Commercial Scale Geopolymer Concrete Construction

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1. Introduction

Geopolymer concrete is a new class of concrete that is attracting growing interest around the world due to its environmental and performance benefits compared to conventional Portland cement concrete. The technology has now moved beyond the realm of university scale studies into commercial sized construction projects.

Brisbane West Wellcamp Airport (BWWA) in Australia opened for commercial flights in November 2014, marking a very significant milestone in engineering - the world's largest modern geopolymer concrete project. A commercial geopolymer concrete was supplied by Wagners under the brand name "Earth Friendly Concrete" (EFC) for the construction of the heavy duty machine laid aircraft pavements, covering some 50,500 m^2 in area and being 435 mm thick. In addition to the pavements, a further 15,000 m^3 of geopolymer concrete was used in a variety of applications including an entry bridge to the airport, extruded kerb and road barriers, precast culverts, site cast tilt panels, footings, median strip pavements and sewer tanks.

This innovative application follows previous commercial scale projects in Australia like the 5 storey Global Change Institute in Brisbane, Queensland that contains precast EFC floor beams spanning 10.5 metres.

Geopolymer concrete has particular application for a wide range of projects in the Middle East that will benefit from the following performance properties:

- Low heat of reaction
- High sulfate, acid and chloride ingress resistance
- High flexural tensile strength
- Low shrinkage
- Extremely low CO_2 emissions

This paper describes the geopolymer concrete pavements project at BWWA as well as other significant commercial scale work in this field that has occurred in Australia over the past 5 years. The author discusses the potential for geopolymer concrete to be supplied in Middle Eastern countries and the types of projects that would benefit most from it.

2. EFC - Commercial Scale Geopolymer concrete

Over the past 10 years, Australian construction materials company, Wagners, have developed a truly commercial form of geopolymer concrete that is totally Portland cement free and a complete replacement for conventional concrete. The binder in EFC is made by the chemical activation of two industrial wastes – ground granulated blast furnace slag (waste from iron production) and fly ash (waste from coal fired power stations). The other main concrete constituent materials of coarse and fine aggregate remain the same. This alternative binder reduces the carbon emissions associated with Portland cement by 80 - 90%, and also greatly lowers the embodied energy. The development of EFC has been acknowledged in Australia by several significant awards:

- 2011 Queensland Government Premiers Climatesmart awards. Category winner 'Product innovation of the year'. Judged best of best across all categories.
- 2012 Brisbane City Council Innovation Survey. 1 of 18 case study examples selected from 400.
- 2013 BPN Sustainability Awards. Category winner 'Product innovation of the year'. Judged best of best across all categories.
- 2013 The Australian – Shell Innovation awards. Category winner 'Manufacturing and Hi-tech Design.

Importantly, the structural and durability performance of this geopolymer concrete is better than conventional concrete. EFC has improved durability, lower shrinkage and higher flexural tensile strength. These important benefits have been reported elsewhere by Glasby et al (1) and Aldred (2).

Wagners have undertaken commercial projects in EFC for the past 5 years, producing 55,000 m^3 for a wide variety of projects which clearly separates this geopolymer concrete from the "labcrete' of the many university studies. These projects have been undertaken using standard concrete production plants and traditional delivery and placement techniques. Project types include:

- In situ placed pavements and bridge decks
- Precast panels, boat ramp planks and architectural elements
- Precast tunnel segments
- Precast floor beams in a multi-storey building (GCI building at UQ, Brisbane)
- In situ heavy duty aircraft pavements (Brisbane West Wellcamp Airport)
- In situ extruded road barrier and kerb
- Site cast water tanks and sewer tanks

2.1 In situ Pavement Slabs

Placement of thin EFC slabs on ground is somewhat more difficult and labour intensive than traditional concrete due to its higher internal cohesion coupled with a propensity for rapid surface drying. The development of purpose designed admixtures and refinement of the chemical activators has produced an EFC pavement mix with a modified rheology more suited to thin slab construction. Development work continues in this area, however currently EFC can be produced as a suitable thin slab pavement mix with some modifications in the placement techniques, figure 1.

