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E-Crete™ Engineering Summary

This document describes the specific technical aspects, engineering properties and the Life Cycle Analysis of E-Crete™.

Australia has a wealth of expertise in the research and development of geopolymer technology, with a track record of excellence principally located in Victoria. Much of the publically available information in the properties of geopolymers emanates from the Geopolymer and Mineral Processing Group headed by Zeobond founder Prof. Jannie van Deventer.

This document is focused on conveying the principle properties of E-Crete to enable engineers, designers and architects to specify E-Crete in projects. In particular, this document focuses on the mechanical properties and strength development profiles relative to existing Ordinary Portland Cement (OPC) based concrete products and standards. The document draws together information validating the technology from a broad selection of publically available sources.

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History of Zeobond

Zeobond Pty Ltd was founded by Professor Jannie S.J. van Deventer (Former Dean of Engineering Faculty, The University of Melbourne), a world leading expert in geopolymer technology.

After over a decade of academic research at the top level, Zeobond Pty Ltd was formed to take the technology of geopolymers from promise to reality, and provide a model of energy efficient concrete production in Australia and throughout the world.

After two years of intense research, development and construction, Zeobond began commercial supply of our concrete product, E-Crete™.

Demonstration Plant

Our demonstration plant shown below in Melbourne is located in Campbellfield, 25 km to the north of the CBD. As a demonstration facility this plant is capable of producing between 150-200 m^3 of concrete per day, which is very small by comparison with large metropolitan concrete plants that can produce this volume every hour. This limits our ability to tackle large projects that demand mass volumes of concrete, but allows us to provide concrete into smaller projects from footpaths to house slabs and pre-cast concrete panels. The small scale of the demonstration facility allows Zeobond to complete both small commercial projects, but also continue to develop and lead the world in geopolymer concrete technology*. The foundations for this plant visible in the photo below are made from E-Crete™.*

Specific Testing and Verification Requirements

Like most construction industry based products applications where public liability and risk profiles are critical, use of E-Crete is required to meet many standard specified properties. Before moving from the laboratory to the field, verification of the technical qualities of geopolymer concrete was required. When considering that the material standards have generally been developed with the use of Ordinary Portland Cement expressly in mind, several specific challenges are imposed.

The following items were considered critical with respect to verification and testing before moving into full commercial production:

a) Compressive Strength (28 Days)
b) Drying Shrinkage (up to 56 days)
c) Strength Development Profile
d) Flexural Strength
e) Tensile Splitting Strength
f) Poisson's Ratio
g) Bond Strength -Rebar Pullout
h) Creep

Items a) and b) are absolute values upon which the material is generally classified. i.e. N25 concrete implies 25 MPa compressive strength at 28 days, and nominally less than 1000 microstrain at 56 Days.

Items c) to h) are non-prescribed values or ranges in terms of Australian and international standards, but contribute substantially to the application of concrete in usage.

Verification and Testing from other Sources

In the past decade several reputable bodies have investigated geopolymer concrete properties. Material available in the public domain detailing investigations into the engineering properties of geopolymer concrete, specifically addressing many of the relevant Australian Standards is presented below.

Sofi, M. M.Eng. Thesis, University of Melbourne 2003.

Six IPC mixes were studied in the Masters thesis of Massoud Sofi, completed within the Department of Civil and Environmental Engineering at the University of Melbourne, co-supervised by Prof. Jannie van Deventer. The mix proportioning and other mix-design variables are presented in Table 1. Three different sources of Class-F Australian fly ash and Ground Granulated Blast Furnace Slag (GGBFS) were used in this work, being Port Augusta (South Australia), Gladstone (Queenslad) and Tarong (Queensland). All of these fly ashes are widely utilised in the Australian concrete industry as SCMs.

Table 1 Compositions of geopolymer concrete mixes used in the work of Sofi (2003).

	Mix					
	1	2	3	4	5	6
Component[a]						
Na_2CO_3/SiO_2	0.681	0.681	0.681	0.681	0.217	0.000
Na_2O/SiO_2	1.617	1.617	1.617	1.617	0.702	0.970
K_2O/SiO_2	–	–	–	–	0.003	–
Component[b]						
Fly ash type	PA	G	T	PA	PA	PA
H_2O/fly ash	1.280	1.500	1.520	1.067	0.300	0.208
Slag	0.146	0.143	0.143	0.097	0.069	–
Coarse aggregates	–	–	–	0.336	–	–
Sand	0.635	0.626	0.625	0.430	0.763	0.667
Fly ash	0.066	0.065	0.065	0.044	0.092	0.222

The following sub-sections detail the main findings of Sofi (2003) with respect to the engineering properties of geopolymer concrete.

