Development of an Acid Resistant Concrete

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Abstract: Modern infrastructures are designed for long service life and are increasingly being built in more aggressive greenfield and brownfield areas. Sulfate, acid-sulfate and acid resistant concrete are engineering solutions to these challenges in infrastructures without the need for additional protective membrane associated with conventional concrete. This paper presents an experimental investigation on mechanical properties of concretes made from a new acid-resistant mortar and a conventional concrete, and corresponding reinforced concrete beams, subjected to accelerated acidic environments in UTS laboratory. Concrete properties including compressive strength, modulus of elasticity, modulus of rupture, indirect tensile and drying shrinkage were examined. The load carrying capacity of companion reinforced concrete beams were also determined. The specimens were tested before and after periods of exposure to sulphuric acid solution with the concentration of 7% and changes of their properties were evaluated. The results enable an understanding of the mechanism of acid attack and the benefit of the use of acid resistant concrete. On the other hand, the effect of acid attack on reinforced concrete beams is highly dependent on the design of the reinforced concrete beams and to a lesser extent on the acid resistant property of the concrete.

Keywords: Acid resistant mortar, Acid resistant concrete, Acid Attack on concrete.

1. Introduction

Given the existence of acidic soil and acidic groundwater in acid sulfate soils, particularly in coastal areas in Australia [1], introduction of new acid resistant materials and investigation of the effect of acidic environments on performance of reinforced concrete (RC) structures is of importance. These structures could be piers, footings or foundations of different structures such as buildings and bridges [2]. Acidic environments cause the degradation of concrete and hence, decrease of load bearing capacity in these structures as well as serious durability issues.

Penetration of aggressive agents into the concrete and their chemical reaction with the cement matrix including decalcification, gypsum formation and ettringate formation causes the deterioration of concrete [3]. These chemical reactions can lead to expansion and cracking of concrete and loss of strength and elastic properties of concrete [4, 5, 6, 7].

In Australian Standard AS 3600 there are some precautions for concrete structures in acidic environments such as, some recommendations about the use of Sulphate Resistant (SR) cement in harsh environments. However, for prolonged exposure periods, SRPC does not appear to provide a better resistance to sulphuric acid attack than that provided by conventional Portland cement (OPC) [8, 9]. Some polymer modified concretes have also shown a better performance against the sulphuric acid [10]. However, they have not been mentioned as a viable solution in these environments due to implied high cost [11].

In this study a new structural concrete is developed by use of a novel acid resistant mortar (ARM) which was initially used for lining and repair purposes in Australia. For this purpose, mechanical properties of the ARM, the new acid resistant concrete (ARC) made from the ARM and a conventional concrete as the control concrete were tested before and after exposure to sulphuric acid solution (7%). Then flexural strength of reinforced concrete members made from the ARC and conventional concrete was tested before and after exposure to acid that will be presented.

2. Experimental Work

Experimental tests of this research include two main parts, namely, mechanical properties tests and structural tests of reinforced concrete members. The details of experimental tests will be explained in this section.

2.1. Test materials

2.1.1. Conventional concrete (CC)

The first series of specimens were cast from a conventional concrete as control concrete. The characteristics of this concrete are shown in Table 1. The target slump was 140 ±10 mm.

Table 1. Mix design of the conventional concrete (CC).

Nominal compressive strength (MPa)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Cement (Shrinkage limited) (kg/m^3)	Water/Cement Ratio	Fly ash(kg/m^3)	Pozzolith 80 (liter/m^3)
40	960	661	350	0.4	150	2.3

2.1.2. Acid resistant mortar (ARM)

The second series of specimens were made from the acid resistant mortar (ARM). The ingredients of ARM are shown in Table 2. The mean 28-day compressive strength of ARM is 30 MPa.

Table 2. ARM Compositions.

