DURABILITY OF GEOPOLYMER CONCRETE BOX CULVERTS – A GREEN ALTERNATIVE

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Abstract

Geopolymer is a material resulting from the reaction of a source material that is rich in silica and alumina with alkaline solution. This material has been studied extensively over the past several decades and shows promise as a greener alternative to ordinary Portland cement concrete. It has been found that geopolymer has good engineering properties with a reduced carbon footprint resulting from the zero-cement content. The research recently undertaken studied the feasibility of geopolymer concrete for pre-cast products (box culverts of size 1200x600x1200mm), and their durability. The research was undertaken by the Main Roads Western Australia in cooperation with a local pre-cast industry and Curtin University of Technology. It was found that durability parameters depend on permeability of concrete matrix. Tests performed to measure absorption, void, and permeability coefficient have shown that geopolymer concrete has the potential to be a durable concrete [2], [14].

1. INTRODUCTION

The need for reducing the environmental impact of concrete has been recognised by the concrete industry. The American Concrete Institute document entitled " Vision 2030: A vision for US Concrete Industry" states that "concrete technologists are faced with the challenge of leading future development in a way that projects environmental quality while projecting concrete as construction material of choice." Another issue that relates to concrete containing ordinary Portland cement is durability. Many structures in urban and costal environments start to deteriorate in 20-30 years when their design life is 50 years or more. Researchers have examined the durability of ancient structures and found that concrete structures built more than two to five thousand years ago remained intact. It has been observed that the concrete used in these ancient structures is alkali–activated alumino-silicate binders or geopolymer concrete [1].

The production of Portland cement is not only energy intensive but also releases into the atmosphere approximately one tonne of carbon dioxide (CO_2) for every tonne of Portland cement produced [5]. Currently, partial replacement of cement by either slag or pozzolanic material up to 5% - 25% is in practice. Many efforts are being made to use other binders to make concrete. In this regard, fly ash-based geopolymer concrete shows considerable promise. In geopolymer concrete, the Portland cement is totally replaced by fly ash; fly ash reacts with an alkaline liquid comprising a mixture of sodium silicate solution and sodium hydroxide solution to form the binder. Fly ash based geopolymer concrete reduces CO_2 emissions associated with the production of Portland cement significantly [6]. The production of one tonne of geopolymer cement generates 0.18 tonnes of CO_2, from the combustion of carbon-fuel, compared with one tonne of CO_2 from Portland cement [4], [5]. One tonne of fly ash can be utilised to produce about 3 cubic metres of high quality geopolymer concrete [6].

This paper presents the preliminary findings of the research work undertaken recently using Reinforced Low Calcium Fly Ash based Geopolymer Concrete (RLCFGC) in the manufacturing of box culverts. The research involved the study of strength and durability behaviour of RLCFGC box culverts, and the development of production and construction control requirements for the pre-cast industries to manufacture and supply the products to the specifications[2],[14].

2. MATERIALS

The two main constituents of geopolymer binders are low-calcium (Class F) fly Ash and the alkaline liquid as given below.

2.1 Fly Ash

The fly ash used in the study was sourced from Collie Power Station in Western Australia. The chemical composition of fly ash as determined by X-ray Fluorescence (XRF) (mass %) is summarised in Table 1 [7].

Table1: Chemical Composition of Fly Ash

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	ZrO_2	Cr	MnO	LOI
Mass %	48.00	29.00	12.70	1.78	0.39	0.55	1.67	0.89	1.69	0.50	0.06	0.016	0.06	1.61

2.2 Alkaline Liquid

The alkaline liquid used was from a combination of sodium silicate solution and sodium hydroxide solution. The sodium silicate solution (Grade A53) comprised 14.7% of Na_2O, 29.4% of SiO_2, and 55.9% of water by mass. The sodium hydroxide solution was prepared by mixing 98% pure flakes in water. Both the solutions were mixed together at least 24 hours before use [7].

2.3 Super plasticiser

To improve the workability of the fresh geopolymer concrete, a high range water reducing (naphthalene sulphonate- based) super plasticiser, supplied by BASF Construction Chemical Company Australia was used in the mixtures at the rate 1.5% of fly ash [7].

2.4 Aggregates

Aggregates currently used by the local concrete industry in Western Australia, supplied by BGC Concrete and Asphalt were used. Both coarse and fine aggregates were wet. The moisture contents of the aggregates over and above the saturated-surface-dry (SSD) condition were determined by tests. The aggregates comprised 30% of 14 mm, 38% of 10 mm, and 32% of fine sand [2], [7].

