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EFFECT OF SILICA FUME ON RECYCLED AGGREGATE CONCRETE

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ABSTRACT

The ever increasing concrete usage has raised concerns over its environmental impact because when reaching the end of the design life, concrete waste usually ends up as landfill. This creates a significant problem because of the difficulties associated with managing the increased volume of concrete waste. As a result, use of recycled concrete to replace the coarse aggregate has attracted attention as it can reduce the amount of landfill as well as requirement of virgin aggregate. Past studies have indicated some bonding issues of recycled concrete aggregate (RCA) at the interfacial transition zone (ITZ) preventing usage of material in structural concrete applications. The main objective of this investigation was to determine whether compression and flexural strength improvements could be gained with the addition of silica fume in the concrete mix. It was hypothesised that silica fume's fine particles reduced the porosity of the RCA which should result in an increased modulus of elasticity and improve the bond at the ITZ. This paper presents an experimental investigation into the effect of replacement of virgin aggregate with recycled concrete aggregate (RCA) with the addition of silica fume on the compressive and flexural strength of a blended cement concrete. Varying amounts of silica fume was used in addition to 100% coarse aggregate replacement. The investigation indicated that favourable strength results are achieved with the addition of 10% silica fume in RCA.

KEYWORDS

Recycled concrete aggregate (RCA), silica fume, interfacial transition zone (ITZ), fly ash.

INTRODUCTION

Concrete is one of the most commonly used materials in the construction industry due to its versatility, strength and visual appeal. As concrete structures reach the end of their design life, concrete waste ends up as landfill. In Australia during the period of 2009-2012 masonry was the largest contributor (37%) to landfill (ABS 2013). Ways to harness the strength from concrete wastes are being investigated.

Substitution of virgin natural aggregate with recycled concrete aggregate (RCA) has gained interest over the past 20 years and more recently the potential for use in a structural application. Minimising the use of natural aggregate prevents depletion of resources, reduces mining and decreases harmful emissions by reducing transport of aggregate for locations that do not have access to quarries.

Research of this nature is also beneficial for the construction industry as it is becoming increasingly aware that there is a need to reduce their carbon footprint and re-use and re-cycle resources.

Key issues have been noted with the substitution of coarse aggregate with RCA in terms of decreased strength, which is believed to be due to an inferior interfacial transition zone (ITZ) bond strength (Katz 2004, Tam 2006, Kong 2010). It is believed silica fume can positively influence the ITZ. This paper aims to examine the impact of silica fume on RAC in terms of compressive strength and flexural strength.

RECYCLED AGGREGATE CONCRETE

RCA is produced by crushing concrete rubble. Due to the high variability in quality of RCA, applications have been limited to non-structural purposes such as concrete kerb and gutter mix, road base coarse material, paving blocks, backfill and building blocks (Portland Cement Association 2007). In general, RCA contains 65-70% of natural aggregate (coarse and fine) and 30-35% of cement paste by volume (Kong 2010). Because of this high variability, the resulting aggregate is non-uniform, more porous and less dense than conventional natural aggregates. In conventional concrete a point of weakness occurs at the ITZ. The weakness at the ITZ occurs due to the "wall effect" which prevents packing of particles around the aggregate surface. This is a result of water being trapped in the pores of the coarse aggregate and bled during the curing process, which creates a differential water-cement (w/c) ratio around the aggregate surface (ITZ) (Neville 1995).