Bond Strength – Rebar Pullout

Figure 1 shows bond strength measurements from rebar pullout tests relative to the level recommended in AS 3600, from Sofi (2003). Full discussion is also provided in Sofi *et al.* (2007). It is clear from Figure 1 is that geopolymer concrete exceeds the performance design requirements in terms of bonding to rebar.

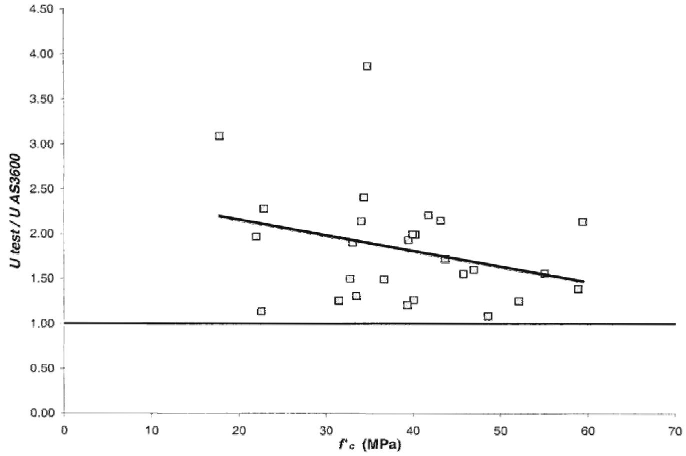


Figure 1 Comparison between the bond strength between geopolymer concrete and rebar with the values required in AS 3600, from Sofi (2003).

Splitting Tensile Strength

Figure 2 shows the splitting tensile strength of geopolymer concrete. Geopolymer concrete generally exceeds AS 3600 design expectations with confidence.

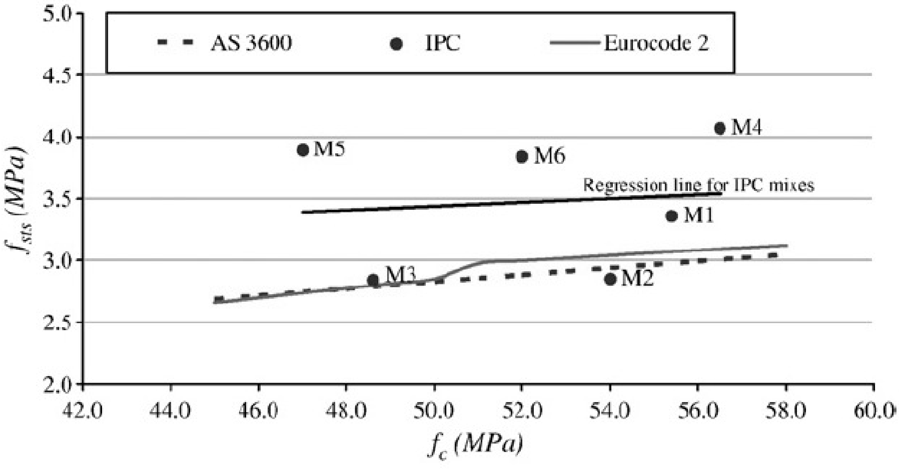


Figure 2 Splitting Tensile Strength of geopolymer as a function of compressive strength, from Sofi *et al.* (2007).

Flexural Strength

Figure 3 shows the flexural strength of geopolymer concrete mixes normalized to their compressive strengths with reference to the model equation presented in AS 3600. For design calculations, it is usual to estimate the tensile strength from the compressive strength for OPC-based concretes. The flexural strengths of geopolymer concretes are generally higher than the standard model line for OPC based concrete.

