Earth Friendly Concrete – A sustainable option for tunnels requiring high durability

Authors:
(1) Tom Glasby, EFC Manager, Wagners, Toowoomba, Australia
(2) John Day, Group Technical Manager, Wagners, Toowoomba, Australia
(3) Michael Kemp, GM – Engineering, Wagners, Toowoomba, Australia
(4) Dr James Aldred, Technical Director, AECOM, Sydney, Australia

1 Corresponding Author ; email contact <tom.glasby@wagner.com.au>

Abstract: "Earth Friendly Concrete" (EFC) is a commercial form of geopolymer concrete that has been developed by Wagners in Australia over the last 8 years. EFC contains a geopolymer binder made from the reaction of blast furnace slag and fly ash with concentrated alkaline solution. The complete replacement of Portland cement with recycled waste products contributes extremely low CO_2 emissions. Apart from its environmental attractiveness, EFC offers significant performance improvements in the common durability issues associated with Portland cement based concrete – chloride ion penetration, sulfate attack, acid attack, shrinkage and heat of hydration.

Initial research on geopolymers commenced in the 1940's following application of alkali activated slag concretes throughout Eastern Europe. While there has been significant academic work since then, geopolymer concrete has failed to attract modern commercial uptake. The application of EFC in the production of precast tunnel segments is suggested in this paper as an ideal opportunity for utilising its unique benefits in the Middle East region where high levels of sulfates are routinely encountered in the ground water. Projects undertaken in Australia include precast floor beams in a multi-story building, tunnel segments and a range of other precast and in situ pavement applications.

This paper presents data on the engineering properties of EFC which demonstrates compliance with the relevant performance requirements of international standards. Results from durability studies undertaken by RMIT University in Melbourne will be presented that demonstrate the outstanding sulfate and acid resistance of EFC.

Keywords: geopolymer, tunnel segment, shrinkage, sulfate, durability.

1.0 Introduction

“Earth Friendly Concrete” (EFC) is the brand name of a proprietary geopolymer concrete that has been developed by an Australian company, Wagners. Geopolymer is a generic term coined by Prof Joseph Davidovits (1) in the 1970’s to describe the reaction of materials containing aluminosilicate with concentrated alkaline solution to produce an inorganic polymer binder. Initial research began in the 1940’s following construction of a range of projects using alkali activated slag cement concretes produced throughout Eastern Europe (2). While there has been significant academic work carried out since then, full commercial exploitation of this promising technology has not occurred.

Interest in geopolymer research in Australia has been motivated by the considerable sustainability benefits of using a binder system composed almost entirely of recycled materials. A geopolymer binder has approximately 80 % reduction in carbon emissions compared to Portland cement (3).

EFC has a geopolymer binder made from a combination of ground granulated blast furnace slag (GGBS) and fly ash as its aluminosilicate powder which is activated by the addition of chemicals either as powders or in solution under ambient curing temperature. An important improvement to the field of commercial geopolymers has been the development of a new admixture capable of providing the necessary workability and slump retention required for the full range of commercial concrete delivery and placement methods.

Over the past 4 years Wagners have produced in excess of 6,000 m^3 of EFC covering a wide range of applications including structural precast applications, in situ pavements, precast prestressed bridge beams, precast floor beams in a multi-story building, road bridge decks, precast boat ramps and water tanks.

Several of these projects have been done for R&D purposes with monitoring instrumentation included and testing to capture the necessary engineering and materials data on EFC. As a result, a broad knowledge of the structural behaviour of this particular geopolymer concrete is now well established and has been reported by Dr James Aldred (4).

Geopolymer research suggests improved durability properties however the term “geopolymer” refers to a very wide range of binder types depending on the aluminosilicate source powder and the activators used. To assess EFC, Wagners commissioned RMIT University in Melbourne to undertake a durability study which commenced in March 2012. This study demonstrates a vast improvement over Portland cement based concrete in the following important durability properties: acid resistance, sulfate resistance and chloride ion resistance.

