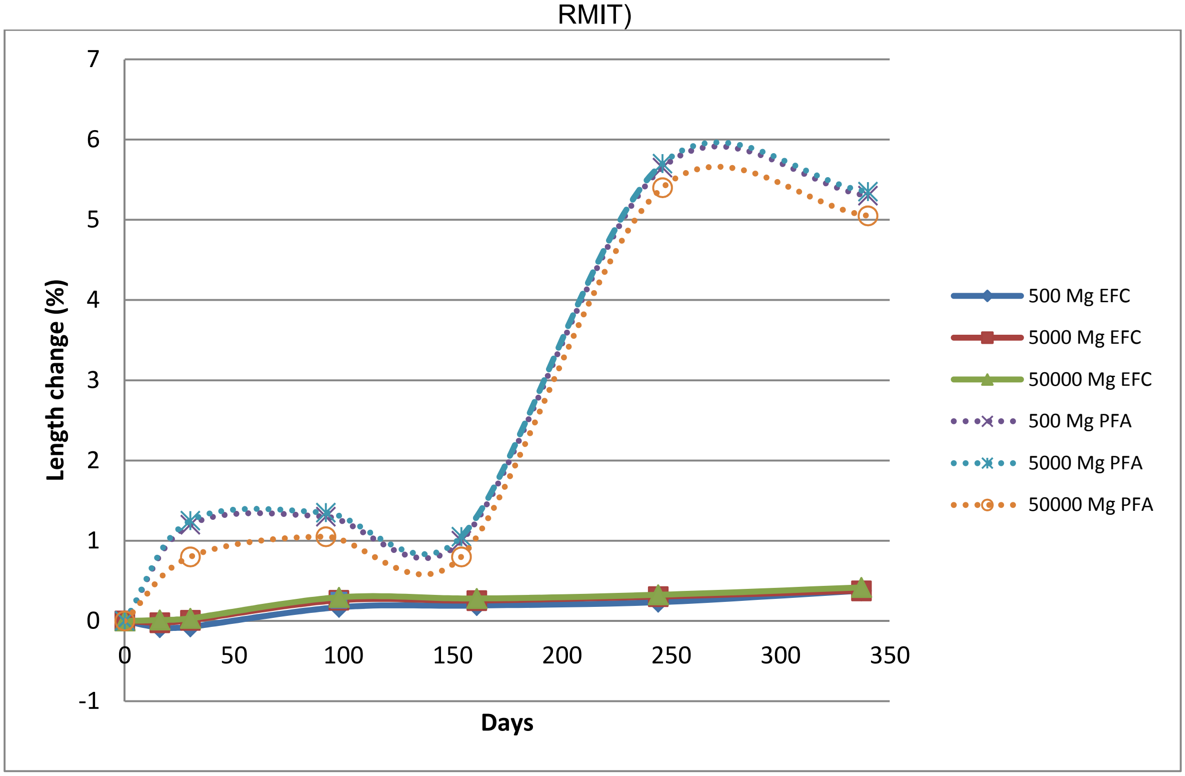

Figure 7: Length change vs time in magnesium sulfate solutions for geopolymer and fly ash concrete (After RMIT)

Alkali Aggregate Reaction

AS 3600 Clause 4.2 states that; “members susceptible to damage due to AAR shall be assessed and appropriate measures shall be taken.” It mentions HB 79 for guidance on appropriate measures. In section 3.2, HB 79 discusses the environmental factors leading to AAR, a limit of 2.8 kg/m^3 on NaO equivalent for concrete containing Portland cement only. Clearly an alkali activated binder system such as a geopolymer concrete would not be expected to comply with a 2.8 kg/m^3 limit on sodium oxide (NaO) equivalent.

AAR performance has not been assessed on this proprietary geopolymer but the literature suggests that AAR was not a significant problem in the geopolymers tested, particularly containing significant quantities of silica rich pozzolans (8, 9).

Carbonation

RMIT conducted accelerated carbonation testing on this geopolymer concrete with a binder content of 400 kg/m^3. The carbonation depth after 56 days exposure was 12.6 mm compared to 10.0 mm for a 50 MPa concrete containing Portland cement only and 13.2 mm for a 40 MPa concrete with 30% GGBS replacement. These data suggest that the rate of carbonation for this proprietary geopolymer should be similar to normal concrete in Australia, most of which would use blended cement.

