Fibre reinforced geopolymer concrete products for underground infrastructure

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Synopsis: This paper presents the initial findings of a 3-year project to develop Fibre Reinforced Geopolymer Concrete (FRGC) products for underground infrastructure. The work is funded by the Victorian Science Agenda Investment Fund and a consortium of five organisations. By combining synthetic fibre reinforcement and geopolymer technology, it is possible to remove Portland cement and steel reinforcement from structural concrete to produce a new generation of structural concrete with potential benefits of improved durability and reduced embodied carbon content.

The work involves laboratory studies, long-term exposure tests, production of prototype tunnel segments and a life cycle assessment of embodied carbon for the products. The properties of the fresh and hardened FRGC have been investigated, including workability, strength and durability. The latter has included standard parameters, such as apparent volume of permeable voids (AVPV), as wells as chloride migration testing and exposure to acid and sulphate solutions.

Mix designs utilising different fibre dosages and geopolymer binders have been assessed, together with standard and accelerated curing regimes. The objective of the testing has been to provide information on the essential engineering characteristics of the material using a typical specification as the basis for compliance. Control mixes using Portland cement and 40kg/m^3 of steel fibres were also tested for comparison purposes.

The test results show the FRGC mixes outperform the Portland cement based control mixes in terms of strength, shrinkage and durability, and at the same time can reduce carbon emissions by approximately 70%.

Keywords: strength, chloride diffusion, synthetic fibres, flexural, geopolymer, carbon emissions.

1. Introduction

Concrete makes a substantial contribution to society, from its use in large infrastructure projects through to public buildings and social housing schemes. Use of concrete in construction is also a major contributor to greenhouse gases, reportedly generating more than 5% of worldwide carbon dioxide (CO_2) emissions, over three-quarters deriving from the Portland cement binder. Approximately half the CO_2 emissions from Portland cement are associated with energy used in the heating and grinding processes. The remaining emissions derive from the chemical de-carbonation of the limestone. The cement industry has made considerable improvements in energy efficiency and use of alternative fuel sources. However, if worldwide emissions targets are to be met, some radical changes are required to further reduce the CO_2 emissions derived from the use of concrete.

A study carried out on behalf of the UK Environment Agency has identified concrete using geopolymer binders as the most promising low carbon alternative to conventional concrete (1).

In reinforced concrete, the second highest source of carbon emissions is the steel reinforcement. Recent developments in the production and use of synthetic fibres position these materials as an alternative to steel reinforcing bar and steel fibres, with benefits of lower carbon emissions as well as the possibility of enhanced durability (2).

This paper presents the initial findings of a 3-year project to develop Fibre Reinforced Geopolymer Concrete (FRGC) precast products for underground infrastructure. By combining synthetic fibre reinforcement and geopolymer technology, it is possible to remove Portland cement and steel reinforcement from structural concrete to produce a new generation of structural concrete with potential benefits of improved durability and reduced embodied carbon content.

The work is funded by the Victoria's Science Agenda Investment Fund and a consortium of five organisations. The consortium members are able to provide all the facets required to successfully develop FRGC, from design and specification through to testing and production:

a) Design and specification of fibre reinforced concrete - Halcrow

b) Fibre technology – EPC

c) Geopolymer technology – Zeobond

d) Testing – University of Melbourne

e) Precast production - Humes.

The grant funded portion of the project is due to be completed in mid-2012.

2. Scope and objectives

The introduction of new products in the construction industry is controlled by the understandably conservative nature of the engineering profession and the need to meet existing industry specifications. Some of the issues relating to adoption of geopolymer and fibre technology are indicated in Table 1. In order to address these issues, this project pre-empts the normal approvals process by testing the FRGC products against the requirements of a typical performance specification. In addition, the project aims to develop guidance on structural and durability design and produce prototype products.

Table 1. Key issues to address in the adoption of FRGC technology.