The tunnel boring machine construction method requires precast concrete tunnel linings. In many Middle Eastern regions, specification for the precast segments call for the highest level of sulfate resistance to cope with the high sulfate concentration in the ground waters. From the above discussion, EFC appears to be a superior solution to Portland cement based concrete due to its higher resistance to these attack mechanisms.

This paper will present the engineering and durability data that has been compiled on EFC against a background of real world projects undertaken with it. The use of EFC for precast tunnel segments will be highlighted by recent production conducted at a major precast factory.

2.0 Projects Undertaken with EFC

Over the past 4 years Wagners have produced in excess of 6,000 m^3 of EFC which clearly separates it from the “labcrete’ of the many university studies. The range of projects undertaken in standard concrete production plants using traditional delivery and placement techniques demonstrates the commercial nature of this particular geopolymer concrete.

2.1 In situ Pavement Slabs

A number of slab on ground projects have been undertaken in EFC. Figure 1 shows a slab being poured at the Port of Brisbane site and a 1 km long private road pavement project. These applications have been useful in establishing the practical aspects of EFC, including:

- workability
- set time
- pumpability
- placement techniques
- curing techniques

Early trials indicated that placement of EFC in slabs on ground was more difficult and labour intensive than traditional concrete. Higher cohesion or “stickiness” coupled with a propensity for premature surface drying were problems that needed to be overcome. Since those early trials a proprietary purpose designed admixture has been developed for EFC by a well known German company specialising in that field. Additionally the chemical activators have been refined. While development work continues in this area, as it does in traditional cement chemistry, EFC can now be produced as a suitable pavement mix with some modifications in the placement techniques.

Figure 1 EFC pavements

2.2 Structural Precast Applications

Figure 2 shows a variety of precast elements made from EFC which is ideally suited to precast manufacture for the following reasons:

- EFC has a natural off-white appearance which is highly desired for architectural concrete
- EFC has an excellent off form surface quality with fewer blow holes
- Accelerated curing can be achieved at much lower temperatures than Portland cement concrete. Maximum efficiency is achieved by keeping EFC at an internal concrete temperature of 38 ^{0}C.

Figure 2 EFC precast

2.3 Prestressed Bridge Beams

In December 2010, two precast prestressed bridge beams were cast from EFC, 50 MPa grade, at Wagners Precast facility in Brisbane, Australia as an R&D study of load and deformation behaviour. Internal vibrating wire strain gauges were cast into the beams to allow monitoring of creep and shrinkage over a period of time. The prestress was transferred after 3 days. The girders were left unloaded for 100 days and monitored for hogging deflection under the internal prestress.

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 period which is now 3 years. The hogging prior to load and deflection under sustained load were monitored using transducers and the results are shown in figure 3. The structural behaviour in the girders was consistent with the compressive strength and modulus indicating no unusual deformation properties. Analysis of the strain data revealed very limited creep in the girder beyond 17 months.