Ingredients	Silica sand	Fly ash	Silicates and poly silicates	Silica fume	Portland cement	Other ingredients
*** Proportion**	30-60%	10-30%	1-10%	1-10%	1-10%	1-10%

** The exact amount of the ingredients of ARC has not been mentioned here due to the confidentiality agreements with the manufacturer.*

2.1.3. Acid resistant concrete (ARC)

The last series of specimens as the main purpose of this study was made from the acid resistant concrete (ARC) which contains ARM and coarse aggregates with the coarse to fine aggregate ratio of 0.5. Water to binder ratio for both ARM and ARC was 0.4 and ARC had a slump of 140 ±10 mm. Type and grading of coarse aggregates in the conventional concrete and acid resistant concrete (ARC) were the same and the maximum size of aggregates was 10mm.

2.2. Test procedure

2.2.1. Mechanical properties tests

The mechanical properties tests included the compressive strength, modulus of elasticity (MOE), modulus of rupture (MOR) and Indirect tensile test, according to the relevant standards in Australia, namely, AS1012 [12,13,14,15,16].

To investigate the mechanical properties, 120 standard cylinders with the dimensions of 100 in diameter by 200 mm in height; 50 cylinders with the size of 150 in diameter by 300 mm in height and 80 prisms with the size of 100mm by 100mm by 400 mm were tested. For each test, three concrete specimens were tested to ensure repeatability and the reported results are the average values of these three specimens.

Each series of the specimens were kept under standard curing conditions for 28 days. Afterwards, half of the specimens were washed with water, dried to a saturated surface dry condition and were then immersed in acid solution (five folds of their volumes) and then covered to eliminate evaporation of the solutions. The density of acid solution was monitored weekly to control the acid concentration (7%). Each time the same number of specimens, not exposed to acid, was also tested to compare the behaviour of ARC with CC in the presence and absence of acid.

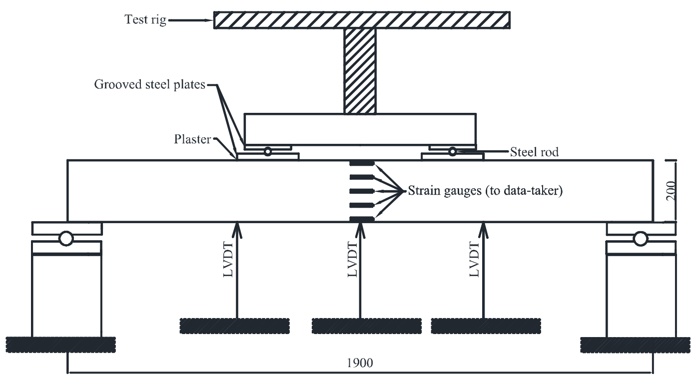
As this concrete is developed for structural applications, the amounts of drying shrinkage are of importance. Hence, 9 prisms with the size of 75mm by 75mm by 400 mm were cast and their ultimate drying shrinkage was measured in accordance with AS 1012.13 (1992).

2.2.2. Flexural strength of reinforced concrete (RC) members

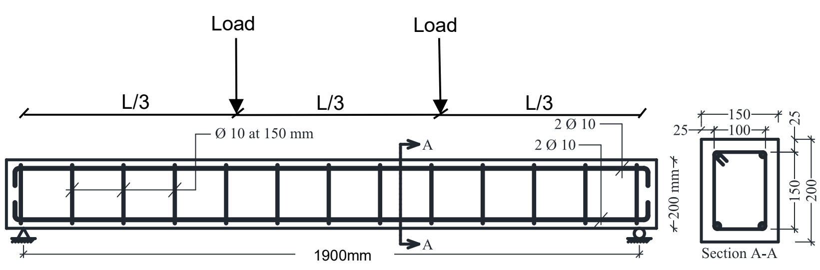
Flexural strength of 15 RC beams made from ARC and CC with the dimensions of 150mm by 200mm by 2000 mm were evaluated through four-point loading test before and after four, eight and twelve weeks of exposure to sulphuric acid solution. The RC beams were designed for tensile failure. Test set-up for these tests is shown in Figure 1 a, b and c and the beams' reinforcement details are shown in Figure 1 d. Three LVDTs were used at ¼, ½ and ¾ of the span of the beam to record the deflections. The beams were loaded with the rate of 0.5 mm/sec by deflection control method till failure.

a)

b)



c) Test set up for flexural strength test



d) Details of RC beams

Figure 1. (a) & (b) Photos from the flexural strength tests, (c) & (d) Test set up and beam details for flexural strength tests.