3. MIXTURE PROPORTIONS

Six geopolymer concrete mixtures, designated as Mix 1 to 6, were used. The details of these mixtures are given in Tables 2 &3.

Table 2: Geopolymer Concrete Mixture Proportions

Materials		Mass (kg/m^3)					
		Mix 1	Mix2	Mix3	Mix4	Mix5	Mix6
Coarse Aggregates							
	14mm	554	554	554	554	554	554
	10mm	702	702	702	702	702	702
Fine Sand		591	591	591	591	591	591
Fly Ash (Low Calcium ASTM Class F)		409	409	409	409	409	409
Sodium Silicate Solution (SiO_2/Na_2O =2)		102	102	102	102	102	102
Sodium Hydroxide Solution		41	41	41	41	41	41
Super Plasticiser (SP)		6	6	6	6	6	6
Extra water in aggregates		22.5	22.5	35	34	19	33

Table 3: Details of Geopolymer Concrete Mixtures

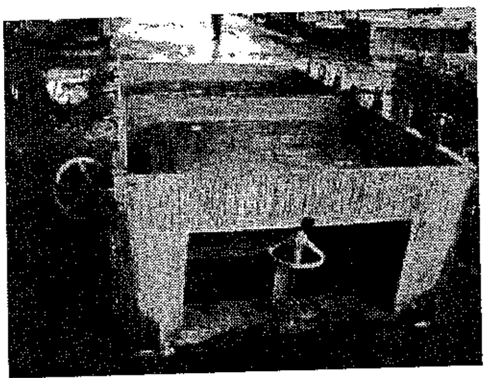
Mix	Water in kg/m^3				Geopolymer Solids in kg/m^3						
	Water in NaOH	Water in Sodium Silicate	Extra water in aggre-gates	Total Water	Fly-Ash	Solid NaOH	Solid Sodium silicate	Total Solids	Water-to-geopoly-mer solid Ratio	SteamCur-ing Temp in °C	90 day mean compres-sive strength (MPa)
Mix1	30.00	57.00	22.50	109.50	409	11.00	45	465	0.24	90	39
Mix2	30.00	57.00	22.50	109.50	409	13.00	45	467	0.23	90	58
Mix3	30.00	57.00	35.00	122.00	409	13.00	45	467	0.26	80	30
Mix4	27.00	57.00	34.00	130.43	409	14.00	45	468	0.28	60	25
Mix5	27.00	57.00	19.00	103.00	409	14.00	45	468	0.22	90	57
Mix6	27.00	57.00	33.00	129.43	409	14.00	45	468	0.28	90	35

4. MANUFACTURE OF TEST SPECIMENS

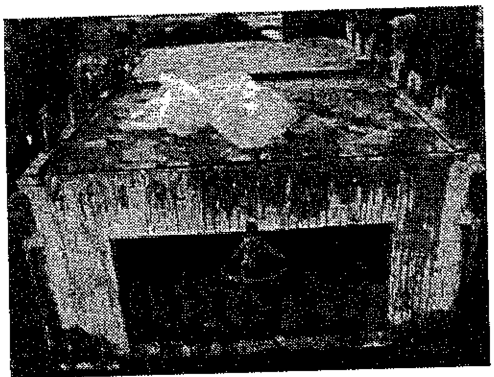
Reinforced geopolymer concrete box culverts of 1200 mm (length) x600 mm (depth) x1200 mm (width), and 100 mmx200 mm cylinders were manufactured in Rocla's precast concrete plant located in Perth, Western Australia. The dry materials were mixed for about 3 minutes. The liquid component of the mixture was then added, and the mixing continued for another 4 minutes. The geopolymer concrete was transferred into a kibble from where it was then cast into the culvert moulds (one mould for two box culverts) and cylinder moulds as shown in Figure 1. The culverts were compacted on a vibrating table and using a hand -held vibrator.

The cylinders were cast in 2 layers with each layer compacted on a vibrating table for 15 seconds. The slump of every batch of fresh concrete was also measured in order to observe the consistency of the mixtures.