Figure 1 EFC hand placed pavements

2.2 Structural Precast Applications

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

- Natural off-white appearance which is highly desired for architectural concrete
- 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 40 – 50 ^{0}C.

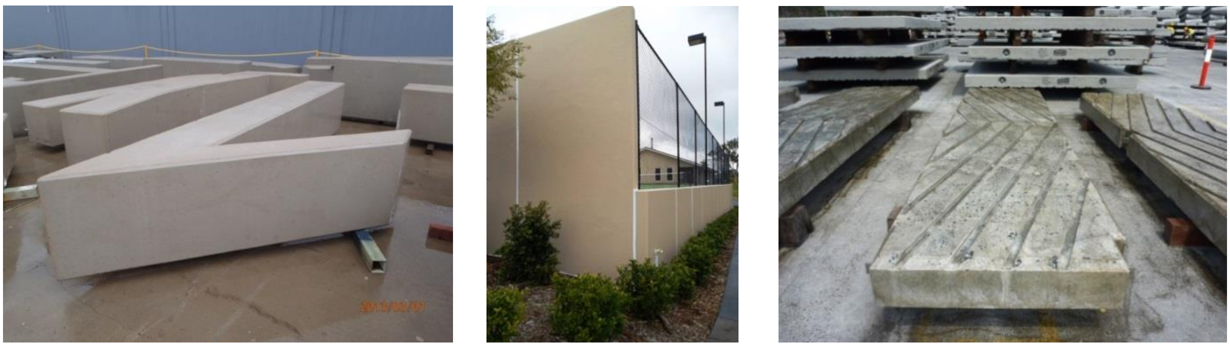


Figure 2 EFC precast

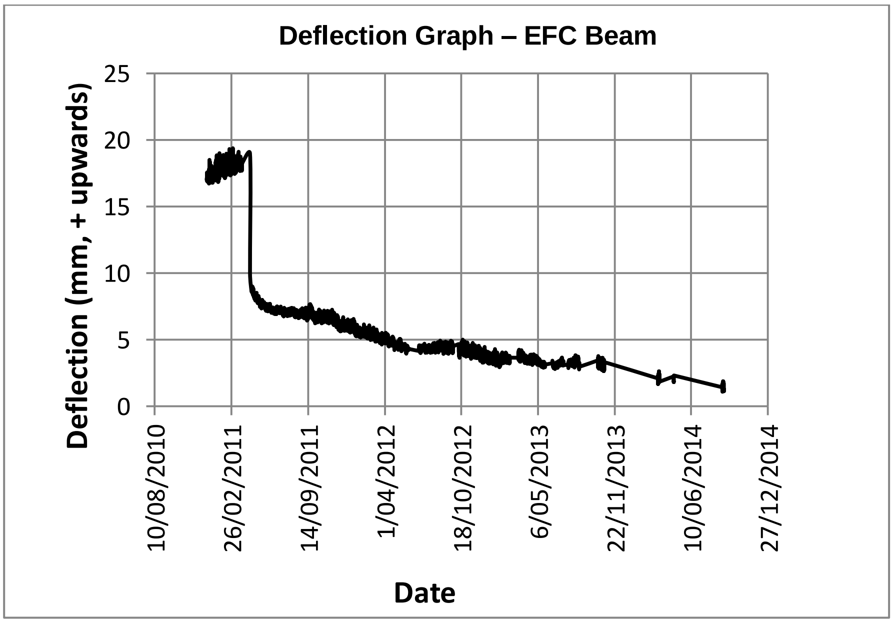
2.3 Prestressed Bridge Beams

In December 2010, two precast prestressed bridge beams were cast from 50 MPa EFC at Wagners Precast factory in Brisbane, Australia as an R&D study of load and deformation behaviour. Internal vibrating wire (VW) strain gauges were cast into the beams to allow monitoring of creep and shrinkage with time. After de-moulding, 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 (3) and continuously measured for deflections over the subsequent period which is now 4 years, 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.

Internal VW strain gauges

Beam de-moulding



Beams loaded

Figure 3 EFC bridge beam

2.4 Water Tanks

Two water tanks were cast in 2011 as part of an R&D study. The first water tank was constructed using a conventional 32 MPa concrete with a blended cement consisting of 80% Portland cement and 20% flyash. The second tank was constructed with a 32 MPa EFC geopolymer concrete. 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 Portland cement based concrete.