Geopolymer	Synthetic fibres
Absence of structural design parameters	Absence of structural design parameters
Practical constraints (e.g. controlling workability, setting time and strength development)	Uncertainty over long-term performance (eg creep)
Uncertainty over long-term performance (eg permeability and diffusion properties and acid resistance)	Urgent need to identify appropriate test methods and limits to control properties but avoid unacceptably high rates of non-compliance

In order to ensure that industry concerns are properly addressed by the project, independent oversight is provided by a stakeholder group comprising representatives from academia, the engineering profession, the concrete industry and asset owners. The objective of the project is to achieve acceptance of FRGC products by the industry and commercialise the technology to generate economic and environmental benefits for the State of Victoria.

The focus of the project has been the production of precast tunnel segments because the use of fibre reinforced concrete is already the preferred material for casting segments, because there are established design methods (3), and because these are high-value products with a potential for good commercial return. The project involves planning, laboratory and field trials, testing and marketing. A simplified flow diagram is given in Figure 1, and the specification requirements are summarised in Table 2. The tests include Australian Standard strength and durability tests, such as cylinder strength and apparent volume of permeable voids, as well as European tests for water penetration and chloride migration.

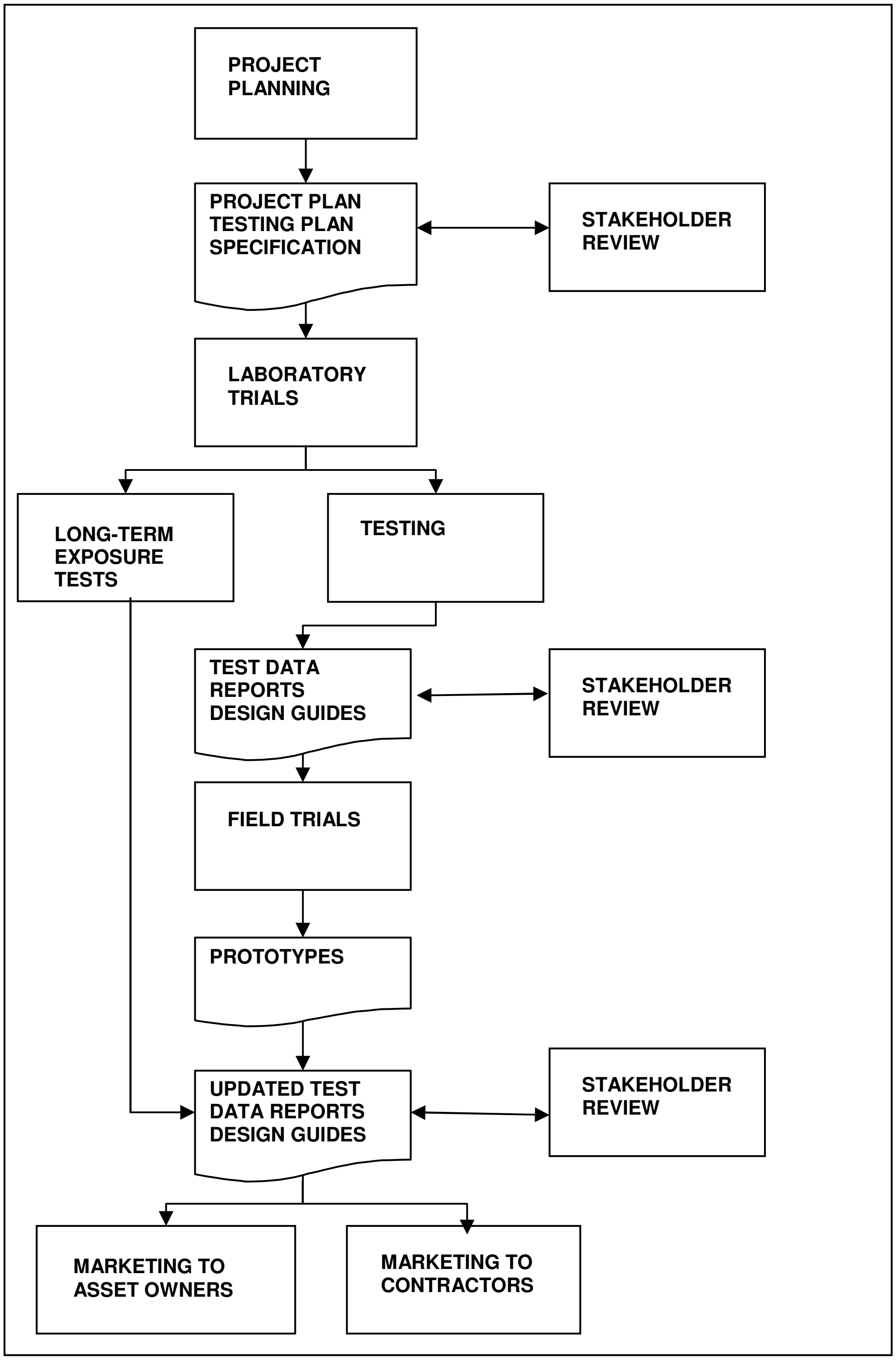

Figure 1. Flow diagram showing the stages and output of the project.

Table 2. Summary of performance specification requirements.

Parameter	Requirement	Test Method
STRENGTH		
28-day cylinder strength (MPa)	≥50	AS 1012.9
Cylinder strength for demoulding (MPa)	≥ 10	AS 1012.9
28-day tensile splitting strength (MPa)	≥4.2	AS 1012.10
28-day flexural strength (MPa)	≥4.6	ASTM C1609