3. Results and Discussion

The results of experimental tests including the mechanical properties tests and structural tests will be presented.

3.1. Mechanical Properties Tests

The results of mechanical properties tests of the conventional concrete (CC), Acid resistant mortar (ARM) and acid resistant concrete (ARC) are summarized in Table 3. All reported times in this Table are the time of exposure to acid or water after 28 days of standard curing. Another important point in this table and Figure 2 is that the test results of control concrete have not been reported after eight weeks of exposure due to degradation of the concrete samples.

Table *3*. Mechanical Properties of CC, ARM and ARC after exposure to sulphuric acid.

Type \ Time		2 weeks			4 Weeks			8 Weeks		
		exposure to water	exposure to acid	Change (%)	Curing	Acid	Change (%)	Curing	Acid	Change (%)
CC	Compressive Strength (MPa)	46.1	44.7	-3.0%	53.8	44.2	-17.8%	-	-	-
	MOR (MPa)	5.8	6.0	3.4%	5.9	6.2	5.1%	-	-	-
	MOE (GPa)	33.0	32.0	-3.0%	37.0	35.0	-5.4%	-	-	-
	Indirect Tensile (MPa)	6.6	7.1	7.6%	6.7	8.6	28.4%	-	-	-
ARM	Compressive Strength (MPa)	31.4	31.1	-1.0%	35.1	34.4	-2.0%	37.1	32.5	-12.4%
	MOR (MPa)	5.1	4.9	-3.9%	5.3	4.8	-9.4%	5.4	4.4	-18.5%
	MOE (GPa)	26.0	26.0	0.0%	28.0	28.0	0.0%	29.0	29.0	0.0%
	Indirect Tensile (MPa)	3.9	4.1	5.1%	4.1	4.5	9.8%	4.2	4.6	9.5%
ARC	Compressive Strength (MPa)	43.0	42.3	-1.6%	44.5	41.8	-6.1%	51.6	45.0	-12.8%
	MOR (MPa)	5.6	5.6	0.0%	5.7	5.7	0.0%	6.0	5.3	-11.7%
	MOE (GPa)	32.0	32.0	0.0%	33.0	32.0	-3.0%	33.0	28.0	-15.2%
	Indirect Tensile (MPa)	3.8	4.0	5.3%	3.9	4.5	15.4%	4.4	4.5	2.3%

- *Compressive strength*

Regarding the compressive strength of concretes it should be mentioned that after introduction of coarse aggregates to ARM to produce ARC, compressive strength increased from 31.4 to 43 MPa at the age of six weeks (42 days) and from 35.1 to 44.5 MPa after eight weeks (56 days) of standard curing which suggests about 30% increase of compressive strength.

As shown in Figure 2, CC had 3% and 17.8% compressive strength loss after two and four weeks of exposure to acid solution respectively, whereas, these strength loss decreased by 1.6% and 6.1% for the ARC.

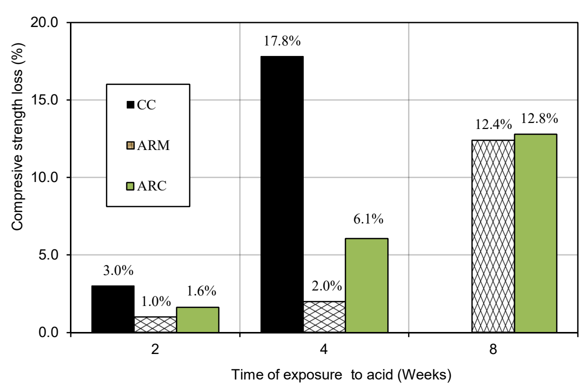


Figure 2. Compressive Strength of CC, ARM and ARC after exposure to acid.