In RAC, two transition zones are present, which play an important role in determining the strength of RCA. One is between the old mortar and original aggregate, and the other, between the new mortar and RCA as shown in Figure 1. Additionally the porous nature of RCA, loose mortar and aggregate micro-cracking further affect the strength and bonding of the new ITZ. Therefore, the ITZ can be improved by:

1. Removing residual mortar, loose particles and dirt through cleaning
2. Reduction of RCA porosity through addition of pozzolans
3. Thorough mixing process to encourage bonding at the ITZ

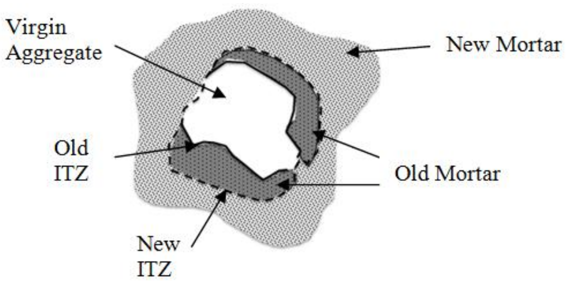

Figure 1. Interfacial Transition Zone of RAC

Aggregate Cleaning

Katz (2004) conducted a study of the surface of RCA using a scanning electron microscope and observed that a significant amount of "crumbs" were loosely attached to the bulk aggregate as a result of the crushing process. In this investigation the RCA was cleaned using an ultrasonic cleaning method which involved immersing the crushed concrete in an ultrasonic bath over 10 minutes and then changing the water and repeating the process for an additional 10 minutes. The results obtained from ultrasonic cleaning led to an improvement of 7% in the compressive strength of the concrete.

Addition of Pozzolans

The addition of silica fume provides a dense accumulation of concrete particles around the ITZ and negates the "wall effect" generally observed at the ITZ. This occurs as silica fume fine particles prevent "bleed water" from being trapped in coarse aggregate pores (Neville 1995). Therefore silica fume is most effective when it can be located on the aggregate surface. This generally equates to approximately 10% silica fume.

Using this theory Katz (2004) impregnated RCA with 10% (total cementitious content) silica fume to determine the effects on mechanical properties. The RCA was first saturated in a silica fume solution and then dried out again. An overall 15% increase in compressive strength was achieved at 28 days. It is suggested that silica fumes fine particles (100 times smaller than cement (Neville 1995)) decreased the RCA surface porosity. Silica fume also encouraged pozzolanic action converting calcium hydroxide to calcium silicate hydrate which enhances the concrete matrix and ITZ between the RCA and concrete mortar (Elhakam et. al, 2012, Olliver, Maso & Bourdette 1995).

The addition of pozzolanic materials to mix designs containing recycled concrete aggregate was also discussed by Liang & Tian (2011) who believe that mineral blending materials such as fly ash (FA), ground granulated blast furnace slag (GGBFS), silica fume and zeolite reduce the porosity of the aggregate and mend surface cracking which enhances the bond at the ITZ.

Mixing Method

Investigations conducted by Tam et al. (2006) and Kong et al. (2010) indicate that coating RCA with a 'cement slurry' prior to mixing the aggregate bulk in the concrete increases the overall strength of recycled aggregate concrete (RAC).

As silica fume is a very fine powder, adequate mixing must be conducted to ensure uniformity and that the agglomerations, which comprise the densified silica fume, are broken down. Therefore, the mixing method recommended by the Silica Fume Association was used to mix the concrete.

METHODOLOGY

RCA was procured through Gladstone Regional Council. All material was procured from a single site which included various concrete members previously used for structural purposes. The concrete members were crushed onsite to the maximum size of 20 mm. The age of the concrete is approximately 40 years and strengths may range up to 50 MPa. Initially the aggregate was cleaned to remove any contaminants and any excess mortar particles.

A mid-range structural grade concrete in a moderate environment was the basis for the concrete mix design. The mix was developed based on the following key considerations:

- Target Strength of the concrete was selected as 40MPa
- Blended cement was used with a cementitious ratio of 65% General Purpose (GP) cement (Portland cement) and 35% FA. A Target w/c ratio of 0.46 was adopted. As silica fume percentages increased, the FA content decreased. A summary of the mixes developed and the cementitious components has been shown in Table 1. FA was sourced through Gladstone Power Station and Rheomac SF 100 (silica fume) was sourced through BASF.
- The mix was designed for a typical slump of 80mm to ensure adequate workability
- As per the requirement of Australian Standard, at least 3 samples were tested for each test (compression and flexural) and the average values are summarised in Tables 3 and 5.