28-day equivalent post-crack residual flexural strength $F_{e3.0}$ (MPa)	≥3.2	ASTM C1609
DURABILITY		
AVPV rodded (%)	13	AS 1012.8
28-day water penetration (mm) Mean of 2 tests	≤20	BS EN 12390-8
56-day chloride migration coefficient (m^2/s) 91-day chloride migration coefficient (m^2/s)	$\leq 4\times10^{-12}$ $\leq 2\times10^{-12}$	NTB 443
Sorptivity (mm)	≤8	RTA T362
56-day drying shrinkage (microstrain)	≤600	AS 1012.13

3. Discussion

3.1 Laboratory Trials

3.1.1 Initial and Main Trials

The initial laboratory trials assessed the workability characteristics of FRGC mixes using different fibre types, and doses of synthetic fibres from 8-12 kg/m^3. A Portland cement based concrete containing 8 kg/m^3 of synthetic fibres and geopolymer concrete with 40 kg/m^3 steel fibres provided two control mixes. The Portland cement control mix was based on an existing production mix, with 20% fly ash in the binder and a water/binder ratio of less than 0.4.

The synthetic fibres are manufactured from polyolefin and are 60mm long and 0.5-1mm in diameter with an embossed profile. The steel fibres are formed from cold drawn high tensile carbon steel and are 60 mm long and 0.75 mm in diameter with hooked ends.

Based on the initial trials a geopolymer mix with 8 kg/m^3 of synthetic fibre with was selected for further development in the main trials. This mix gave a 100mm target slump 60 minutes after mixing (allowing for permissible tolerances).

The main laboratory mixes were 0.35m^3 in size and were produced at a batching plant at Campbellfield in Victoria. A large number specimens were produced, including ASTM C1550 round panels for toughness. The key findings from the laboratory trials are discussed below.

3.1.2 Strength

The strength results are summarised in Table 3.

Standard and accelerated curing were used to determine the effect on the early strength gain for demoulding. For one production cycle every 24 hours the strength gain of the FRGC mix did not require any accelerated curing, although at lower ambient temperatures (<15℃) heat curing may be beneficial

Table 3. Summary of strength results for laboratory trials.