After casting, the cylinders were covered with plastic bags and placed under the culvert moulds. A plastic cover was placed over the culvert mould and the steam tube was inserted inside the cover. The culverts and the cylinders were steam-cured for 24 hours. The steam-curing was carried out in stages. Initially, the specimens were steam-cured for about 4 hours; three cylinders were then tested in compression to estimate the strength. It was considered that the strength at that stage was adequate for the specimens to be released from the moulds. The culverts and the remaining cylinders were however released from the moulds when further steam-curing for another 20 hours was completed. The operation of the Rocla plant was such that the 20 hours of steam-curing has to be split into two parts. That is, the steam-curing was shut down at 11 PM and restarted at 6 AM next day. In all, the total time taken for steam-curing was 24 hours. Figure 1 shows the manufacture of test specimens [2], [14].


Box culvert mould


Kibble


Steamed-curing

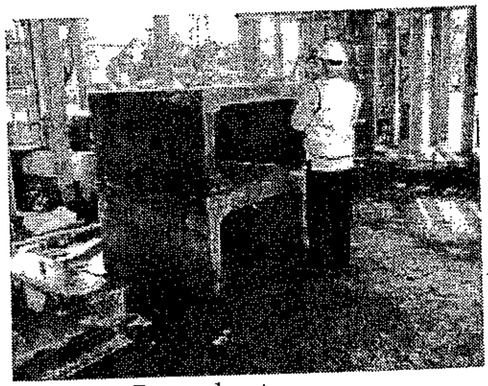

Box culverts

Figure 1 - Manufacture of Test Culverts and Cylinders

5. EXPERIMENTAL RESULTS

5.1 Compressive Strength

From each of the six mixtures (Tables 2&3) of fly ash-based geopolymer concrete made in this study, three 100 x 200 mm cylinders were tested for compressive strength at different ages. The test results shown in Figure 2 confirm past research [9] that the strength-gain of fly ash-based geopolymer concrete after 24 hours of steam-curing is only marginal.

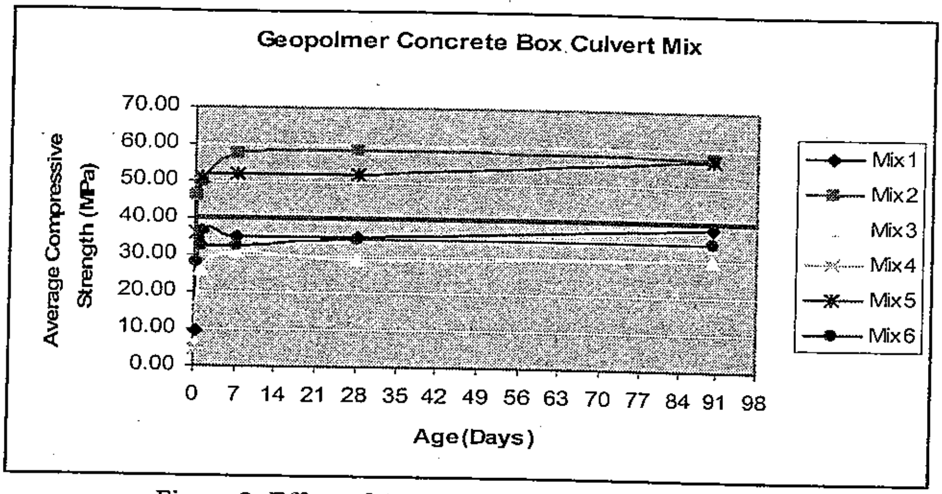


Figure 2: Effect of Age on Compressive Strength

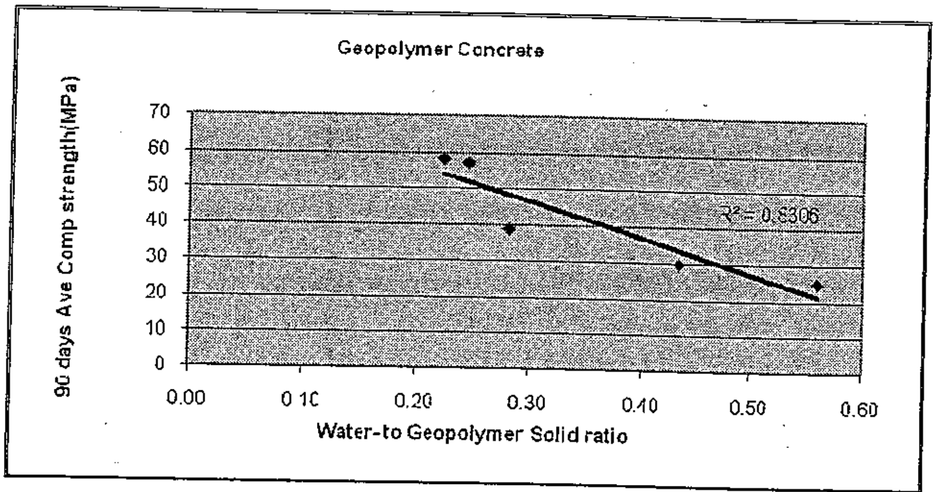


Figure 3: Effect of Water/Geopolymer Solids Ratio on Compressive Strength.