Acid Resistance

RMIT measured the change in mass after immersion in different concentrations of sulfuric acid (Molarity - 0.005, 0.05 and 0.5). Figure 6 shows that after nearly one year immersion, there is virtually no change in mass for the geopolymer specimens mass. The solid lines show the mass changes for a concrete with a comparable binder content (400 kg/m^3) with 30% fly ash replacement and a w/cm ratio of 0.4. This geopolymer appears to have excellent resistance to sulfuric acid attack.

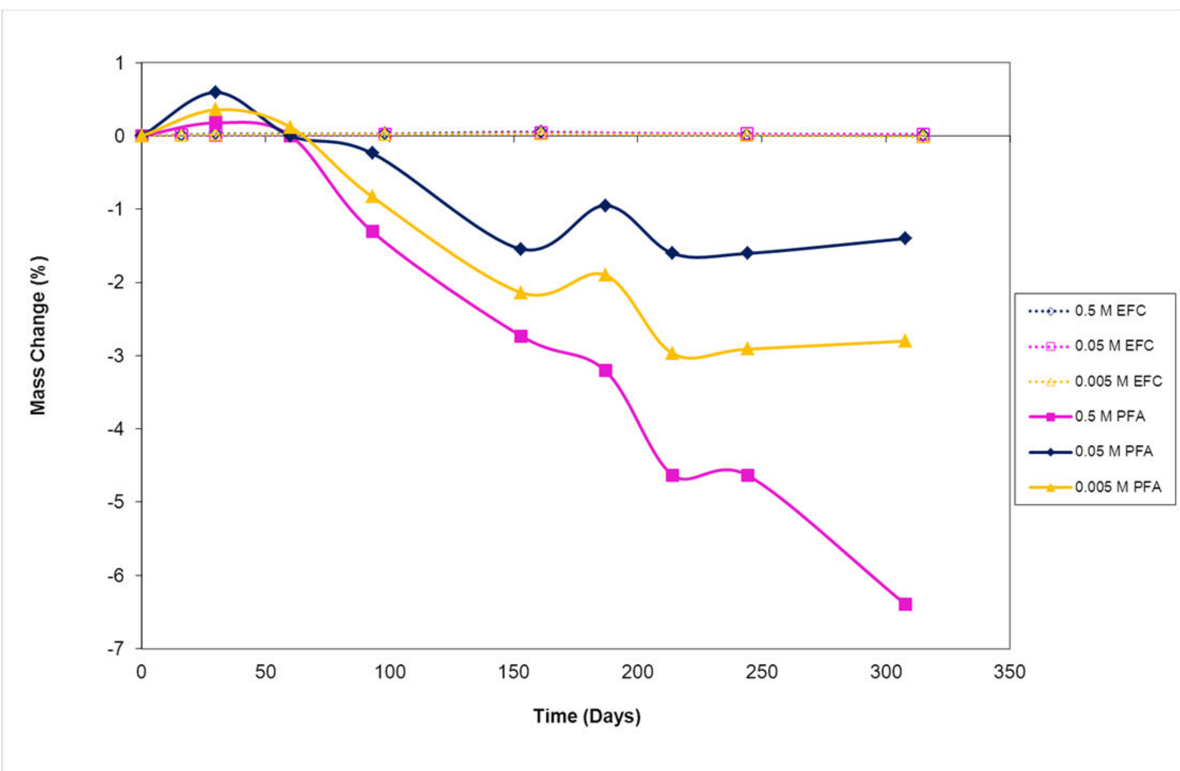

Figure 8: Mass change due to immersion in sulfuric acid solutions for fly ash and geopolymer concrete.

5. Other Significant Properties

Sustainability

Turner and Collins (10) reported that a geopolymer concrete which contained high activator content and required steam curing had slightly less embodied energy and emissions than a pure Portland cement concrete. The product discussed in this paper has a different composition and can be ambient temperature cured. A carbon emission life cycle assessment of this geopolymer concrete/binder compared with slag/GP blended cement concrete/binder estimated a reduction of more than 60% of the emissions associated with a reference blended cement concrete and a reduction of more than 80% of the emissions associated with a reference blended cement binder system.