Parameter	Conventional concrete with synthetic fibres	Geopolymer concrete with steel fibres	Geopolymer concrete with synthetic fibres
28-day cylinder strength (MPa)	52.5	46.0	49.5
1-day cylinder strength for demoulding (MPa)*	25.0	24.0	25.0
28-day tensile splitting strength (MPa)*	4.8	4.0	3.4
28-day flexural strength (MPa)*	5.5	6.4	7.4
28-day equivalent post-crack residual flexural strength $F_{e3.0}$ (MPa)*	3.7	3.8	3.9

Note: * denotes accelerated-cured specimens

It can be observed that the compressive and tensile splitting strengths of the geopolymer concrete were lower than those of the Portland cement based control and the typical specification requirements. However, the flexural strength is of primary importance in the performance of tunnel segments, and the flexural strength and equivalent post-crack residual flexural strength value at 3.0mm deflection of the geopolymer with synthetic fibres slightly exceed those of both the Portland cement based control and the geopolymer mix with steel fibres. This is shown graphically in Figure 2.

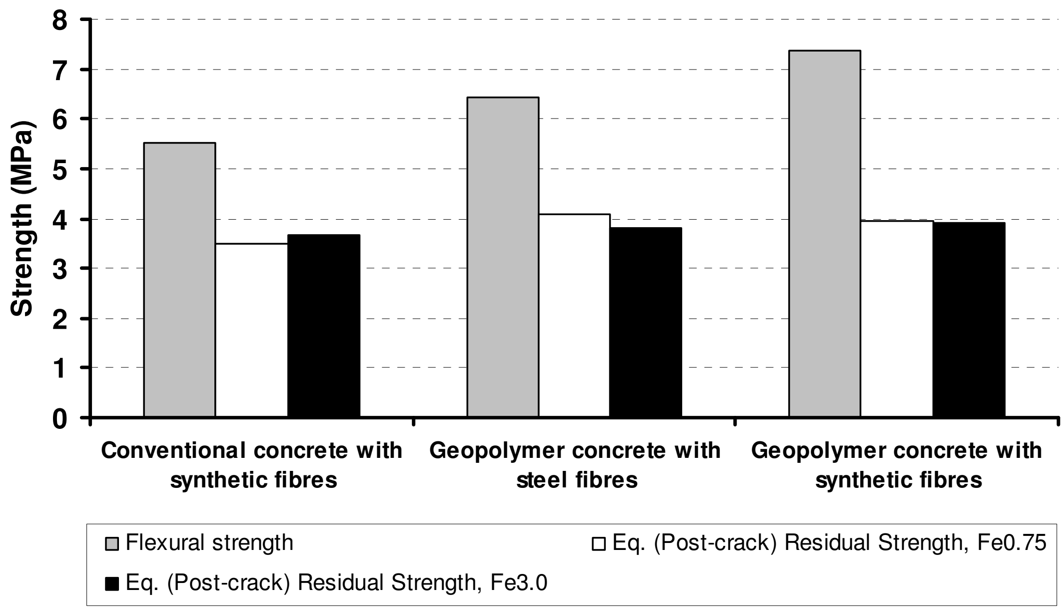

Figure 2. Flexural strength results.

Conventional concrete mixes with steel fibres have shown a tendency to embrittlement as the concrete strength increases due to fibre rupture rather than gradual pull-out (2). The good equivalent post-crack residual flexural strength values of the geopolymer mix with synthetic fibres is encouraging, and this value would not be expected to be reduced by long-term strength gain of the concrete in the same way as steel fibres because of the lower elastic modulus of synthetic fibres.

3.1.3 Durability

The durability test results are summarised in Table 4.

The Apparent Volume of Permeable Voids of the geopolymer mixes were higher than that of the Portland cement based control, and also exceeded the specified limit of 13%. In contrast, the chloride migration, sorptivity and dying shrinkage of the geopolymer mixes are significantly better than those of the Portland cement based control.

Table 4. Summary of durability test results for laboratory trials.

Parameter	Conventional concrete with synthetic fibres	Geopolymer concrete with steel fibres	Geopolymer concrete with synthetic fibres
AVPV rodded (%)	13	17	14
28-day water penetration (mm) Mean of 2 tests	<20mm	<20mm	<20mm
56-day chloride migration coefficient (m^2/s)	3.45	Not tested	1.08
91-day chloride migration coefficient (m^2/s)	1.87	Not tested	0.91
Sorptivity (mm)	9.0	6.1	6.2
56-day drying shrinkage (microstrain)	530	240	400

One potential reason for the above differences is the lack of a conventional capillary pore structure in geopolymer concrete. This means that parameters which are heavily influenced by capillary porosity and capillary transport of moisture could be beneficially influenced by using geopolymer concrete.

