Recycled glass as a partial replacement for fine aggregate in structural concrete – Effects on compressive strength

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ABSTRACT: Waste management is becoming a major issue for communities worldwide. Glass, being non-biodegradable, is not suitable for addition to landfill, and as such recycling opportunities need to be investigated. Due to the high material consumption of the construction industry, the utilisation of waste glass as a partial replacement for fine aggregate in structural concrete is particularly attractive. This project aimed to determine the level of glass replacement resulting in optimal compressive strength. Three concrete samples were tested at 7 and 28 days, for glass replacement proportions of 15, 20, 25, 30 and 40%. Compressive strength was found to increase up to a level of 30%, at which point the strength developed was 9% and 6% higher than the control after 7 and 28 days respectively. This demonstrates that concrete containing up to 30% fine glass aggregate exhibits higher compressive strength development than traditional concrete.

Keywords: Waste Management, Concrete, Compressive Strength, Waste Glass

1 INTRODUCTION

Waste management has become a significant issue in today's growing society. Population levels around the globe are increasing rapidly, resulting in unprecedented levels of waste material. New and innovative methods of recycling need to be established in order to ensure that we do not run out of room for storage. Glass, being non-biodegradable, is one such material that is not suitable for addition to landfill. Fortunately, glass can be recycled indefinitely without any loss in quality, but first needs to be sorted by colour. This is an expensive process, and subsequently waste glass is increasingly being used in applications where mixed colour is not an issue, such as an aggregate in civil construction. Despite these markets, the recycling rate of post-consumer glass within Australia was only 47.3% in 2012 (Australian Packaging Convent 2013). This clearly demonstrates the need for an alternative method of glass recycling, one in which large quantities of waste can be consumed.

The construction industry presents an attractive market for the use of waste glass. One of the principal components of construction is concrete, due to its high compressive strength, durability and ease of construction. However, concrete production is highly resource and energy intensive, with the industry responsible for approximately 5-8% of worldwide greenhouse gas emissions (Scrivener and Kirkpatrick 2008). As such, opportunities to reduce the environmental impacts of the concrete industry are required.

With natural aggregates within Australia being present in limited quantities, producing crushed aggregate for use in the construction industry is costly. It can therefore be seen that incorporating recycled glass as an aggregate in structural concrete has the potential to not only produce environmental benefits in the reduction of landfill and the consumption of raw materials, but to also reduce costs for industry costs.

Early studies into the effects of incorporating waste glass into concrete focused on its suitability as a replacement for coarse aggregate. The results from these tests demonstrated that the presence of larger glass particles caused excessive expansion and cracking of the concrete specimens, resulting in compromised structural integrity. These effects can be attributed to the strong reaction between the alkali in cement and the reactive silica in glass (Johnson 1974). In order to minimize alkali-silica reactions

(ASR), the partial replacement of fine aggregate and/or cement in concrete has been investigated. Research has concluded that the increasing proportions of crushed glass as a replacement for fine aggregate results in an increase in ASR expansion (Oliveira et al. 2013, Serpa et al. 2013). Saccani and Bignozzi (2008) found that mixes containing up to 35% fine glass aggregate displayed levels of expansion that were below the deleterious limit set in ASTM C1260 (American Society for Testing and Materials 2007). Furthermore, Zhu et al. (2004) identified that glass particles finer than 1.18 mm exhibited lower expansion than natural fine aggregate, even after extended testing. When glass was crushed to a particle size finer than 75µm, concrete specimens were found to achieve prolonged compressive strength development, which can be attributed to the pozzolanic nature of very fine glass powder (Chen et al. 2006).

A study undertaken by Shayan and Xu (2006) demonstrated that concrete specimens containing glass as a fine aggregate achieved higher levels of compressive strength than those containing glass as a cement replacement. Similar results were obtained by Taha and Nouno (2009), who found that concrete containing glass as a partial replacement for cement exhibited lower levels of compressive strength than the control mix. Due to the importance of compressive strength development in structural concrete, it is concluded from these findings that the greatest benefits may be derived from incorporating waste glass as a replacement for fine aggregate, with particle size limited to ensure detrimental ASR effects are mitigated.