This decrease was 1% and 2 % for the ARM, effectively unchanged. Comparison of the strength loss of CC and ARC after two weeks and four weeks of exposure to acid solution reveals that the strength loss of ARC was about 1/3 of CC.

- *Modulus of Rupture (MOR)*

Modulus of rupture (MOR) of CC had a slight increase in acid. ARM had 3.9% and 9.4% decreases after two and four weeks of exposure to acid, respectively. This shortcoming was resolved after addition of coarse aggregates to ARC and there was no change in MOR characteristics of ARC samples after two and four weeks (28 days) of exposure.

- *Modulus of Elasticity (MOE)*

Tests of modulus of elasticity (MOE) of CC showed a slight decrease after two and four weeks (14 and 28 days) of exposure to acid solution (3% and 5.4%), whereas, ARM did not show any change in MOE characteristics even after eight weeks of exposure to acid. ARC did not have any change of MOE after two weeks and 3% decrease after four weeks (28 days) of exposure that was less than CC. In addition, comparison of the MOE test results of ARM and ARC without acid confirms the increase of MOE by addition of coarse aggregates to the ARM. This was predicted due to the role of aggregate in stability of concrete.

- *Indirect Tensile strength*

As shown, for all types of specimens, tensile strength measured by splitting test, increased after exposure to acid compared to the specimens under standard curing conditions. This unexpected increase was greater for the control concrete. For instance, after four weeks of exposure to acid CC had 28% increase compared to ARM (9.8%) and ARC (15.4%). The reason behind this increase is currently being explored through microstructural analysis in the UWS laboratory.

The same trend was initially expected for the changes of indirect tensile and flexural strength in acid. However, for MOR, the unaffected concrete at the extreme fibre of the conventional concrete is tested, whereas, for ARM and ARC the partially acid corroded extreme fibre of the ARM and ARC is tested. In indirect tensile test, the external layer that is to carry the compressive load is unaffected concrete in CC and the acid-affected layer in ARM and ARC.

- *Drying shrinkage*

Given the purpose of this project, which was developing the ARC for structural application, amounts of drying shrinkage of ARC was an important factor. ARM naturally had a high amount of drying shrinkage due to its fine nature. This issue was addressed by addition of coarse aggregate in ARC which led to the ultimate drying shrinkage of 900 micro strains which is within the acceptable range for structural concretes according to AS3600 (See Figure 3).

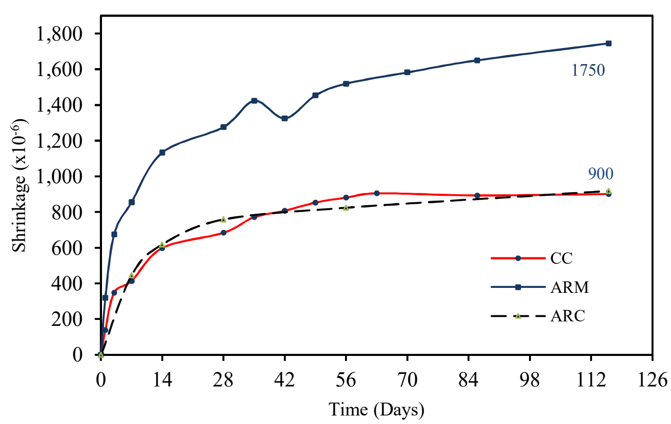


Figure 3. Drying Shrinkage of CC, ARM and ARC

3.2. *Flexural strength of reinforced concrete (RC) beams*

Two groups of RC beams were tested for flexural strength namely, CC and ARC. Figure 4 shows the load deflection of concretes before exposure to acid. As can be seen ARC had similar ultimate load but greater ultimate defection comparing to CC, displaying more ductile behaviour.