3.2 Field Trials

Field trials of up to $2.5m^3$ size were undertaken at the Hume precast plant in Echuca, Victoria. Tunnel segment moulds were already available at this plant from a recently completed project. The objective of the field trials was to produce prototype segments, as well as larger specimens for further testing (Section 3.4). A conventional concrete control mix with steel fibres was also included.

The field trials used a FRGC with 8 kg/m^3 of synthetic fibres and Portland cement based concrete with 40 kg/m^3 of steel fibres (with and without the addition of 1 kg/m^3 of synthetic microfibers for improved fire spalling resistance).

Four rectangular bolted segments (each approximately $0.4m^3$ and 0.8 tonnes in weight) and four smaller tapered key segments (each approximately $0.1m^3$ and 0.2 tonnes in weight) were produced from the FRGC mix. The compressive strength development of the FRGC mix was similar to the control mix and met the performance specification. The segments were successfully stripped to allow a single casting cycle every 24 hours at an ambient temperature at casting of 22°C.

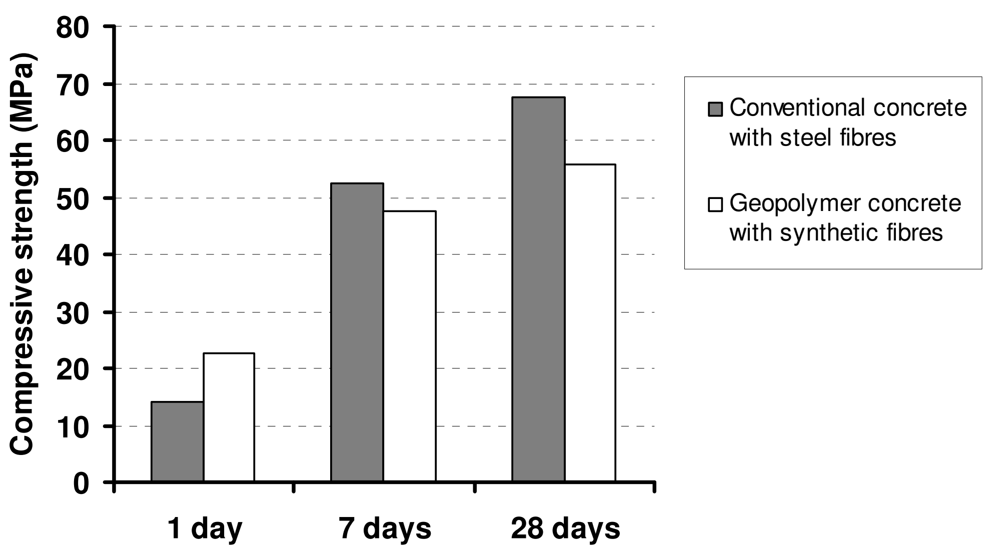

Figure 3. Compressive strength development, field trials.

Figure 4 shows the typical condition of the demoulded segments and a sawn cross-section. The cross-section shows good uniformity and compaction, although care has to be taken to evenly disperse the fibres during mixing and to cure the concrete adequately.

Figure 4. Prototype tunnel segments and sawn cross-section

3.3 Embodied carbon

Reducing the carbon emissions of concrete is a key driver for the project. In order to assess the impact of using FRGC compared to conventional concrete, two scenarios were considered:

a) Casting FRGC or conventional concrete segments at Echuca, Victoria for delivery by road 220km to a project site in Melbourne; and

b) Casting FRGC segments at Echuca, Victoria for delivery by road 3310km to a project site in Perth, Western Australia.

The first case represents a realistic supply situation for precast segments, whereas the second case is intended to represent a maximum transport distance in order to assess the influence of haulage on carbon emissions.