Figure 3 shows the effect of water-to-geopolymer solids ratio by mass (Table 3) on the compressive strength of fly ash-based geopolymer concrete. In this, the mass of water is the mass of water contained in both the alkaline solutions plus the mass of extra water contained in the aggregates. The mass of geopolymer solids is the sum of mass of fly ash, and the mass of solids contained in both the alkaline solutions. The test trend shown in Figure 3 confirms past research [7]

5.2 Box Culvert Load Bearing Strength

Box culvert made of geopolymer concrete Mix 4 (Tables 2&3) was tested for load bearing strength in Rocla's load testing machine which had a capacity of 370 kN and operated to Australian Standards, AS 1597.1-1974. The culvert was positioned as shown in Figure 4 with the legs firmly inside the channel supports. Load was then applied and increased continuously so that the proof load of 125 kN was reached in 5 minutes. After the application of the proof load, the culvert was examined for cracks using a crack-measuring gauge. The measured width of cracks did not exceed 0.08 mm. The load was then increased to 220kN and a crack of width 0.15 mm appeared underside the crown. As the load increased to about 300 kN, a crack of 0.4 mm width appeared in the leg of the culvert. The load was then released to examine to see whether all cracks had closed. No crack was observed after the removal of the load.

According to Australian Standard AS 1597 [10], a reinforced concrete culvert should carry the proof load without developing a crack greater than 0.15 mm and on removal of the load, no crack should be greater than 0.08 mm. The test demonstrated that geopolymer concrete box culvert met these requirements [2], [14]. Further test work is in progress.

