Fly Ash Based Geopolymer Concrete with Recycled Concrete Aggregate

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Synopsis: Concrete is one of the most consumed resources in the world. With an increased global focus on environmental concerns such as global warming, sustainable development and recycling; alternatives to conventional concrete are being researched, such as geopolymer concrete. Geopolymer concrete replaces cement based binder with an alternative binder which contains no Portland cement. One type of geopolymer binder is that which contains fly-ash activated by an alkaline solution of sodium silicate and sodium hydroxide. Utilising recycled concrete waste from construction and demolition sites, that would otherwise be disposed of into landfill, as a source of aggregate offers a potential environmental and economic benefit. The term recycled concrete aggregate (RCA) is used to define aggregate produced from crushed demolition and construction waste.

Used together, geopolymer concrete and recycled concrete aggregate eliminate the need for Portland cement and makes use of waste materials. Significant research has been conducted into both recycled concrete aggregate (RCA) ordinary Portland cement concrete and geopolymer concrete; however there was limited published data on using RCA in geopolymer at the time of this research. Thus the aim was to investigate the mechanical properties of geopolymer concrete with recycled concrete aggregate as partial replacement of the natural coarse aggregate. This paper reports on the outcomes of the research which indicate the potential of incorporating RCA in geopolymer concrete mixtures.

Keywords: geopolymer, fly-ash, recycled concrete aggregate, compressive strength

1. Introduction

1.1 Environmental Concerns

Global warming and climate change are increasingly important issues, with many governments looking at different ways to reduce greenhouse gas emissions to help fulfil their obligations under the Kyoto Protocol [1]. Carbon dioxide is one of the most detrimental greenhouse gases with 65 percent of global warming caused by carbon dioxide [2]. Portland cement contributes significantly to greenhouse gas emissions with total emissions due to cement production estimated to be about 1.35 billion tons annually [3]. Cement production results in approximately 0.8-1 tonne of carbon dioxide per tonne of cement [4], equating to approximately 3 percent of global total greenhouse emissions [1]. One option to reduce cement utilization is to use geopolymer concrete.

Increased focus is also being placed on recycling as the world’s natural resources are being depleted and the amount of waste being disposed of into landfill is increasing globally. Therefore, as the industrial development process continues, the re-use of construction and demolition waste is becoming increasingly important and various solutions have been researched for high-volume use of recycled concrete. The properties of concrete made with either recycled natural aggregate or recycled concrete as coarse aggregate have been researched and presented elsewhere [5-9]. An option that is being widely researched and adopted is utilising recycled concrete aggregate in pavement construction and road base [10-14].

1.2 Geopolymer Concrete

1.2.1 Development

The development of geopolymer concrete is attributed to Davidovits [15] who, in 1978, first proposed that a geopolymer matrix could replace cement as the binder in concrete. Davidovits’ theory was that an alkaline solution could be added to an aluminium-silicon rich source material to produce cement-like binder and termed this a ‘geopolymer’ binder.

Fly ash is the most widely used source material for geopolymer concrete in Australia because of its availability and suitable composition, being a low calcium content fly ash with low loss of ignition. However, other materials that are high in silicon and aluminium can be used including rice husk ash, blast furnace slag, metakaolin and natural Al-Si minerals. Fly ash is a by-product of the coal industry. It is a fine particulate that is produced from the burning of coal and collects in the particle removal system of the combustion system and its use in Portland cement concrete is well documented [16]. In Australia alone 14 million tons of fly ash was produced in 2008 [17]. However, less than 30% is used in a beneficial way despite increased utilisation for some applications [17]. The alkaline solution, used to activate the fly ash or other source material, is generally a combination of sodium hydroxide and sodium silicate or potassium hydroxide and potassium silicate. The silicates result in a reaction which is very rapid and significantly faster than that caused by the hydroxides [18]. Therefore a combination of the two is used to provide a matrix which is both workable, strong and sets fairly rapidly.