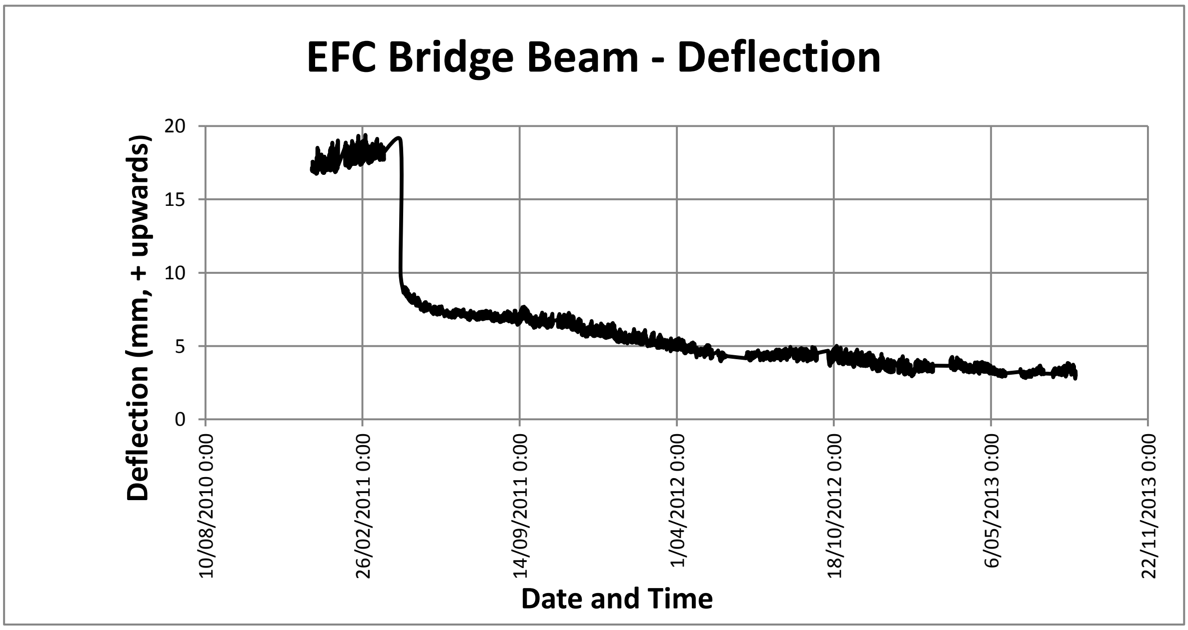

Figure 3

2.4 Water Tanks

Two water tanks (10 m diameter x 2.4 m high) were cast in March 2011 as part of an R&D study. 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 EFC geopolymer concrete also with a 10 mm maximum aggregate. Figure 4 shows the EFC tank on the right and crack width monitors used. Note the strong calcium deposits in the right hand side image typical of cement based concrete.

The objectives of the study were firstly to assess the water resistant properties of EFC and secondly 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 no calcium hydroxide present in EFC, the performance of it in a water retaining application is of considerable interest. Nominal leaking through cracks in the EFC tank did heal relatively rapidly. Ahn and Kishi (5) suggest that geomaterials may be able to autogeneously heal due to a gel swelling mechanism.

Figure 4 EFC Water Tank

2.5 Global Change Institute, multi-storey building

The new Global Change Institute building at the University of Queensland in Brisbane has 3 suspended floors of 40 MPa precast EFC beams, figure 5. A total of 33 no. beams, each spanning 10.5 m and a width of 2.4 m make a large contribution to the building owner's goal for a building design to meet the world's highest sustainability standards (6).

Performance compliance testing and specified engineering certification on the beams was supplied by Wagners to meet the requirements based on AS3600 "Concrete Structures". Results of the testing on structural material properties show the EFC to be well above the minimums specified in AS3600 and are reported by Aldred (4).

Figure 5 EFC beams in Global Change Institute building

3.0 Engineering Data on EFC

Aldred (4) reports on a comprehensive range of engineering material properties of EFC geopolymer concrete that are used in the design of reinforced and prestressed concrete structures, including: compressive strength, tensile strength, modulus of elasticity, stress - strain curve, poisons ratio, drying shrinkage, creep and fire resistance.

EFC can be produced in all typical commercial compressive strength grades. Extensive compressive test data is available for 32, 40 and 50 MPa. Under an ambient temperature curing range of 20 – 35 ^{0}C, EFC displays good early age strength development with 80% of the 28 day strength being achieved in 7 days.

In comparison to Portland cement based concrete, for each strength grade, EFC has a distinct advantage in flexural tensile strength and drying shrinkage. EFC achieves approximately 30% higher flexural tensile strength than would be expected for a similar compressive strength grade Portland cement based concrete. On the GCI project, the grade 40 EFC supplied achieved an average flexural tensile strength of 6.4 MPa.

Across all frequently tested EFC grades, the average 56 day drying shrinkage tested to the Australian Standard AS 1012.13 is 350 microstrain. This is a significant reduction to typical Australian concretes made with similar sands and aggregates that have an average 56 day drying shrinkage of 650 microstrain.