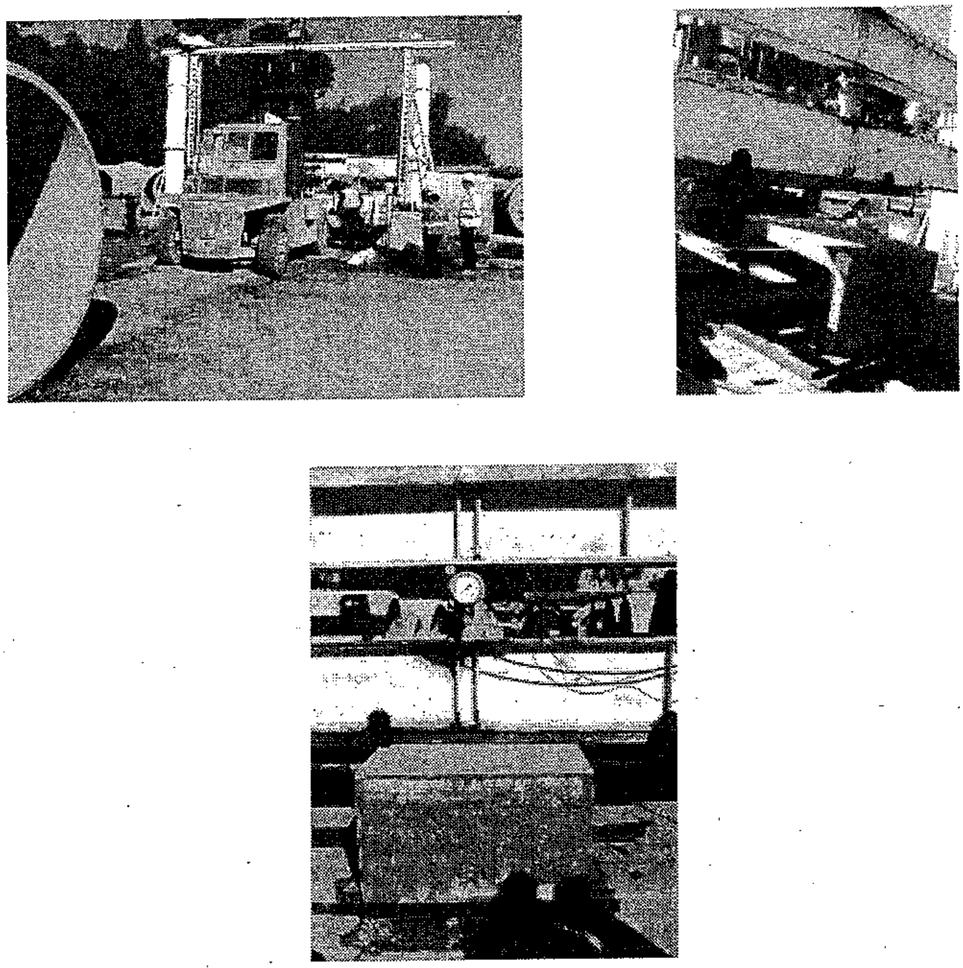


Figure 4: Test of Geopolymer Concrete Culverts

6. DURABILITY TESTS

6.1 Water Permeability Test

Table 4 and Figure 5 summarise the water permeability test data obtained from specimens made of the six geopolymer concrete mixtures (Table 2) in accordance with the test method specified by Main Roads WA [11].

Table 4: Water Permeability Test data

Mix	Compressive Strength (MPa)	Permeability Coefficient		Ave Permeability (m/s)
		Specimen 1	Specimen 2	
Mix1	39	9.60E-12	9.60E-12	9.60E-12
Mix2	58	4.10E-13	3.20E-13	3.65E-13
Mix3	30	1.60E-11	2.50E-11	2.05E-11
Mix4	25	5.30E-11	6.30E-11	5.80E-11
Mix5	57	8.50E-12	7.30E-12	7.90E-12
Mix6	35	2.40E-11	2.40E-11	2.40E-11

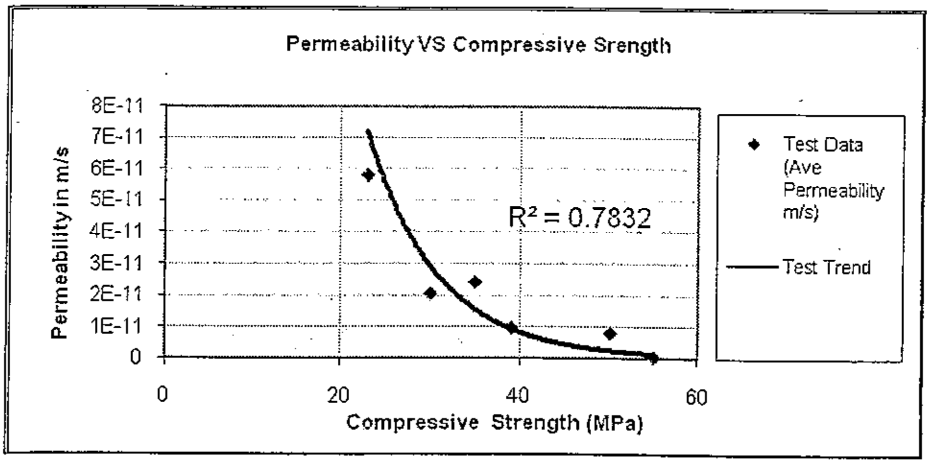


Figure 5 Water permeability of Geopolymer Concrete

The trend of test data shown in Figure 5 is similar to that observed for Portland cement concrete [2], [14].

6.2 VPV Test

Table 5 summarises the test data obtained from water absorption and permeable voids tests conducted on geopolymer concrete specimens. The tests were performed in accordance with the relevant ASTM Standard [12]. The test trend is similar to that observed in the case of Portland cement concrete [2], [14].

Table 5: Porosity and Absorption Test Data

Mix	Compressive Strength (MPa)	%voids Specimen1	%voids Specimen 2	Ave % Voids	% Absorption Specimen1	% Absorption Specimen2	Ave % absorption
Mix1	39	12.3	11.3	11.8	5.4	4.9	5.2
Mix2	58	10.4	10.3	10.4	4.4	4.4	4.4
Mix3	30	10.6	11.8	11.2	4.4	4.5	4.5
Mix4	25	11.0	11.7	11.4	4.7	5.0	4.9
Mix5	57	10.4	10.3	10.4	4.4	4.4	4.4
Mix6	35	11.4	11.1	11.3	4.9	4.7	4.8

7. CONCLUDING REMARKS

The paper presented the results of a preliminary study carried out to study the application of fly ash-based geopolymer concrete in reinforced box culverts. The study demonstrated that reinforced geopolymer concrete box culverts can be manufactured using the facilities currently available in a precast concrete plant. The test data showed that geopolymer concrete box culverts meet the requirements of relevant Standards with regard to strength. Preliminary data on durability parameters are also promising. Further work in this area is currently in progress.

8. ACKNOWLEDGEMENTS

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