The objectives of the study were firstly to assess the water resistant properties of EFC and secondly to investigate the autogenous crack 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 (4) discuss a re-crystallization mechanism occurring in geo-materials which may be the mechanism responsible for the crack healing noted above.

Figure 4 EFC Water Tank

2.5 Global Change Institute, multi-storey building

The 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 (5).

Performance compliance testing and specified engineering certification on the beams were supplied by Wagners to meet the requirements based on the Australian concrete structures standard, AS 3600 (6). 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 (2).

Figure 5 EFC beams in Global Change Institute building

2.6 EFC Tunnel Segments

Successful tunnel segment production trials have been undertaken in Australia, Malaysia and Germany, figure 6. The application of tunnel segments is of particular interest to the Middle East region due to the far greater resistance of EFC to sulfate attack, acid attack and chloride ion ingress. Glasby (1) cites independent R&D studies on EFC by RMIT university to show the large improvement that this proprietary geopolymer concrete would make in the performance of tunnel linings exposed to sulfate laden ground conditions as well as sewer tunnels that are subject to sulfuric gas forming above the water level.

EFC segments produced in a carousel factory, Brisbane Australia

EFC segments, MDC Precast, Malaysia **EFC segments, Max Bögl Precast, Germany**

Figure 6 EFC Tunnel Segments

3. EFC Pavements at Brisbane West Wellcamp Airport (BWWA)

BWWA is Australia's first greenfield public airport to be built in 48 years and is the world's largest modern geopolymer concrete project. EFC was used for the construction of the heavy duty pavements in the aircraft turning node and apron areas which was undertaken in the period August – October 2014. Figure 7 shows an overall plan and an aerial photograph of the completed pavement works at the BWWA site. The turning node is located at the Northern end of the runway and the apron is located on the Western side of the runway in front of the terminal and carpark.

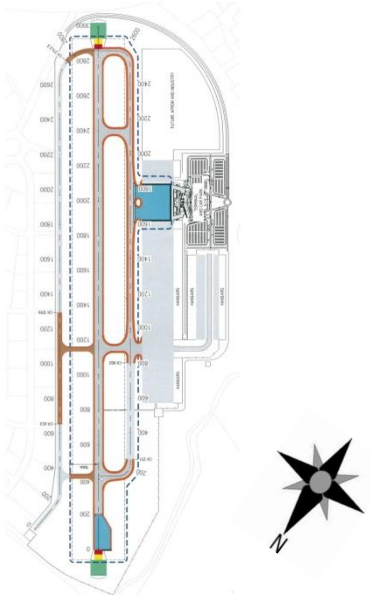
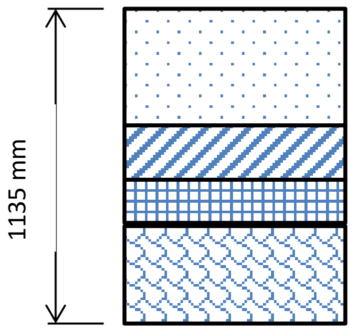


Figure 7. Site plan and aerial photograph – BWWA.

The concrete materials specification written by the project engineering consultants required:

- 4.8 MPa average flexural strength at 28 days of age, AS 1012.8.2 (7) and 1012.11 (8)
- 450 micro-strain maximum drying shrinkage at 28 days of age, AS 1012.13 (9)

Flexural strength testing was conducted by the project site laboratory and the results are shown in table 1.



(pavement design by ACG Engineers)

Figure 8. High Strength Concrete Pavement Design Cross Section.

Table 1. Flexural tensile strength results (28 days).

No. of Samples	502
Average flexural strength (MPa)	5.8
Standard Deviation	0.58

3.1 EFC Production and Supply

The EFC was produced in a twin mobile wet mix batch plant established on the BWWA project site, figure 9. The standard concrete production plants shown have been modified to accommodate the chemical activators which are added to the mix as a solution. A maximum supply capacity of 120 m^3/hr was required to provide a continuous feed of concrete to the slip form paving machine, figure 10, which was successfully achieved using several tipper trucks for delivery. An advantage of wet mix production is that concrete agitator trucks are not required for short transit times. The use of tippers allowed a significantly improved discharge rate at the paver face.