All tested engineering properties outlined above show that EFC can be designed using normal reinforced concrete design rules with the same reliable structural performance. Two engineering properties are worth noting as being significantly better than traditional concrete that would lead to improvements in the structural and serviceability performance of many structure types – increased flexural tensile strength and reduced drying shrinkage.

4.0 Durability Data on EFC

The body of research literature on geopolymer concrete strongly suggests an increased resistance to a range of common degradation mechanisms that negatively affect Portland cement based concrete. These include: high sulfate resistance, high acid resistance, high resistance to chloride ion ingress and steel corrosion and low heat of reaction.

The term geopolymer encompasses a wide range of different binders depending on the source aluminosilicate powders and activators, admixtures and whether elevated temperature curing is required. The chemistry of the geopolymer binder and the performance of the resulting concretes from these different approaches vary substantially. For this reason it is essential to match geopolymer research results with appropriately similar concretes. EFC contains both slag and flyash in its feedstock powder and is more aligned with an alkaline activated slag system that is ambient cured than to a fly ash geopolymer binder cured at elevated temperature.

An independent study on EFC has been undertaken by leading Australian concrete researchers Prof Tom Molyneaux and Dr David Law of RMIT University in Melbourne and the results are shown in the following sections.

4.1 RMIT Research on EFC – 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 show the length change for EFC geopolymer concrete with a binder content of 400 kg/m^3 compared with a reference Portland cement concrete with 30% fly ash immersed in sodium sulfate and magnesium sulfate respectively. The EFC 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).

These results compare favourably with Douglas et al. (8) who found little changes in mechanical properties of sodium silicate activated slag concrete after 120 days of immersion in 5% sodium sulfate solutions, even smaller than the controlled specimens in lime saturated for water or tap water for the same time period.

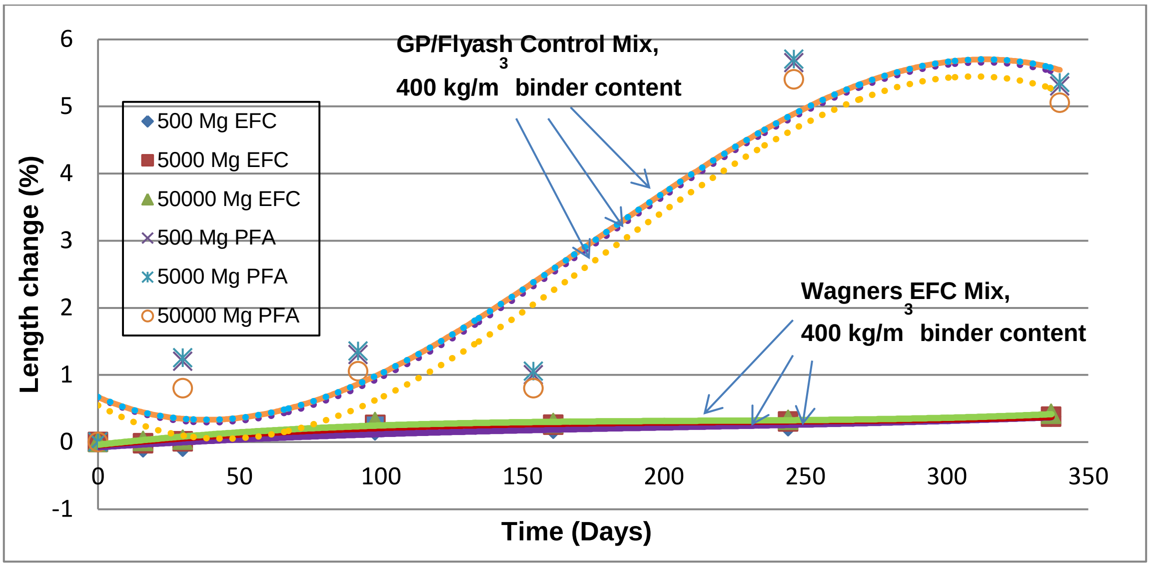

Figure 6: Length change vs time in sodium sulfate solutions for EFC geopolymer and fly ash concrete (After RMIT)