Recent studies which have focused on the suitability of using waste glass as a partial replacement for fine aggregate have found promising results. One crucial finding from this research has been that glass colour has no influence on concrete properties (Park et al. 2004), eliminating the need to sort post-consumer glass by colour, and thus making this an attractive form of recycling.

The addition of waste glass to the concrete mix has been found to decrease concrete slump, yet workability was still deemed sufficient adequate without the need for admixtures at for replacement levels up to 50% (Taha and Nounu 2008). In higher mix proportions, the addition of waste glass was found to negatively affect the properties of fresh concrete, resulting in severe segregation and bleeding of the mix (Taha and Nounu 2009).

Fresh and dry densities of concrete have been shown to be directly influenced by the addition of glass aggregate. An increase in the percentage of natural aggregate replaced with glass leads to a reduction in the unit weight of concrete (Józsa and Nemes 2002,Topcu and Canbaz 2004), and can be seen as one of the key benefits of incorporating glass aggregate into concrete.

Conflicting results have been obtained regarding the effect of fine glass aggregate upon the development of compressive strength. Tuncan et al. (2001) demonstrated that compressive strength increased along with the addition of waste glass in replacement levels up to 15%. Further studies conducted by Ismail and AL-Hashmi (2009) demonstrated that concrete containing 20% fine glass aggregate exceeded the compressive strength developed by plain concrete. Du and Tan (2014) found that concrete containing up to 100% glass sand obtained similar compressive strength to that of the control after 28 days, with 90 day compressive strength increasing with glass percentage. Park et al. (2004) found conflicting results, with concrete containing in excess of 30% glass aggregate failing to develop strength equal to that of the control, whilst displaying a decreasing trend with the addition of further glass. Similar findings were reported by Limbachiya (2009), with compressive strength decreasing substantially beyond 20% replacement. Malik et al. (2013) conferred with these findings, reporting that concrete containing up to 30% glass aggregate achieved higher compressive strength than plain concrete, with compressive strength decreasing for higher mix proportions. Early strength development was found to be comparable to that of natural aggregate concrete (Topcu and Canbaz 2004; Tuncan et al. 2001).

With no clear consensus currently available in literature, this study will seek to clarify the effects that fine glass aggregate has on the compressive strength of concrete, especially focusing on the materials available in Australia. Specifically, the percentage of fine glass aggregate resulting in optimum compressive strength development will be identified for structural concrete through testing at both seven and twenty eight days.

2 METHODOLOGY

2.1 *Mixture design*

Concrete mix designs adopted throughout this study were undertaken in accordance with the procedure specified in ACI 211.1 (American Concrete Institute 2009). All mixes were proportioned in order to achieve a design compressive strength of 40 MPa after 28 days. Corresponding water-cement ratio was calculated as 0.42. A control mix was produced containing only natural aggregate, with five resulting mixes incorporating waste glass as a partial replacement for fine aggregates in proportions of 15, 20, 25, 30 and 40%. As the crushed glass exhibited a lower fineness modulus than the natural aggregate, minor adjustments were made to each mix design to ensure that strength and workability design parameters remained constant. The adjustments involved increasing the bulk volume of coarse aggregate to compensate for the reduced fineness modulus, and therefore a subsequent reduction in fine aggregate volume. These changes ensured a design compressive strength of 40 MPa was achieved for all batches. A summary of the individual mix designs is presented below in Table 1.

Table 1. Concrete mix design summary.

	Glass replacement percentage					
	0	15	20	25	30	40
Water	190	190	190	190	190	190
Cement	458	458	458	458	458	458
Coarse aggregate	925	935	939	942	946	953
Natural fine aggregate	739	613	573	533	493	417
Glass fine aggregate	0	108	143	178	211	278

2.2 *Material preparation*

2.2.1 *Coarse and Fine Aggregate*

The aggregates used in this project were sourced from Australian suppliers and were readily available in the country. The coarse aggregate was of angular nature and originated from Anakie quarry, with a nominal maximum aggregate size of 19 mm. The fine aggregate was in the form of river sand, originating from the Moriac region. The physical properties of both aggregates can be seen in Table 2. Both coarse and fine aggregates used in this project conformed to requirements specified in AS 2758 (Australian Standards 2014).