Figure 5 shows the flexural behaviour of CC and ARC beams after exposure to acid. This reveals that after exposure to acid both types of concretes had some strength loss but there was no significant change. This loss was greater in CC beams comparing to ARC that can be attributed to reduction of the effective depth of the CC beam sections, causing the shortening of lever arm and, therefore, reducing the load capacity. This decrease of effective depth was found by measurement of the depth of the beams before and after exposure to acid. The initial depth of all beams was 200mm that decreased to 180mm and 162mm after four weeks and eight weeks (28 and 56 days) of exposure to acid, respectively. For CC the exposure to acid seems to increase the ductility of the beams, accompanied by loss of load carrying capacity from about 78 kN to about 62 kN after eight weeks (56 days) of exposure due to reasons mentioned above. The impact of acid exposure to ARC is less pronounced than CC with slightly better ductility and less loss of load carrying capacity with time of exposure.

In Figure 6 the normalized ultimate load of specimens is obtained by dividing the ultimate load of RC beams to the ultimate load of non-acid exposed beam. The normalized ultimate load of the beams predicts a dramatic decrease of flexural strength for CC in longer term dropping to 80% of the original strength after 12 weeks (84 days). This factor seems to remain almost constant (at about 90% of strength) for ARC and more resilient for long term exposure to acid. For the first 10 weeks of exposure, CC seems to display a better flexural strength, however, after 10 weeks the ARC behaves much better. Coincidently the value at 10 weeks is about 90% for both CC and ARC. This confirms that ultimate load bearing of CC beams decrease much faster than ARC beams compared to not acid exposed beams from the same materials.

It is important to mention that despite degradation of surface layers of CC beams and loss of a considerable amount of concrete cover (20 mm loss of 25 mm concrete cover), the acid did not reach reinforcing bars after twelve weeks of exposure. However, a major loss of strength is predicted after long term exposure of CC beam to acid due to corrosion of reinforcing bars.

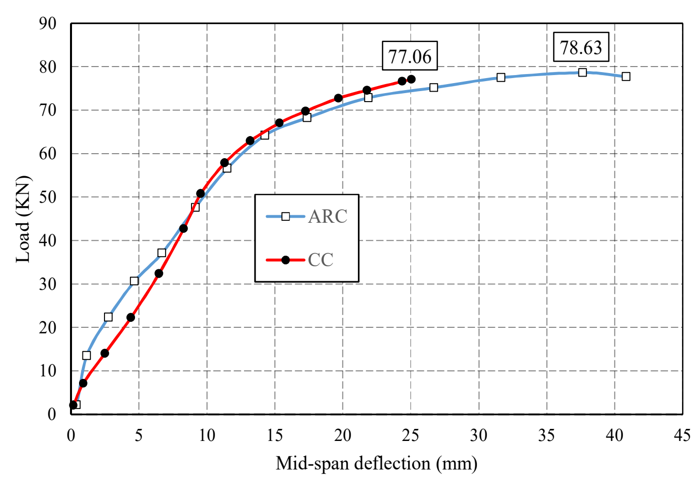
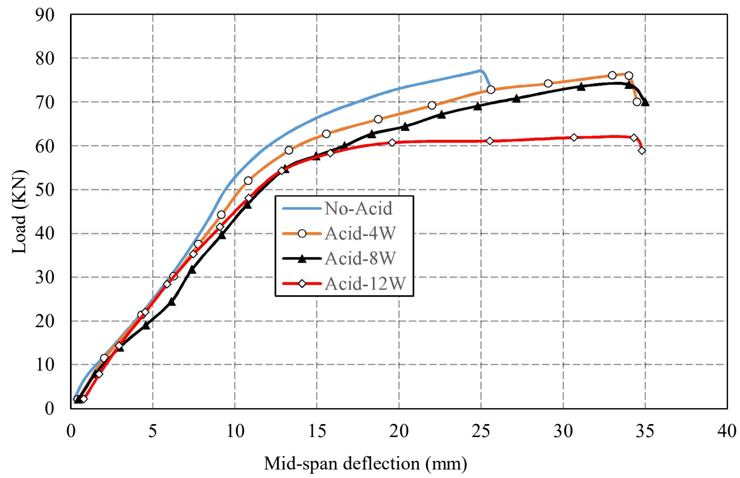
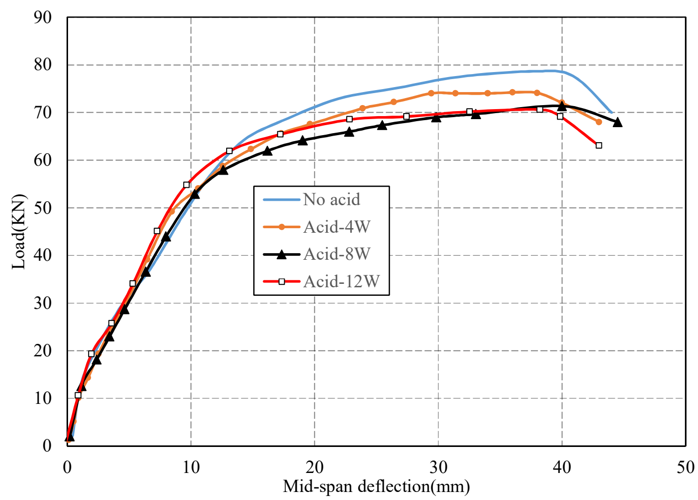