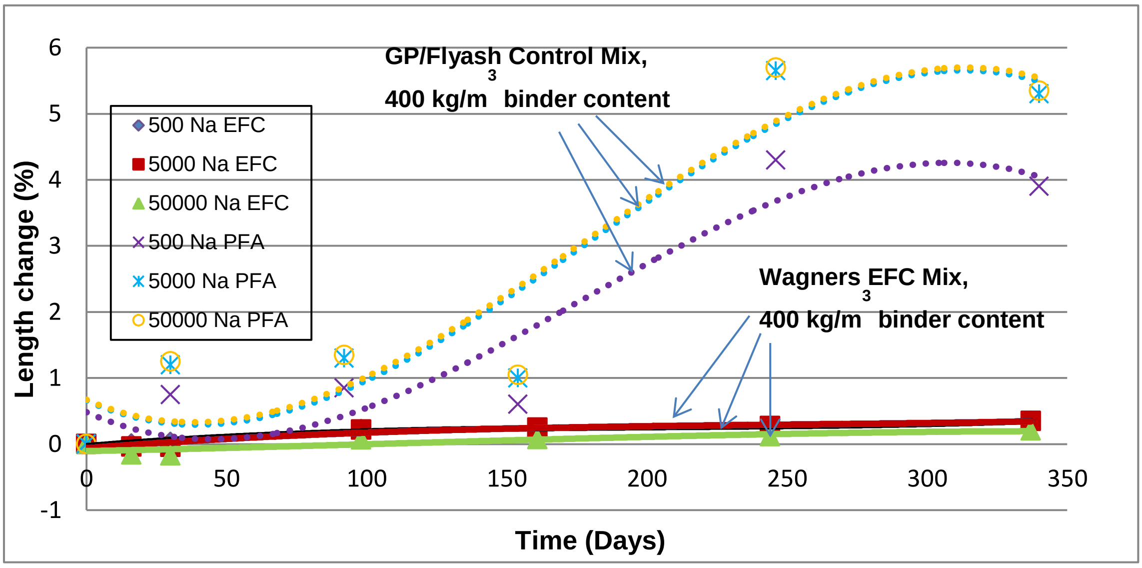

Figure 7: Length change vs time in magnesium sulfate solutions for EFC geopolymer and fly ash concrete (After RMIT)

4.5 RMIT Research on EFC – 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 8 shows that after nearly one year immersion, there is virtually no change in mass for the EFC geopolymer specimens mass. The solid lines show the mass changes for a reference Portland cement concrete with a comparable binder content (400 kg/m³) with 30% fly ash replacement and a w/cm ratio of 0.4. EFC demonstrated excellent resistance to sulfuric acid attack.

These results are supported by Shi (9) who found that alkali activated slag paste provided a much better resistance to acid attack than Portland cement paste, using solutions of nitric acid and acetic acid with pH of 3. The observed improvement was attributed to the difference in nature of hydration products between alkali activated slag and Portland cement.