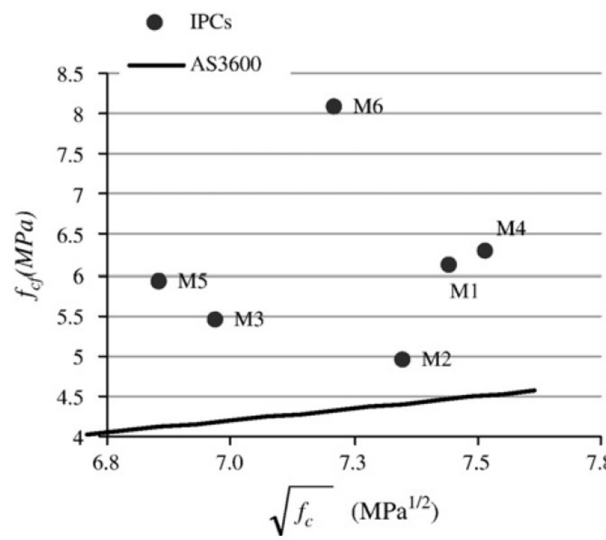


Figure 3 Comparison of geopolymer concrete flexural strength with the model reported by AS 3600, from Sofi *et al*. (2007).

Modulus of Elasticity

Figure 4 shows the reported modulus of elasticity of geopolymer concrete mixes from Sofi *et al.* (2007). In general, the values are below that of the model presented as part of AS 3600. This is somewhat expected in terms of the mix designs used in Sofi *et al.* (2007), which did not utilise large proportions of large aggregates. As the elastic modulus of concrete is determined largely by the properties of the aggregate, which has a higher modulus than the binder (also the case for OPC concrete). Therefore, utilising smaller proportions of aggregate necessarily reduces the elastic modulus.

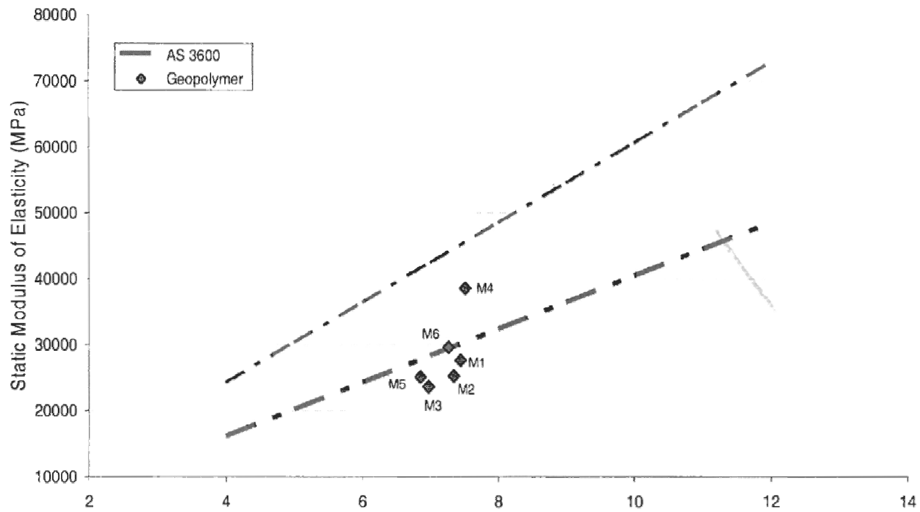


Figure 4 Comparison of modulus of elasticity of geopolymer concrete mixes with the model reported by AS 3600 for OPC-based concrete, from Sofi (2003).

Poisson's Ratio

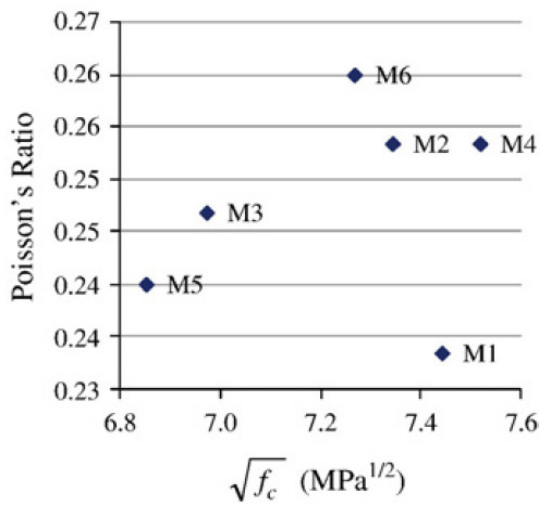


Figure 5 Poisson's ratio of the geopolymer concrete mixes investigated in Sofi (2003).

The experimental values obtained for Poisson's ratio for the geopolymer concrete mixes show an overall increase with the increase of compressive strength. It can be observed from Figure 5 that the values of Poisson's ratio for all of the geopolymer concrete mixes fall between 0.23 and 0.26, which is slightly higher than the values assigned for normal strength OPC-based concrete (0.11–0.21). For high strength concretes the value of Poisson's ratio ranges between 0.2 and 0.25 (Sofi *et al.* (2007)).