1.2.1 Properties

The compressive and tensile strength of fly ash based geopolymer concrete has been shown to be comparable to General Portland (GP) concrete of up to 65 MPa [19]. The strength is mainly dependent on the following parameters: alkaline liquid-to-fly ash ratio by mass, water-to-geopolymer solids ratio by mass, the wet-mixing time, the heat-curing temperature, and the heat-curing time are selected as parameters [20]. The fly ash used in this research typically has a loss of ignition of around 1.6% and calcium oxide content of less than 2% by mass [21]. Geopolymer concrete has also demonstrated very little shrinkage and creep, excellent resistance to sulphate attack and good acid resistance [21]. Research has been progressing into the ambient curing of geopolymer for applications in tropical environments to produce geopolymer concrete of moderate compressive strength suitable for many applications.

1.3 Recycled Concrete Aggregate (RCA)

Construction and demolition waste contributes up to 40 percent of all waste generated worldwide. The majority of recycled aggregate that is used in Australia is recycled concrete aggregate (RCA) produced form construction and demolition waste, as it is the most suitable replacement of natural coarse aggregate. Fine recycled aggregates are also used to replace natural sand however this isn’t as prominent [22]. Utilising recycled aggregate can result in around 60 percent less waste and 50 percentage less mineral depletion per cubic metre of concrete produced [23]. The strength of ordinary Portland cement concrete utilising recycled aggregate depends largely on the percentage of recycled aggregate used. The larger the percentage of RCA, the weaker the concrete becomes in both compressive and tensile strength. Recycled concrete aggregate Portland cement based concrete also suffers from high water absorption and thus up to 160% higher shrinkage and creep concrete made with natural aggregates [6-9,24].

2. Research Programme

2.1 Materials and Mixture design

The basic mixture design used for the non RCA geopolymer mixture was developed based on the geopolymer mix designs formulated at Curtin University in previous research [19]. The other mixtures were derived from this with different percentages of the natural aggregate replaced with the RCA. Only the 20 mm natural aggregate was replaced in order to maintain a relatively continuous grading of the combined aggregates; however the percentage replacement was determined as a percentage of the total mass of coarse aggregates. Thirty percent replacement is a usual percentage of RCA used in recycled aggregate GP concrete as it has been found that higher replacements of the natural aggregate may lead to detrimental effects on the mechanical properties. Thus 30 percent was chosen as a starting point for comparison and 20 and 40 precent batches were also used so that any trends due to variation in RCA percentage replacement in the mechanical properties of the geopolymer concrete could be determined.

This produced the mixture designs outlined in Table 1. When referring to the batches, the notation R# is used, where # refers to the percentage of recycled aggregate in the batch. For example, R20 refers to the batch containing 20 % replacement of the total aggregate mass by recycled concrete aggregate (RCA).

The moisture content was assessed for samples of the aggregates brought to surface saturated dry condition (SSD) by soaking, draining and drying the aggregates on trays in the laboratory. Once the SSD moisture content was determined for each aggregate type (0.8% for coarse aggregate and 2.5% for fine aggregates), the water content of the aggregates at the time of mixing was adjusted to SSD moisture content by adding water to the aggregates before the addition of fly ash or chemicals. This water added to achieve SSD of the aggregates is in addition to the water noted in the mixture details of Table 1.

The RCA was nominal 20 mm aggregate containing granite, quartz and crushed concrete, approximately 1/3 of which contained steel fibres. There were small quantities of plaster and masonry contaminants. The aggregate did not comply with AS 2758.1 limits for a 20 mm aggregate with only 25% of the aggregate retained on the 20 mm sieve (AS 2758.1 limit 85-100%). The fineness modulus of the graded aggregates for all mixtures was approximately 5.0 which had previously been found to be suitable for geopolymer mixtures.

The alkaline solution used was a combination of sodium silicate and 8 M sodium hydroxide. A sodium based solution with a hydroxide to silicate ratio of 2.5 was preferred over a potassium based solution on the basis of cost, availability and familiarity with its use [19]

Table 1. Mixture details.