Table 2: Physical properties of aggregates

Property	Coarse	Fine	Glass
Fineness modulus	-	2.61	2.11
Saturated-surface-dry (SSD) density (kg/m3)	2662	2587	2440
Dry density (kg/m3)	2584	2576	2430
Water absorption (%)	3.0	0.4	0.4

2.2.2 *Waste Glass*

Waste glass for this experiment was sourced from a glass recycling company in the Sydney region. The company collects mixed colour post-consumer container glass, before subjecting the material to a crushing and milling process in order to create a fine aggregate. The typical chemical composition of the glass aggregate can be seen below in Table 3. The glass was further subjected to a mechanical sieving process, with fractions in excess of 1.18 mm being discarded in order to avoid excessive ASR. This also allowed for the removal of organic impurities, which separated to the top during the sieving process. The resulting glass particle size distribution and the gradation of sand are presented in Table 4, whilst the physical properties are summarised in Table 2.

The gradation of glass sand was carefully selected to reduce effects of ASR. This led to non-uniform gradation between the two fine aggregates, with the glass sand displaying a lower fineness modulus (Table 2). These variations were accounted for during mix design process to ensure resulting concrete specimens were comparable.

Table 3: Typical chemical composition of waste glass aggregate

Composition	Percentage (%)
Bound metal oxides (Ca, Mg, Na, Li, K, Al)	20-30
Bound amorphous silica	70-80
Other metal oxides	<1
Free crystalline silica	<1

Table 4: Gradation of sand and waste glass aggregates

Sieve size	Accumulated passing (%)	
	Sand	Waste glass
4.75 mm	100.00	100.00
2.36 mm	93.55	100.00
1.18 mm	71.62	100.00
600 µm	47.44	56.34
425 µm	36.48	40.67
300 µm	22.54	25.00
150 µm	3.69	7.75
75 µm	0.41	1.94

2.2.3 *Cement*

The cement used in the production of all concrete for this project was a general purpose Portland cement manufactured in Australia. The cement conformed to the requirements set out within AS 3972 (Australian Standards 2010), ensuring its suitability for structural applications.

2.3 *Experimental procedure*

In this study, the production of concrete for this test was conducted at the concrete laboratory at Deakin University. All preparation of concrete was undertaken in accordance with AS 1012 (Australian Standards 2014). Six specimens were created for each percentage replacement of glass, with three samples being used for the seven and twenty eight day compressive strength tests, respectively. Mixing of the concrete was carried out in a standard concrete mixer. Slump tests were then undertaken in accordance with the provisions of AS 1012.3.1 (Australian Standards 2014) to measure workability.

Concrete moulds used were cylindrical, being 100 mm in diameter and 200 mm in height. To prevent adhesion, all moulds were coated with a thin layer of concrete release, which consisted of 93% liquid hydrocarbons In preparing the final samples, concrete was added to the concrete moulds incrementally. Each layer was subjected to vibration with a stick vibrator for 5 - 10 seconds, and was ceased once visibly trapped air was eliminated. Concrete was allowed to air-cure for a period of 24 hours, before being removed from the moulds and transferred to a water bath set at 23 degrees for the remainder of the curing period.

The mechanical tests undertaken on the cured concrete specimens were conducted within the concrete laboratory. The equipment used to carry out the tests consisted of a 3000 kN load frame connected to a software system provided by Tecnotest. The bottom plate of the load frame was connected to the hydraulic ram and was in a fully fixed position, whilst the top plate was free to seat itself upon the test object in order to ensure that a uniform pressure was applied.

Tests to determine the compressive strength of the concrete were carried out after both seven and twenty eight days. Once being removed from the water bath, the concrete cylinders were allowed to surface dry before their weight was measured. The samples were then placed within two steel caps, fitted with 15mm thick rubber mats. The rubber mats allowed for a tolerance of 4mm in level across the surface of the cylinder. The individual samples were then centred within the testing frame, with the troweled surface facing the top plate to further ensure that any differences in level did not affect test results.