Figure 9. EFC twin batch plant.

Figure 10. EFC delivery to slip form paver.

3.2 EFC Pavement Construction

Aircraft pavement construction in Australia is normally undertaken by placing and compacting the concrete into steel side forms by a combination of internal mechanical vibration and vibrating beams. Using EFC it was demonstrated that a very high level of compaction could be achieved with a slip form paver machine which was adopted at BWWA due to its efficiency and increased production rate compared to using a vibrating beam. It is estimated that a 30% decrease in the pavement construction schedule was achieved on this project.

The rheology of the EFC geopolymer mix at the specified slump allowed it to extrude considerably better than conventional concrete. This allowed for very efficient placement resulting in the noted schedule gains. The levels of admixtures and activators in the mix were able to be customised for the differing weather conditions and length of transit time across the project site. (Winter to Summer 2°C minimum to 40°C Maximum, 5 minutes to 20 minutes transit time).

Compaction achieved was validated by comparing in situ density test results with fresh concrete density results, table 2. In situ density was undertaken by using both the Nuclear density method (NDM) to AS 1289.5.8.1 (10) and in situ core density testing to AS 1012.14 (11) and AS 1012.12 (12).

Table 2. Density measurements.

	All areas	**Turning node area – In situ testing**				**Apron area – In situ testing**			
	Cast beams and cylinders	Core method middle	Core method top	Core method bottom	NDM method	Core method middle	Core method top	Core method bottom	NDM method
Max	2.540	2.502	2.542	2.507	2.511	2.488	2.489	2.592	2.517
Average	2.401	2.463	2.462	2.467	2.427	2.440	2.464	2.472	2.439
Min	2.280	2.420	2.413	2.412	2.312	2.396	2.429	2.380	2.374
No. Samples	1038	57	57	55	764	72	22	22	364
Standard Deviation	0.040	0.016	0.022	0.022	0.029	0.018	0.015	0.038	0.023

EFC requires particular attention for curing and pre-curing evaporation control when placing open slab surfaces. It displays very low bleed characteristics and the surface will rapidly dry out without otherwise intervening to maintain a moist sheen on the surface. Premature drying of the EFC surface prior to initial set and the application of curing can result in a poorly bound top matrix.

An effective evaporation control and curing methodology was adopted that well suited the slip form placement method. A proprietary alkaline anti-evaporation spray was used that maintained surface moisture by reducing the evaporation rate while at the same time replenishing the fresh geopolymer concrete surface with alkalinity that can be depleted through the process of exposure to the atmosphere. Curing consisted of applying a water based hydro carbon resin curing compound, followed by covering with a geotextile to protect against any thermal shock brought about by the difference of daytime and night time temperatures, figure 11.

Figure 11. Curing and side forms with dowels.

Jointing design of the pavements by the engineering consultants followed conventional rules based on Portland cement concrete. In the direction of paving, joints were provided by saw cutting at 5 m centres with isolation joints provided every 70 m. Early age saw cutting was carried out as soon as possible, generally 1 to 5 hrs after placement depending on ambient temperatures, figure 12. Dowels were located between paving lanes, figure 11.

The geopolymer concrete's lower shrinkage properties compared with conventional concrete would indicate that joint spacing could be increased over those used for conventional concrete. Wagners' test data on EFC indicated an average 56 day drying shrinkage of 350 microstrain, tested to AS 1012.13 (9). A significant benefit and cost saving on future work would be to increase the spacing of joints based on the higher flexural strength and lower shrinkage properties of EFC.

Fine crack in saw cut joint

Saw suspended on bridge to allow earlier joint formation

Figure 12. Early age saw cutting.

Figure 13. Operational BWWA.