Constituent	Mixture constituents (kg/m^3)			
	R0	R20	R30	R40
20 mm	554	306	18	57
10 mm	227	227	227	227
7 mm	462	462	462	462
RCA	0	249	373	497
Sand	554	554	554	554
Flyash	408	408	408	408
Sodium Silicate (55.9% solids)	103	103	103	103
Sodium Hydroxide 8M	41	41	41	41
Water	20	20	20	20
Total Mass	2350	2350	2350	2350
Slump (mm)	250	220	200	220

2.2 Casting and Curing Regime

The methodology of mixing and casting was kept as similar to that of GP cement concrete as possible. This will aid in the commercial adoption of geopolymer concrete by the industry and will also improve quality control because the methodology is familiar. As such, the method described in AS1012.8.1 [25] was used as the basis for casting. The geopolymer cylinders were cured in a steam curing room for 18 hours at 60°C, a curing regime found to be effective in previous research conducted at Curtin University. Data logging of the temperature via K type thermocouple wires within the steam room chamber found the temperature varied between 50-65 degrees Celsius and temperature within the geopolymer specimens was 40 – 50 degrees Celsius within a few hours; consistent with other curing regimes at Curtin University [26].

3. Results and Discussion

The main mechanical properties are summarized in Table 2 and discussed further in sections 3.1 through 3.3.

Table 2: Mechanical Properties data

Property	Mixture Designation			
	R0	R20	R30	R40
Day 1 Compressive Strength f_{cm1} (MPa)	23±2	20±2	20±2	17±1
Day 7 Compressive Strength f_{cm7} (MPa)	26±1	26±1	24±2	22±2
Day 28 Compressive Strength f_{cm28} (MPa)	33±2	29±2	29±1	25±2
Day 91 Compressive Strength f_{cm91} (MPa)	36±3	34±0.5	34±1	30±1
Relative (to R0) compressive strength (average for all days 1, 7, 28 and 91)	1	0.93	0.91	0.80
Day 1 Indirect Tensile Strength $f_{ct.sp1}$ (MPa)	2.2±0.1	2.1±0.4	2.1±0.2	1.6±0.1
Day 28 Indirect tensile Strength $f_{ct.sp28}$ (MPa)	2.7±0.1	2.6±0.3	2.8±0.5	2.5±0.3
Day 91 Indirect Tensile Strength $f_{ct.sp91}$ (MPa)	2.9±0.2	2.9±0.5	3.7±0.2	3.2±0.2
Ratio $f_{ct}/\sqrt{f_{cm}}$ at Day 28	0.42	0.36	0.47	0.41
Ratio f_{cm1}/f_{cm28}	0.70	0.70	0.70	0.68
Density (kg/m^3)	2370±35	2350±30	2360±30	2340±20

3.1 Compressive Strength

Three compression cylinders were tested at 1 day, 7 days, 28 days and 91 days after casting in accordance with AS1012.9 [27]. Prior to testing, all of the compression cylinders were sulphur capped to improve the testing surface. The compressive cylinder tests produced the compressive strengths outlined in Figure 1 and show that the compressive strength was 25 to 33 MP at 28 days and the ratio of day 1 to day 28 mean compressive strength was around 70%. These strengths are suitable for many applications and correspond to a characteristic strength of approximately 30 MPa (25 MPa for the R40 mixture).

The addition of the RCA to the geopolymer concrete did not result in an increase in the standard deviation of the compressive strengths thus showing that the batches had adequate consistency compared with the non RCA batch despite the compositional variability of the RCA. As shown in Figure 1, the 28 day mean compressive strengths of all batches containing RCA were less than the R0 batch; however the strength decrease of the R20 and R30 batches were statistically insignificant. The decrease in strength is expressed by the average ratio of the relative compressive strengths in Table 2 (the ratio is calculated as the ratio of the compressive strengths for each age compared with the corresponding R0 compressive strengths e.g. for R20 the ratio was, at day 28, equal to 29/33 = 0.88).