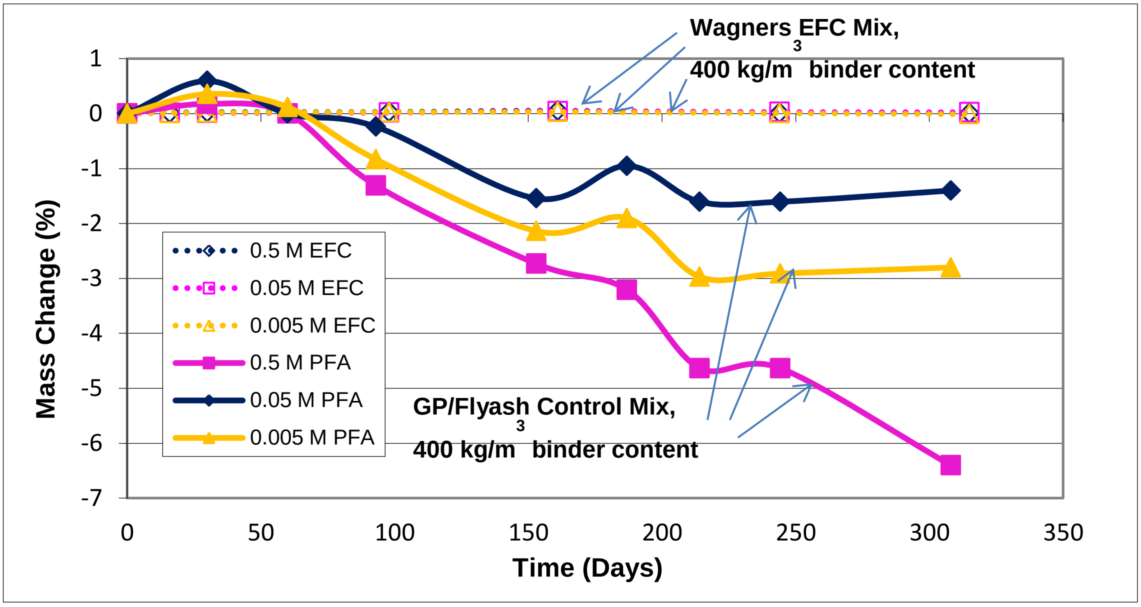

Figure 8: Mass change due to immersion in sulfuric acid solutions for fly ash and EFC geopolymer concrete.

4.6 RMIT Research on EFC – Chloride Corrosion Resistance

RMIT is conducting exposure trials on 600 mm x 600 mm x 200 mm panels of EFC 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 EFC showed virtually no chloride penetration from 0-50 mm depth (less than 0.017%). McGrath and Hooton (10) 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% to a depth of 12.3 mm and 7.7 mm respectively.

Testing to ASTM C1202 “Electrical indication of concrete’s ability to resist chloride ion penetration” by Queensland TMR showed a value of 229 coulombs. This is classified as very low according to Table 1 in the Standard.

Bernal et al (11) compared the ASTM C1202 results for alkali activated slag concretes and OPC concretes with three different binder contents. They found that the slag geopolymer concretes had significantly lower coulomb values for all three binder contents. In OPC based concrete, GGBS replacement has been widely used to reduce chloride penetration to achieve durable reinforced concrete in marine environments and where de-icing salts are used (12). Roy et al (13) measured the effective chloride diffusion coefficient for pastes containing a range of GGBS percentages and included activated and non-activated systems. Their results demonstrate a clear trend of decreasing diffusion rate with increasing percentage slag for both non-activated and activated systems.

4.7 RMIT Research on EFC – Carbonation

Carbonation is the mechanism of de-passivation of reinforcing steel embedded in concrete. In Portland cement concrete, carbonation is the result of CO_2 dissolving in water to form carbonic acid which reacts with $Ca(OH)_2$ to form calcium carbonate reducing the pH in cement matrix (14). Carbonation in Portland cement based concrete is usually accompanied with a shrinkage, which may produce cracking or surface crazing of concrete.

RMIT conducted accelerated carbonation testing on EFC 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.

4.8 EFC Heat of reaction

EFC has a very low heat of reaction. Figure 9 shows the temperature rise in one cubic metre insulated blocks compared with a reference concrete containing low heat cement with 65% GGBS and a cementitious content of 425 kg/m^3. The temperature rise for EFC was only 15 ^{0}C compared to 37 ^{0}C for a concrete with 65% GGBS replacement.