Table 1. Mix Summary

Mix No.	Description	Coarse Aggregate	Cementitious material	Silica Fume (%)
1	Control	Natural Aggregate	65% PC 35%FA	0
2	Control RCA	RCA	65% PC 35%FA	0
3	RCA Silica Fume-1	RCA	65% PC 30%FA	5
4	RCA Silica Fume-2	RCA	65% PC 25%FA	10
5	RCA Silica Fume-3	RCA	65% PC 20%FA	15

In the initial control mixes, there was some variability with the workability (slump) while the concrete was being mixed in the concrete mixer. Therefore, the water content was adjusted to have a suitable workability. The final ratio of water used for each mix is shown in Table 2. Relevant Australian Standards were followed for both compression and flexural tests.

Table 2. Adjusted Water-Cement Ratio

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Revised w/c Ratio	0.49	0.40	0.46	0.46	0.46

RESULTS AND DISCUSSION

Compression Strength

The resulting compressive strengths have been tabulated below in Table 3.

Table 3. Compressive Strength Results

Mix No.	Compressive Strength (MPa)		
	7 Day	14 Day	28 Day
Mix 1 (Natural Aggregate)	25.24	32.09	39.43
Mix 2 (RCA)	34.10	42.26	47.44
Mix 3 (5% silica fume)	32.25	37.21	43.28
Mix 4 (10% silica fume)	32.81	40.49	44.27
Mix 5 (15% silica fume)	33.49	40.37	43.25

It should be noted with the results presented in Table 3 that Mix 1 and Mix 2 had varying w/c ratios when compared to Mix 3, 4 and 5. Therefore, the compressive strength results presented cannot be directly compared. Strengths obtained were compared to the anticipated strengths of a conventional mix for the same w/c ratio. It should also be noted that the time for strength development of a sample is dependent on the w/c ratio. The theoretical strengths shown in Table 4 were used to 'normalise' the experimental results as shown in Figure 2.

Table 4. Estimated Compressive Strength Development of Samples

Concrete Mix	Compressive Strength (MPa)		
	7 Day	14 Day	28 Day
Mix 1 (w/c = 0.49)	23.1	35.3	42
Mix 2 (w/c = 0.40)	41.6	46.8	52
Mix 3, 4 and 5 (w/c = 0.46)	35.1	39.6	45

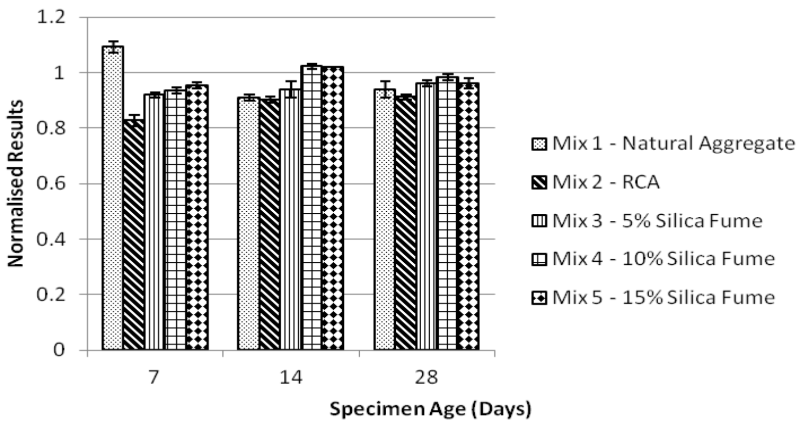

Figure 2. Normalised Compressive Strength Results

The compressive strength test results indicate some correlation between early strength increase and the addition of silica fume. Towards the end of the 28 day curing period the strength of the specimens appear to converge.

Overall, little variance in compressive strength between the samples was noted, indicating little benefit with the addition of silica fume. RCA samples with the addition of 10% silica fume did however result in a concrete with comparable strength to conventional mix concrete at 28 days. This is an improvement of 7% when compared to RCA samples with no silica fume.