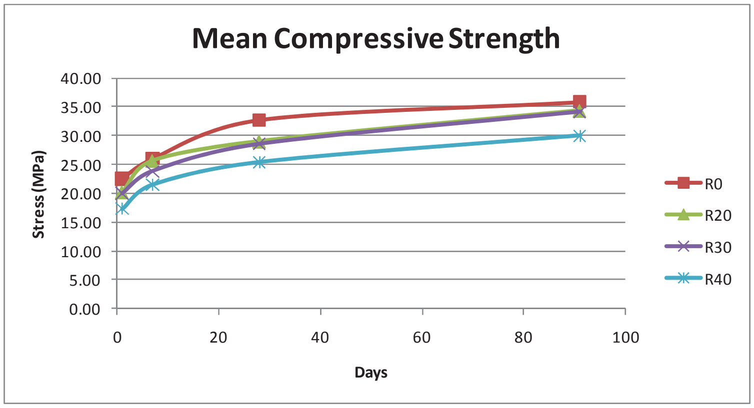

Figure 1. ***Compressive Strength Gain with Time*.**

The reduction is similar to what has been observed with GP concrete containing RCA and falls within a range of strength reduction (less than 10%) for the R20 and R30 mixtures observed in OPC mixtures with similar proportions of RCA. However, a more severe reduction (of the order of 20% for the mean compressive strengths) is shown in the R40 mixture which is greater than that indicated by other research on GP cement concrete with RCA [28]. This suggests that the proportion of RCA should be limited to 30 percent due to strength considerations. However, the mix design can be adapted to produce geopolymer concrete with a similar compressive strength to the R0 batch. This can be achieved by adjusting the water-to-geopolymer solids ratio by mass. Changing the ratio can be accomplished through one or a combination of the following methods: reducing the water content or increasing the amount of binder (fly ash and alkaline solution). The mixtures had constant (0.2) water to geopolymer solids by mass ratio. If the water was reduced or the binder content increased the decrease in compressive strength may be counteracted in a manner analogous to adjusting the eater to cement ratio in conventional concrete.

3.2 Indirect Tensile Strength

The tensile cylinders were tested using the Brazilian indirect tensile method. Tensile tests were conducted on 2 cylinders at 1 day, 28 days and 91 days in accordance with AS1012.10 [20]. The tensile cylinder tests produced the tensile strengths illustrated in Figure 2 and Table 2.

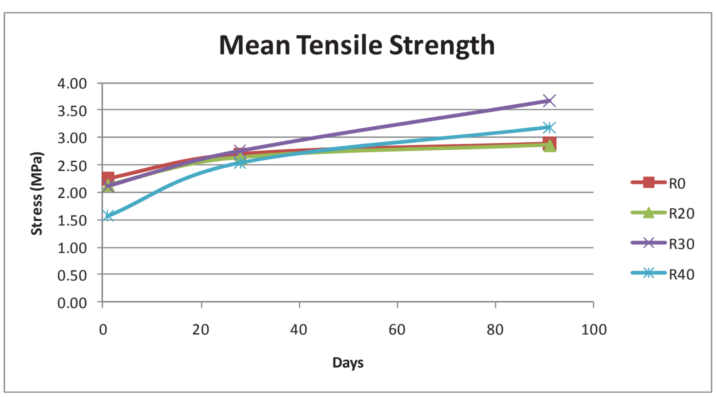

Figure 2: Tensile Strength Gain with Time

The tensile strengths of the different batches appear to show no discernable trend due to percentage replacement of aggregate with RCA and the limited data inhibits interpretation. However the indirect tensile strength was determined to be approximately 2.5 MPa for all mixtures. The general observation is that the tensile strength was approximately 15% greater than the predicted value using A.S. 3600- 2009 where f_{ct} =0.9 $f_{ct.sp}$ or in the absence of such data may be estimated as $0.36\sqrt{f_{cm}}$. This is consistent with other geopolymer concrete mixtures with a variety of compositions and curing conditions [26]. The ratio of f_{ct} to $\sqrt{f_{cm}}$ for the geopolymer mixtures was 0.41 at 28 days, 15% greater than 0.36. The influence of the steel fibre content and variable content of the RCA is possibly reflected in the larger standard deviations for the batches containing RCA.

3.3 Shrinkage

The shrinkage was measured using a micrometer and standard shrinkage specimens. Testing was done every two or three days during the first week, weekly for the first month and less regularly until 91 days in accordance with AS1012.13 [30]. The experimental shrinkage results can be compared to the theoretical shrinkage. The theoretical values in Figure 3 are based on a grade 30 MPa GP concrete using natural aggregates and data in AS3600 [31].