The carbon emissions were calculated using published values for converting energy and fuel to CO_2 (4). The calculations assumed that the strength and durability performance of the FRGC and conventional concrete mixes are similar. The FRGC concrete has 8 kg/m^3 of synthetic fibres and conventional concrete assumes 40 kg/m^3 of steel reinforcing bar or steel fibres.

The calculations allow for the embodied carbon in the constituent materials (including obtaining and processing the raw materials), transportation to the precast plant, production of the segments and their transportation to the project site. The calculations do not assess the effects of carbonation, or the carbon emission associated with demolition and reuse of tunnel segments.

Figure 5 shows the comparison between FRGC and conventional concrete. The CO_2 emissions of segments produced at Echuca using FRGC are 34% and 60% of the values for conventional concrete segments delivered to sites in Melbourne and Perth, representing a reduction of up to approximately 70% in emissions. The influence of binder and reinforcement upon carbon emissions predominates over transportation. The CO_2 emissions for FRGC segments transported to Perth are slightly less than those associated with conventional concrete segments delivered to Melbourne, indicating that binder and reinforcement type predominate over transportation.

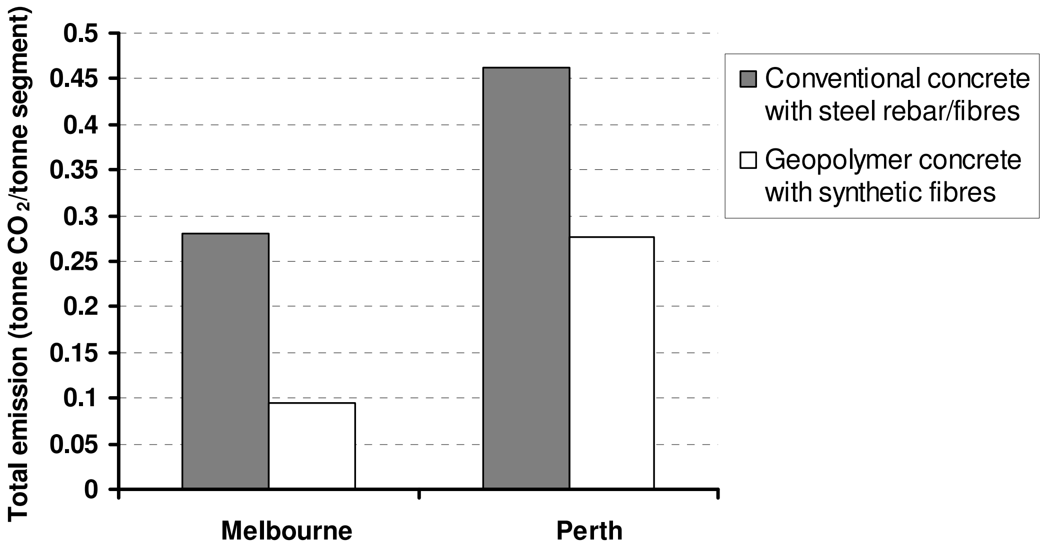

Figure 5. Carbon emissions associated with FRGC and conventional concrete segments produced in Echuca and delivered to sites in Melbourne and Perth.

3.4 Further work

The following further work is planned:

- Exposure tests
- Creep tests
- Fire resistance tests
- Project trials.

FRGC samples are being exposed to abrasion and acid sulphate conditions to simulate a sewer environment. These exposure conditions, using a sulphuric acid solution with a pH of 2, are intended to last at least 2 years. The interim results at 140 days are shown below in Figure 6. These very early results indicate a slightly lower depth of attack in FRGC concrete compared to the Portland cement based control. The steel fibres produce a slightly lower depth of attack, which may reflect enhanced abrasion resistance compared to synthetic fibres. These trends need to be verified in the long-term exposure data.

Creep tests will be undertaken using cracked ASTM C1550 round panels to establish the difference in performance between a Portland cement based control with steel fibres and FRGC using synthetic fibres. Previous results of such tests using Portland cement based concrete have shown comparable performance of steel fibre and synthetic fibre reinforced concrete, dependent on the loading (2).