4. Discussion - Commercial Geopolymer Concrete for the Middle East

As demonstrated in the above examples, the technology in Wagners EFC is well placed to provide a practical geopolymer alternative to Portland cement concrete for a wide cross section of the construction industry internationally. These areas can include beams, pavements, footings, tunnels and marine structures. The pavements project at BWWA outlined in this paper is believed to be the largest commercial application of modern geopolymer concrete (defined by the authors as post-1970) in the world. Some 25,000 m^3 of aircraft pavement grade concrete was supplied and constructed over a 3.5 month period. EFC was also employed extensively in other sections of the project for a total of 40,000 m^3.

While having a history dating back to the 1930's with activated slag cements used to make a variety of concrete structures throughout parts of Europe (13), geopolymer concrete is still deemed a new technology in the commercial world of modern concrete construction. The successful and rapidly built BWWA project provides an excellent real world demonstration for contractors, builders, specifiers and approval authorities that geopolymer concrete can be designed, produced and constructed within accepted QC levels at the commercial scale.

A major challenge to parties wishing to include geopolymer concrete in projects is the lack of an international standard for manufacture and specification. Wagners are addressing this for their proprietary EFC geopolymer concrete by undertaking an assessment for a general technical classification through the Deutsches Institut fur Bautechnik (DIBt) of Germany which will be complete by the end of 2015. In Australia, the writing of a Handbook on geopolymer concrete has commenced that should lead to an Australian standard being published by 2018. The Concrete Institute of Australia published a recommended practice note for geopolymer concrete in 2011 (14).

A key driver for geopolymer concrete in Australia and elsewhere has been the environmental attractiveness of a concrete that utilises a large component of recycled material (slag and / or flyash) which completely replaces carbon intensive Portland cement (15). By using a figure of 80% reduction in CO_2 emission from the binder content in this geopolymer concrete compared to a conventional 75% GP / 25% supplementary cement in an equivalent normal concrete, some 5,600 tonnes CO_2 emissions were saved from polluting the environment in this project's pavements alone.

Another strong driver for geopolymer concrete is the performance and durability improvements that are possible due to the different chemistry of the binder. This inherent resistance is sure to provide benefits to structures when contrasted to conventional (susceptible) concrete with polymer liners or coatings. Geopolymer concrete, therefore, has particular application for a wide range of projects in the Middle East that will benefit from the following performance properties:

- Low heat of reaction
- High sulfate, acid and chloride ingress resistance
- High flexural tensile strength
- Low shrinkage
- Extremely low CO_2 emissions

In the BWWA project the high flexural tensile strength coupled with low shrinkage of EFC made it an ideal pavement concrete. In other projects, particular durability properties of acid, sulfate and chloride ingress resistance will offer high value to applications including sewer systems, marine structures and underground works through sulfate soils / ground waters. A cautionary note should be heeded that the term 'geopolymer' can apply to a wide range of alumino-silicate activated materials and their performance will vary depending on a range of factors, including:

- Source of alumino-silicate powder – type, reactivity, quality, etc.
- Alkaline activator chemicals
- Curing regime – ambient vs elevated temperature
- Total water and water:binder ratio for geopolymer concrete

Quality control during production and placement are extremely important in producing high quality geopolymer concrete, even more so than in the case of conventional concrete. Purpose made admixtures are a vital component in enabling EFC to have the necessary workability and slump retention at low water contents.

5. Conclusion

The proprietary geopolymer concrete discussed in this paper, EFC, is a fully commercial product as evidenced by the successful delivery of BWWA as well as a wide range of previous projects. The significant improvement in both structural performance, durability and carbon emission reduction of EFC compared to traditional cement based concrete should have good market attractiveness for a range of applications in Middle East countries. Heavy duty pavements and tunnel segments for transport systems as well as bored sewers would particularly benefit from these attributes.

BWWA is built on some 40,000 m^3 of geopolymer concrete making it the largest application of this new class of concrete in the world. The heavy duty pavements that comprise the turning node and apron are all made from EFC produced in commercial scale concrete batch plants that delivered a continuous supply to a slip form paving machine and returned an excellent production rate. EFC proved an ideal material for the construction method due to its high flexural tensile strength, low shrinkage and workability characteristics.

This successful application of geopolymer concrete at the full commercial scale should support future uptake of a truly novel, reliable and environmentally responsible technology.

8. References

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