Investigations from Curtin University of Technology

The following details are taken from the research reports from Curtin University of Technology, who have a team of researchers working on geopolymer technology as part of the Cooperative Research Centre for Sustainable Resource Processing (CRC-SRP).

Modulus of Elasticity and Poisson's Ratio

Tests for Elastic Modulus and Poisson's Ratio were carried out in accordance with the relevant Australian Standards, the results of which are presented in Table 2.

Table 2 Compressive strength, Modulus of Elasticity and Poisson's Ratio of geopolymer concrete formulations from Hardjito and Rangan (2005).

Compressive Strength (MPa)	Age of concrete (days)	Modulus of Elasticity (GPa)	Poisson's Ratio
89	90	30.8	0.16
68	90	27.3	0.12
55	90	26.1	0.14
44	90	23.0	0.13

For OPC concrete, the Australian Standard AS 3600 recommends the following expression to calculate the value of the modulus of elasticity within an error of plus or minus 20 %:

$$E_c = \rho^{1.5} \times (0.024(f_{cm} + 0.12)^{0.5} \text{ (MPa)} \quad \text{(Equation 1)}$$

where ρ is the density of concrete in kg/m^3, and f_{cm} is the mean compressive strength in MPa.

The average density of the geopolymer concretes in the work of Hardjito and Rangan (2005) was 2350 kg/m^3. Table 3 shows the comparison between the measured value of modulus of elasticity of IPC with the values determined by Equation 1.

Table 3 Comparison of Elastic Modulus (Measured) with Elastic Modulus (model) for AS 3600, from Hardjito and Rangan (2005)

Compressive Strength (MPa)	Modulus of Elasticity (measured) (GPa)	Modulus of Elasticity (Equation 1) (GPa)
89	30.8	39.5 □7.9
68	27.3	36.2 □7.2
55	26.1	33.9 □6.8
44	23.0	31.8 □6.4

It can be seen from the above table that the values of Young's modulus are consistent with that of Sofi (2003), but that they are also lower than the recommended values for concrete according to AS 3600. In the instance of AS 3600, it should be noted that the incorporation of density (ρ) into calculations of Young's Modulus contribute to this problem, as geopolymer concrete made from fly ash and slag is necessarily lower in density which may contribute to differences. Nonetheless, it is clear that geopolymer concrete does have a lower Young's modulus, which should have no adverse implications in terms of performance, but must be accounted for in structural design.

The Poisson's ratio of geopolymer concrete falls between 0.12 and 0.16 (Table 2). For Portland cement concrete, the Poisson's ratio is usually between 0.11 and 0.21, with the most common value taken as 0.15 or 0.15 for high strength concrete and 0.22 for low strength concrete. These ranges are similar to those measured for geopolymer concrete.

Indirect Tensile Strength

Hardjito and Rangan (2005) measured the tensile strength of geopolymer conrete was measured by performing the cylinder splitting test in accordance with the relevant Australian Standard, with the results presented in Table 4.

Standards Australia (2001) recommends the following design expression to determine the characteristic principal tensile strength of OPC concrete:

$$f'_{ct} = 0.4(f_{cm})^{0.5} \text{ (MPa)} \quad \text{(Equation 2)}$$

The calculated values of Tensile Strength, f'_{ct}, using Equation 2 is also given in Table 4.

Table 4 Comparison of Indirect Tensile Strength from cylinder splitting with model values determined from the relevant Australian Standard, from Hardjito and Rangan (2005).

Mean Compressive Strength (MPa)	Mean Indirect Tensile Strength (MPa)	Characteristic principal tensile strength Equation 2 (MPa)
89	7.43	3.77
68	5.52	3.30
55	5.45	3.00
44	4.43	2.65

Table 4 shows that the indirect tensile strength of geopolymer concretes are greater than the values recommended by the relevant Australian Standards for OPC concrete.

Creep and Drying Shrinkage

The test results from creep and drying shrinkage from and Wallah and Rangan (2006) generally indicate that geopolymer concrete experiences less creep than Portland cement concrete. The specific creep of 60 MPa Portland cement concrete after one year is generally about 50 to 60 microstrain/MPa, while the value reported by Wallah and Rangan after six months was about 30 to 40 microstrain/MPa for 80 MPa concrete and about 20 to 30 microstrain/MPa for 90 MPa concrete (Wallah and Rangan (2006)).