Fire testing to assess spalling resistance is a common requirement for the lining of transportation tunnels. Tunnel segments from the field trials are being fire tested at Victoria University to simulate a hydrocarbon fire.

Following successful completion of the laboratory and field trials, opportunities are being sought to use FRGC in project trials. This is an important step to secure early application of the technology to benefit the construction industry and wider society.

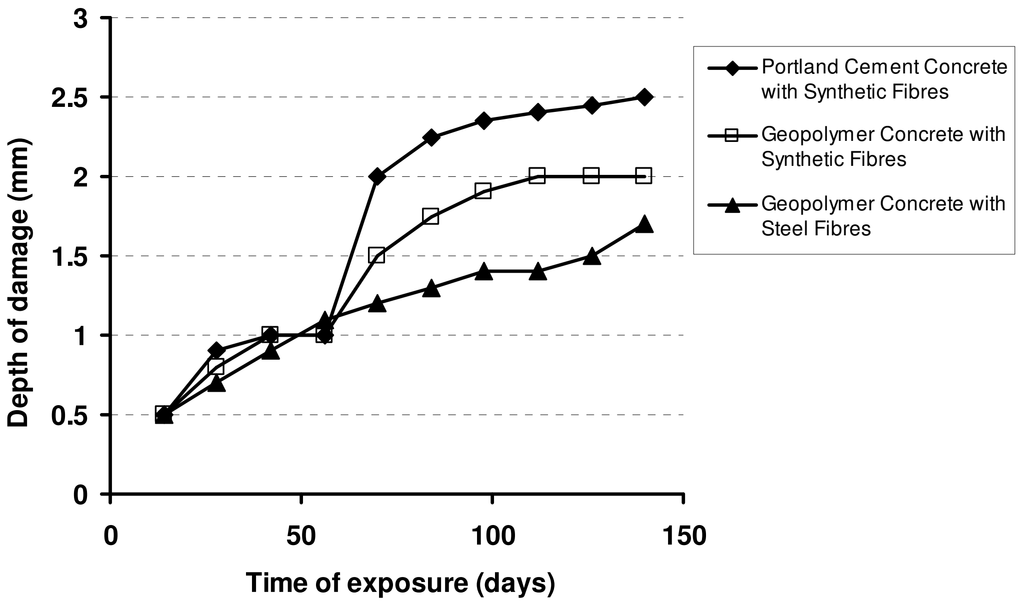

Figure 6. Depth of damage under abrasion and acid sulphate conditions.

4. Conclusions

Use of concrete in construction contributes over 5% of worldwide carbon dioxide emissions. If emission targets are to be met some radical changes need to be made to reduce this value. The use of geopolymer binder and synthetic fibres in place of Portland cement and steel reinforcement to produce fibre reinforced geopolymer concrete (FRGC) provides a lower carbon alternative to conventional concrete.

A 3-year study involving is being undertaken to develop and commercialise FRGC products for use in underground infrastructure. The work involves laboratory studies, long-term exposure tests, production of prototype tunnel segments and a life cycle assessment of embodied carbon for the products. The properties of the fresh and hardened FRGC have been investigated, including workability, strength and durability. The latter has included standard parameters, such as AVPV, as wells as chloride migration testing and exposure to acid and sulphate solutions.

Mix designs utilising different fibre dosages and geopolymer binders have been assessed, together with standard and accelerated curing regimes. The objective of the testing has been to provide information on the essential engineering characteristics of the material using a typical specification as the basis for compliance. Control mixes using Portland cement and 40 kg/m^3 of steel fibres were also tested for comparison purposes.

The work indicates that combining geopolymer binder and 8 kg/m^3 of synthetic fibres produces concrete with acceptable workability. The hardened properties are encouraging when assessed against a typical specification for tunnel segments.

The test results show that FRGC can outperform the Portland cement based control in respect of flexural strength, shrinkage and durability and at the same time can reduce carbon emissions by approximately 70%.

Field trials and production of prototype segments have been successfully completed. Further long-term testing is continuing and opportunities are being sought for project trials.

5. Acknowledgement

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