Figure 4. Load-deflection of ARC and CC beams in flexural test



a) Load-deflection of Conventional Concrete after exposure to sulphuric acid.



b) Load-deflection of ARC after exposure to sulphuric acid.

Figure 5. Load versus deflection in flexural test a) conventional concrete and b) ARC beams after exposure to acid.

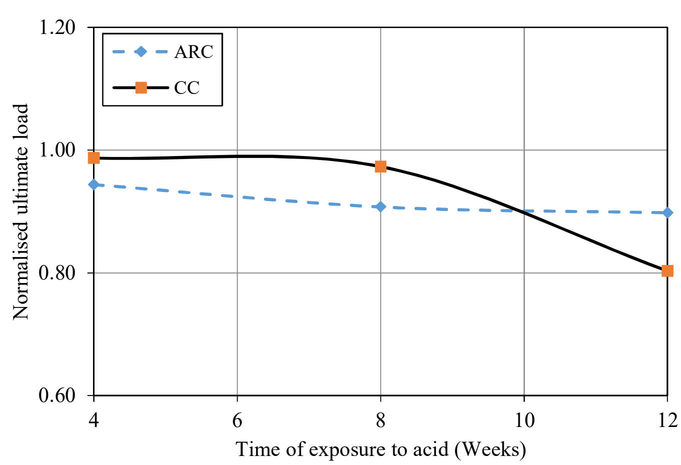


Figure 6. Normalized ultimate load of the RC beams versus time of exposure to acid.

4. Conclusion

In this study, mechanical and structural properties of a new acid resistant concrete (ARC), were investigated and compared to a control concrete in the laboratory. The results of mechanical properties tests of ARC before and after exposure to accelerated acidic conditions were promising. Drying shrinkage of ARC was also in the acceptable range for the purpose of this study. Hence, flexural strength of reinforced concrete beams made from ARC was tested for structural applications and showed that as long as the acid has not reached the reinforcing bars the maximum load bearing capacity of RC flexural members, whether from CC or ARC, does not change significantly. However, there is some strength loss because of decreasing the effective depth of RC beam sections due to degradation of concrete surface layers. Study of the history of flexural strength of RC beams after exposure to acid suggests much better performance for ARC comparing to the conventional concrete.

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