The drying shrinkage results of Wallah and Rangan (2006) are low compared with the nominal value of less than 1000 microstrain required in the relevant Australian Standard.

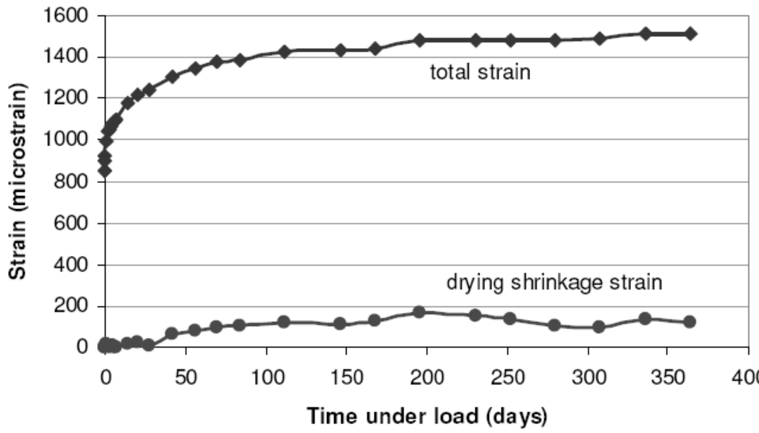


Figure 6 Total strain and drying shrinkage of a geopolymer concrete mix from Wallah and Rangan (2006).

Performance of E-crete™

Compressive Strength and Strength Development

Figure 7 presents some typical strength development profiles of E-Crete™ mixes taken from 200 mm x 100 mm cylinder samples tested according to the relevant Australian Standard. In addition an OPC concrete mix with strength development profile fitting the N32 standard is presented for comparison.

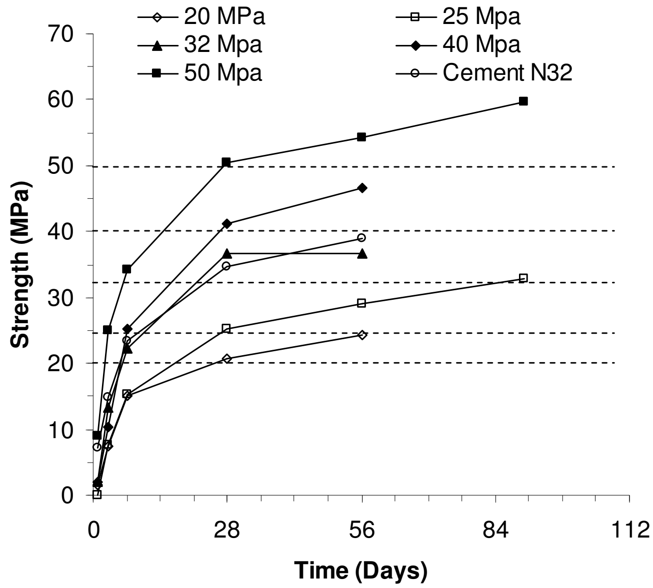


Figure 7 Typical compressive strength development profiles for E-Crete™ reaching nominal 20, 25, 32, 40, and 50 MPa.

Drying Shrinkage

Figure 8 shows a comparison of OPC concrete drying shrinkage and that of E-Crete™. It can be observed that E-Crete™ has a nominally lower drying shrinkage than OPC.

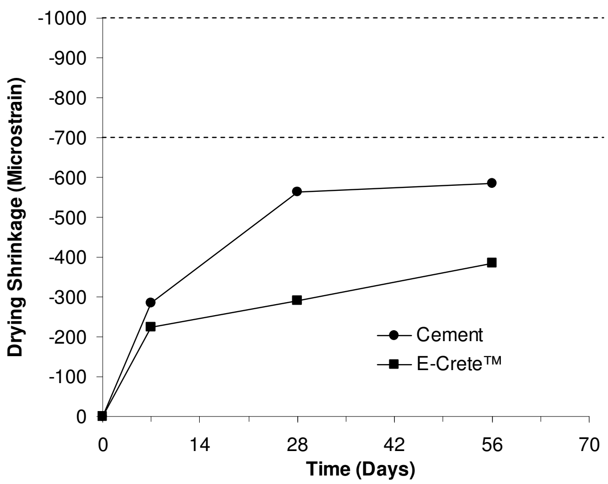


Figure 8 Comparison of typical drying shrinkage of E-Crete™ and OPC concrete.