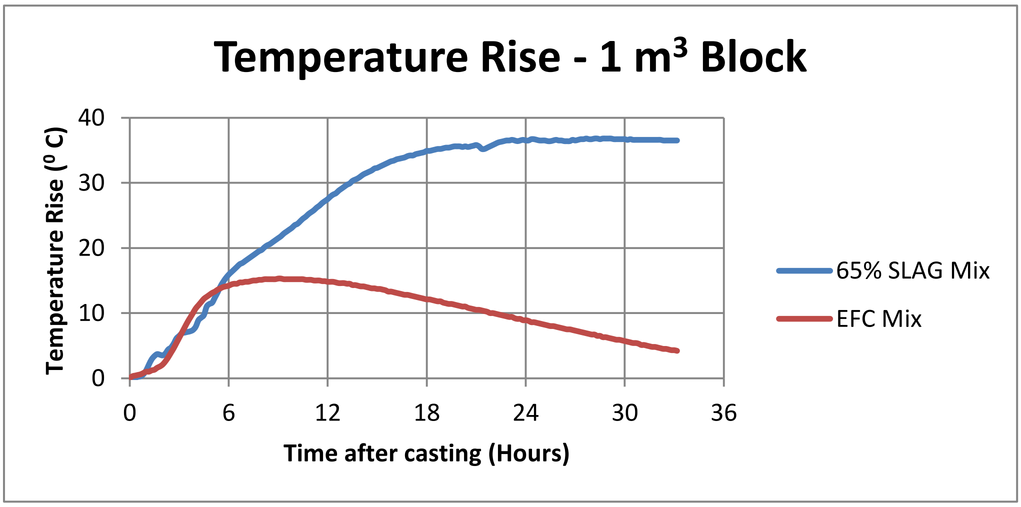

Figure 9 EFC Heat of reaction

5.0 EFC precast tunnel segments

EFC would be an ideal choice for factory produced precast concrete tunnel segments in regions with high sulphate ground waters, such as the Middle East countries. EFC is well suited to precast manufacture, attains high early strength and can be accelerated cured at only 38 ^{0}C and has a high resistance to sulfate attack. The high flexural tensile strength can also be used to refine the structural design of tunnel elements.

Another tunnel related application that beckons is sewer pipes constructed with tunnel boring machines, where the high acid resistance of EFC would offer better protection to attack from sulfuric acid than Portland cement based concrete.

5.1 Production

EFC was delivered to the Dowstress precast factory for the production of a complete tunnel ring of 9 segments, during the production of the Legacy Way tunnel. A low slump EFC mix was designed based on achieving the concrete performance specification and the handling and placement requirements of the precast factory which uses an automated carousel system. Steel and polypropylene fibres were included in the mix as per the Legacy Way Tunnel specification. The EFC tunnel segments were successfully produced and have been kept as a valuable demonstration model. De-moulding of the finished units using the factory’s automated handling system was undertaken as per normal concrete production after the low temperature chamber curing.

The finished units displayed a smooth off form finish and held the curved top surface profile very close to design, as shown in figure 10.