Flexural Strength

The flexural strengths have been tabulated below in Table 5.

Table 5. Flexural Strength Results

Concrete Mix	Flexural Strength (MPa)		
	7 Day	14 Day	28 Day
Mix 1 (Natural Aggregate)	4.76	4.89	5.87
Mix 2 (RCA)	5.14	5.12	5.75
Mix 3 (5% silica fume)	4.86	4.95	4.57
Mix 4 (10% silica fume)	4.77	5.10	5.65
Mix 5 (15% silica fume)	4.17	5.11	5.19

Due to the w/c ratio variations, the flexural strength results were normalised using the same process applied for the compressive strength results. The comparison between the 5 mixes has been shown in Figure 3. Mix 2 was expected to gain a higher strength due to the low w/c ratio while Mix 1 was expected to gain a lower strength. This did not occur in Mix 1 and is likely due to a stronger ITZ bond between the cement paste and natural aggregate.

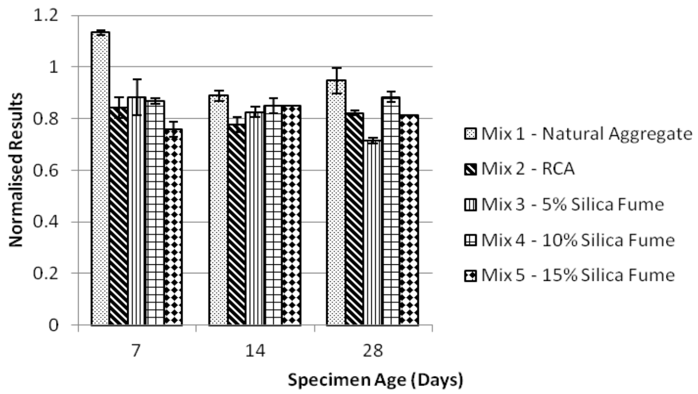

Figure 3. Normalised Flexural Strength Results

The maximum flexural strength reached at 28 days for RCA Mixes is 88% of targeted strength, using a 10% silica fume substitution (Mix 4). While this is less than theoretically expected, the strength is greater than the plain RCA sample (Mix 2). An overall increase in flexural strength of 6% is achieved with the addition of 10% silica fume.

The observed bonding and failure of the specimens support the notion that flexural strength increases with the addition of silica fume. Indication of a good ITZ bond may be found through inspection of the broken specimens. If a good bond between the aggregate and cement mortar has occurred, the broken specimens should contain some cracked aggregate as opposed to de-bonded aggregate. However this should not been in excess, as this would indicate a low strength aggregate as opposed to good bond (Neville 1995).

In the control RCA mix with no silica fume (Mix 2). Some failure of the aggregate was observed in the broken sample. However "de-bonding" of aggregate was the dominant failure mechanism. Conversely, it was noted at 10% silica fume addition (which exhibited the highest flexural strength), less "de-bonding" of aggregate occurred with a greater proportion of "aggregate breakage".

CONCLUSION

This investigation indicates favourable results with the use of silica fume in RAC. In general, the following key observations were noted:

- Comparable compressive strengths to conventional concrete were achieved for RAC.
- Addition of 10% silica fume was observed to be optimum resulting in an increase of 7% in compressive strength when compared to a sample with no silica fume. Further testing around this amount of silica fume may help to confirm this claim.
- No appreciable difference in overall compressive strength was noted with the increasing amount of silica fume although early age (7-14 days) improved with an increase in silica fume.
- Flexural strength was increased by 6% with a 10% addition of silica fume which seems to be the optimum replacement percentage when compared to the control sample.

This initial study indicates that the inclusion of silica fume does improve the properties of RAC to enable use in structural applications. Due to the small sample size, the results from this investigation should not be relied upon exclusively. Further study is necessary to confirm these effects and ensure repeatability of results.

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