Temperature Rise

This geopolymer concrete has a low heat of hydration. Figure 9 shows the temperature rise in one cubic metre insulated blocks for this geopolymer compared with concrete containing LH cement with 65% GGBS and a cementitious content of 425 kg/m³. The temperature rise for the geopolymer concrete was only 15°C compared to 37°C for a concrete with 65% GGBS replacement.

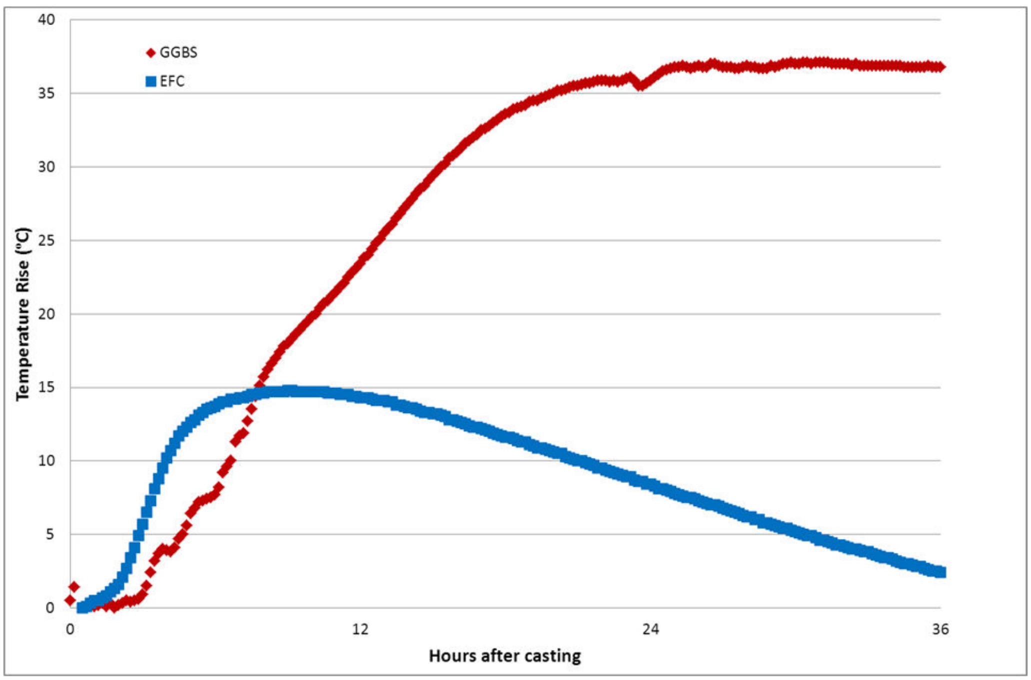

Figure 9: Temperature rise for geopolymer and 65% GGBS mix in 1 m³ insulated block.

Bond Strength

Pull out tests were conducted on beam end specimens in accordance with ASTM A944. The geopolymer concrete used in the tests had a 28 day strength of 45 MPa which was representative of effective characteristic strength of the concrete supplied to the project. The average bond strengths were 17.4 MPa, 13.1 MPa and 10.5 MPa for the N12, N16 and N20 bar respectively. These values are significantly greater than the bond strength required to resist the force at standard development lengths to yield the reinforcement.

Fire Resistance

A fire test in accordance with AS 1530.4 was conducted by CSIRO in North Ryde. The test specimen comprised a nominally 4.7m x 3.0m x 0.17m EFC 40 concrete slab which was subjected to a dead load of 5.5 kPa until 90 minutes. The test demonstrated structural adequacy at 91 minutes as well as integrity and insulation at 121 minutes. The standard fire test facility is shown in Figure 10.

Figure 10: Standard fire testing of geopolymer concrete panel

6. Conclusions

The proprietary geopolymer concrete presented in this paper has been used in a range of precast and in-situ applications. The mechanical, durability and other properties discussed indicate that it complies with most of the performance based requirements of AS 3600 and does provide a viable alternative to Portland cement based systems. The significant benefits in terms of sustainability, drying shrinkage, temperature rise and chemical resistance suggest that it offers the designer important technical benefits in certain applications. This material would appear to provide particular advantages in sulfate rich or acidic environments, such as industrial and sewerage facilities, where Portland cement based products can be subject to significant attack.

7. Acknowledgement

The author would like to thank Dr David Law from RMIT for access to their research data. He would also like to thank Wagners for access to technical information on the product.

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