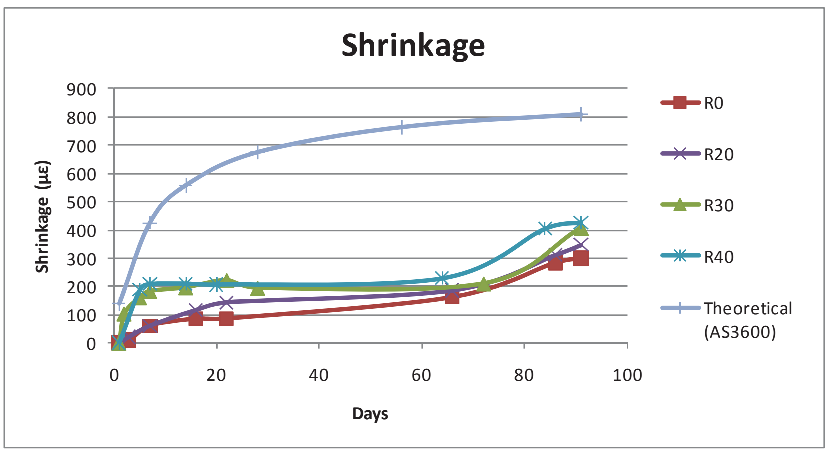

Figure 3: Shrinkage Summary and Comparison with AS 3600

The batches with RCA compare favourably with the R0 batch. The batches with RCA do show greater shrinkage however this is expected based on previous research using GP concrete [24]. The shrinkage of all of the batches is also significantly lower than the theoretical values for GP concrete based on AS3600. These results demonstrate that the shrinkage problems normally associated with RCA GP concrete are not an issue in RCA geopolymer concrete. This is because the lower shrinkage values of geopolymer concrete counterbalances the increased shrinkage associated with the RCA. This leads to shrinkages that are significantly below the predicted values of equivalent strength GP concrete.

4. Concluding remarks

Geopolymer concrete can be produced with fly ash and alkaline solutions utilising conventional concrete mixing and casting procedures. Steam curing at relatively moderate temperatures (60 degrees Celsius) overnight (16 hours) result in geopolymer concrete which exhibits mid-range compressive strengths of the order of 32 MPa and significantly reduced shrinkage and increased tensile strength compared with GP concrete of the same compressive strength. The shrinkage increased as the proportion of recycled concrete aggregate (RCA) increased, however the shrinkage results of the geopolymer mixtures with RCA were significantly lower than the results predicted by AS3600 and this has been demonstrated in previous research on geopolymer concrete. These benefits may be applied in structural applications and research continues on the design and durability of products utilising geopolymer concrete. The partial replacement of coarse aggregate with recycled concrete aggregate in geopolymer concrete may lead to a positive ecological benefit considering the reduction in cement and reuse of industrial by-products, typically destined for land fill, in geopolymer concrete with RCA.

The observed compressive strength decrease in geopolymer concrete mixtures with the partial replacement of natural coarse aggregate with RCA is similar to that observed in comparable GP cement based concrete with RCA. This demonstrates that strengths for nominal grade 32 MPa concrete can be developed by geopolymer concrete containing up to 30 percent RCA with no change to the mix design and higher strengths may be able to be produced with minor changes to the mix design, analogous to adjusting the water to cement ratio, by adjusting the water to geopolymer solids ratio. The compressive strength results of the RCA geopolymer batches presented low standard deviations, which demonstrate that the RCA may not affect the quality and consistency of the mix in terms of compressive strength and further research is currently underway at Curtin to assess this impact in both geopolymer and GP cement base concretes with RCA.