The values stipulated in the designation of normal class concrete in the Australian Standard for maximum drying shrinkage (-1000 microstrain) and nominal drying shrinkage (-700 microstrain) are indicated on Figure 8 with dashed lines.

Flexural Strength

Figure 9 shows typical flexural strength measurements of E-Crete™. These values are consistent with those of Sofi (2003) and Wallah and Rangan (2006), and well in excess of the recommended design criteria in the relevant Australian Standard.

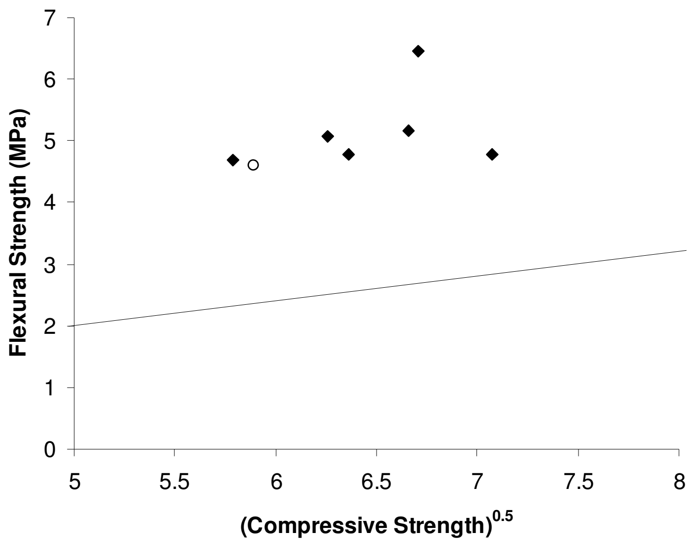
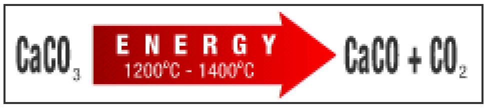


Figure 9 Flexural Strength of E-Crete™

Life Cycle Analysis

According to the World Business Council for Sustainable Development (WBCSD), "Concrete is the most widely used material on earth apart from water, with nearly three tons used annually for each man, woman, and child." Cement is made by burning fossil fuels when the limestone and clay are heated to over 1300°C and $CO2$ is liberated from the decomposed limestone according to the following reaction:



The energy intensive calcination step is a necessary key to cement production. Therefore, the focus of reductions in CO2 emissions during cement manufacturing is on energy use. However, energy efficiency is ultimately limited by two factors: (1) the high temperature needed to drive the calcination of limestone, and (2) 60% of CO2 produced in cement manufacture arises from the calcination reaction itself.

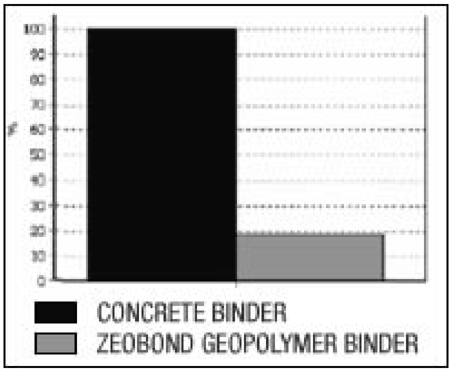
The manufacture of cement produces about 0.9 kilograms of CO2 for every kilogram of cement. Around 5 – 8% of global CO2 emissions result from cement manufacture, making this product one of the more polluting activities undertaken by mankind.

So the question is, can we do this better?

One of the primary advantages of geopolymers over traditional cements from an environmental perspective is largely associated with the much lower CO2 emissions from geopolymer manufacture compared to OPC production. This is mainly due to the absence of the high-temperature calcination step in geopolymer synthesis.

While the activators used in geopolymers do reintroduce some Greenhouse cost, the overall CO2 saving due to widespread geopolymer utilisation is in the order of 80-90% when compared with Portland cement. Zeobond Pty Ltd had the 'green credentials' of E-Crete put to the test by independent experts who conducted a Life Cycle Analysis and found that E-Crete does indeed produce 80% less CO2 than OPC.

COMPARISON OF GEOPOLYMER CONCRETE AND OPC BINDER SYSTEM GREENHOUSE EMISSIONS



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