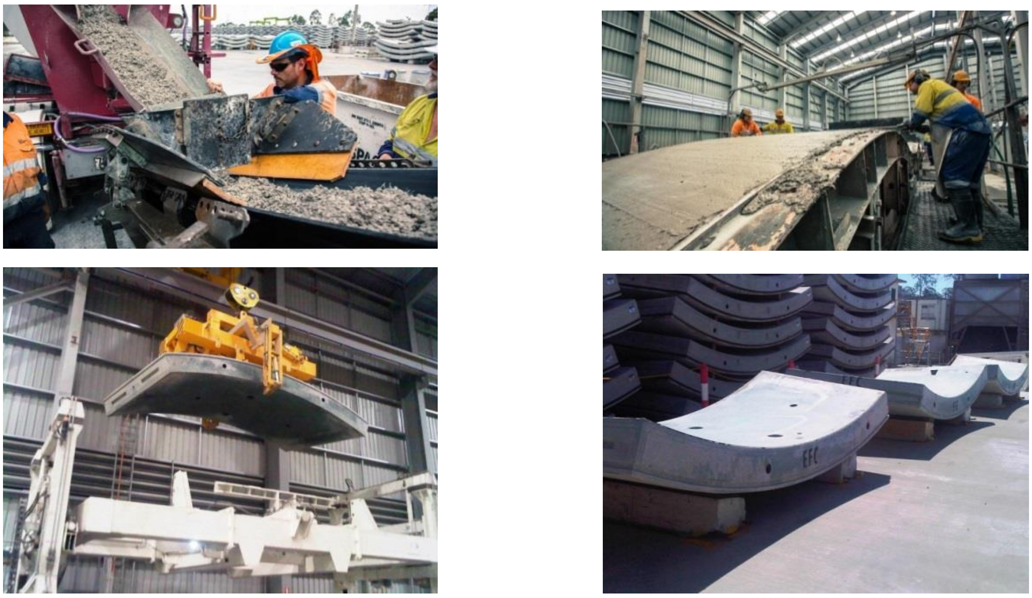

Figure 10 EFC tunnel segments

6.0 Conclusion

Wagners EFC is a proprietary geopolymer concrete that has been used in a range of precast and in situ applications. There now exists comprehensive test data across its material properties to be able to assess its structural and durability properties for use in engineering structures. The mechanical, durability and other properties discussed indicate that it complies with the performance based requirements of the Australian Concrete Structures code, AS 3600, which is in line with similar international standards.

More than just a viable and sustainable alternative to Portland cement based systems EFC provides superior performing concrete for many structural applications, and in particular precast concrete tunnel segments in high sulfate soils. The significant benefits of EFC for precast tunnel segments in the Middle East include: high resistance to sulfate attack, high resistance to acid attack, low heat of reaction, low shrinkage and high early strength development.

7.0 References

1. Davidovits, J., 1991, “Geopolymers: Inorganic Polymeric New Materials”. Journal of Thermal Analysis, no. 37, p1633-1656.

2. Roy, D.M., 1999, “Alkali-activated cements -Opportunities and challenges”, Cement and Concrete Research vol.29, pp.249–254.

3. Concrete Institute of Australia, 2011, “Recommended Practice: Geopolymer Concrete”, CIA, Sydney.

4. Aldred, J., 2013, “Engineering Properties of a Proprietary Premixed Geopolymer Concrete”, Proceedings Concrete Institute of Australia Biennial Conference, Concrete 2013 – Understanding Concrete, Gold Coast, Australia.

5. Ahn, T.H. and Kishi, T., 2010 “Crack Self-healing Behavior of Cementitious Composites Incorporating Various Mineral Admixtures” Journal of Advanced Concrete Technology vol. 8, No. 2, 171-186, 2010.

6. Bligh, R. and Glasby, T., 2013, “Development of Geopolymer Precast Floor panels for the Global Change Institute at University of Queensland”, Proceedings Concrete Institute of Australia Biennial Conference, Concrete 2013 – Understanding Concrete, Gold Coast, Australia.

7. BRE Special Digest 1, 2005, “Concrete in aggressive ground.”

8. Douglas, E., Bilodeau, A., Malhotra, V., 1992, “Properties and Durability of Alkali-Activated Slag Concrete”, ACI Materials Journal, vol.89, no.5, pp.509-516.

9. Shi, C., 2003, “Corrosion Resistance of Alkali-Activated Slag Cement”, Advances in Cement Research, vol.15, no.2, pp.77-81.

10. McGrath, P. F. and Hooton, R. D., 1999, “Re-evaluation of the AASHTO T259 90-day salt ponding test”, Cement and Concrete Research vol.29, pp.1239-1248.

11. Bernal et al., 2011, “Effect of binder content on the performance of alkali-activated slag concretes”, Cement and Concrete Research, vol. 41, pp. 1–8.

12. Shi, C., Krivenko, P., Roy, D.M., 2006, “Alkali-Activated Cements and Concretes, Abingdon: Taylor and Francis.

13. Roy, D.M., Jiang W., Silsbee, MR., 2000, “Chloride Diffusion in Ordinary, Blended, and Alkali-Activated Cement Pastes and Its Relation to Other properties”, Cement and Concrete Research, vol.30, no.12, pp.1879-1884.

14. Neville, A.M., 1995, “Properties of Concrete”, Essex: Addison Wesley Longman Limited, 4th edition.