5. References

1. Rehan, R and Nehdi, M "Carbon dioxide emissions and climate change: policy implications for the cement industry," *Environmental Science & Policy,* vol. 8, pp. 105-114, 2005.
2. McCaffrey, R "Climate Change and the Cement Industry," *Global Cement and Lime Magazine,* pp. 15-19, 2002.
3. Malhotra,V M "Introduction: Sustainable Development and Concrete Technology," *ACI Concrete International,* vol. 24, p. 22, 2002.
4. WBCSD, "Cement Sustainability Initiative: Recycling Concrete," World Business Council for Sustainable Development, Geneva, Switzerland9/5/10 2009.
5. Rao, A "Experimental Investigation on Use of Recycled Aggregates in Mortar and Concrete," Civil Engineering, Department of Engineering, Indian Institute of Technology, Kanpur, India, 2005.
6. Xiao, Jianzhuang; Li, Jiabin; Zhand, Ch "Mechanical Properties of Recycled Aggregate Concrete under Uniaxial Loading", *Cement and Concrete Research*, 2005, 35(6):1187-1194
7. Yang, J A; Du, Q A; Bao, Y W "Concrete with Recycled Concrete Aggregate and Crushed Clay Bricks", *Construction and Building Materials*, 2011, 25(4) 1935:1945
8. Corinaldesi, V "Mechanical and Elastic Behaviour of Concretes made of Recycled-Concrete Coarse Aggregates", *Construction and Building Materials*, 2011, 24(9):1616-1620
9. Domingo, A; Lazaro, C; Gayarre, FL; Serrano, M A; Lopez-Colina, C "Long Term Deformations by Creep and Shrinkage in Recycled Aggregate Concrete", *Materials and Structures*, 2010, 43(8):1147-1160
10. Mills-Beale, J: You, Z P "The Mechanical Properties of Asphalt Mixtures with Recycled Concrete Aggregates", *Construction and Building Materials*, 2010, 24(3) :230-235
11. Batmunk, N (2011) Engineering Characteristics of Construction Waste for Western Australian Road and Highway Materials, PHD Thesis, Curtin University of Technology
12. Bhusal, S; Li, X; Wen H "Evaluation of Effects of Recycled Concrete Aggregate on Volumetrics of Hot-Mix Asphalt", *Transportation Research Record*, 2011, 2205(1):36-39

13. Wong, Y D; Sun, D D and Lai, D "Value-Added Utilization of Recycled Concrete in Hot-Mix Asphalt", *Waste Management*, 2007, 27(2):294-301
14. Paranavithana, S; Mohajerani, A "Effects of Recycled Concrete Aggregates on Properties of Asphalt Concrete", Resources, *Conservation and Recycling*, 2006, 48(1):1-12
15. Davidovits, J "Geopolymers - Inorganic polymeric new materials," *Journal of Thermal Analysis,* vol. 37, pp. 1633-1656, August 1991
16. ACI Committee 232, *Use of Fly Ash in Concrete*. Farmington Hills, Michigan, USA: American Concrete Institute, 2004.
17. ADAA, "Annual Membership Survey Results," Ash Development Association of Australia 2008.
18. Palomo*, A; Grutzeck, M W; Blanco, M T* "Alkali-activated fly ashes: A cement for the future," *Cement and Concrete Research,*1999*,* 29(8) pp. 1323-1329.
19. Hardjito, D and B. V. Rangan, "Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete," Curtin University of Technology, Perth, Australia 2005.
20. B. V. Rangan, "Fly Ash Based Geopolymer Concrete," Curtin University of Technology, Perth, Australia2008.
21. Wallah, S E and B. V. Rangan, "Low-Calcium Fly Ash-Based Geopolymer Concrete: Long Term Properties," Curtin University of Technology, Perth, Australia2006.
22. Cement Concrete & Aggregates Australia, "Use of Recycled Aggregates in Construction," CCAA2008.
23. Marinkovic*,et al*, "Comparative environmental assessment of natural and recycled aggregate concrete," *Waste Management,* vol. In Press, Corrected Proof, 2010.
24. Katz, A "Properties of concrete made with recycled aggregate from partially hydrated old concrete," *Cement and Concrete Research,* vol. 33, pp. 703-711, 2003.
25. Standards Australia, "Methods of testing concrete - Method of making and curing concrete - Compression and indirect tensile test specimens," ed: AS1012.8.1, 2000.
26. Lloyd N A and Rangan B V "Geopolymer Concrete with Fly Ash", in Zachar, J. and Claisse, P. and Naik, T. and Ganjian, G. (ed), Second International Conference on Sustainable Construction Materials and Technologies volume 3, pp. 1493-1504. Ancona, Italy: UWM Center for By-Products Utilization. " Spain,2010
27. Standards Australia, "Methods of testing concrete - Determination of the compressive strength of concrete specimens," ed: AS1012.9, 1999.
28. Li, X "Recycling and reuse of waste concrete in China: Part I. Material behaviour of recycled aggregate concrete," *Resources, Conservation and Recycling,* vol. 53, pp. 36-44, 2008.
29. Standards Australia, "Methods of testing concrete - Determination of indirect tensile strength of concrete cylinders (Brasil or splitting test)," ed: AS1012.10, 2000.
30. Standards Australia, "Methods of testing concrete - Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory," ed: AS1012.13, 1992.
31. Standards Australia, "Concrete Structures," ed: AS3600, 2009.