To assess compressive strength of the samples, the load was gradually added to the specimens, at a rate of 20 MPa/min. Once the software detected that the load acting on the sample had decreased, the addition of load was automatically ceased and the test completed.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Workability*

The slump test was adopted as the primary measure of concrete workability in this study, and was undertaken in accordance with AS 1012.3.1 (Australian Standards 2014). The results obtained from these tests are presented below in Figure 1. An initial slump of 65 mm was obtained for the plain concrete mix, with mixes containing waste glass exhibiting slumps ranging from 15% higher to 30% lower than that of the control. Regardless of these discrepancies, it can be seen that the slump demonstrates a decreasing trend in response to the addition of waste glass. Similar observations have been recorded in previous research, concluding that this may be attributed to a combination of poor glass geometry and reduction in fineness modulus (Ismail and Al-Hashmi 2009). However, the contribution of fineness modulus to this trend may be disputed, as these effects were accounted for during the mix design process via altering the ratio between coarse and fine aggregate. It is therefore suggested that the reduction in slump is solely due to the angular geometry of glass particles, which reduces the availability of cement paste and hence the fluidity of the mix. Despite the reduction in slump values, all concrete mixes were considered workable and were within tolerance levels of 25 mm. No excessive bleeding or segregation of concrete specimens was encountered during preparation, supporting earlier research that indicated fine aggregate replacements less than 50% had minimal negative effects on properties of fresh concrete (Taha and Nounu 2009)

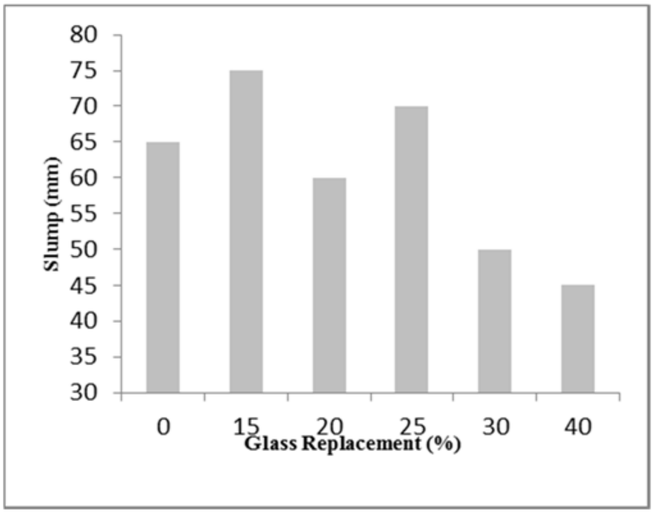

Figure 1. Results from slump test

3.2 *Fresh and Dry Density Tests*

As can be seen below in Figure 2, the replacement of sand with waste glass has a measurable effect on both fresh and dry density, with a decreasing trend resulting from the addition of glass to the mix. At a glass replacement level of 40%, this culminates in a variance of 2.4% and 2% in fresh and dry densities respectively, when compared to the control. This can be attributed to the lighter specific gravity of the glass aggregate, which was 5.4% lighter than the sand used. However, this effect was marginally off-set by the decrease in ratio between fine and coarse aggregate in each resulting mix. These findings support earlier research (Józsa and Nemes 2002; Topcu and Canbaz 2004) which concluded that the unit weight of concrete is reduced by replacing natural fine aggregate with glass.

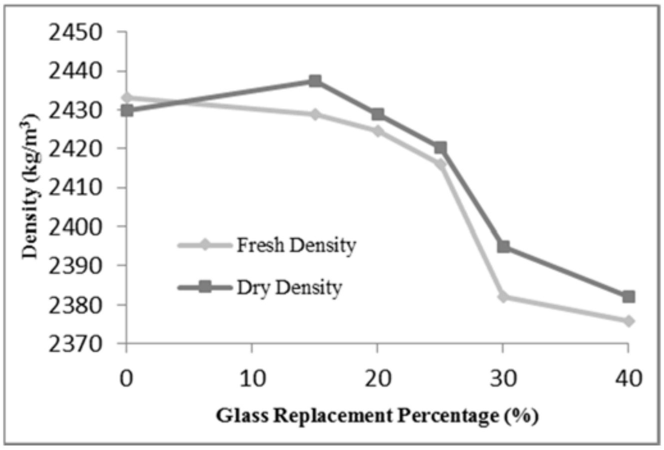

Figure 2. Results of fresh and dry density tests.

3.3 *7 Day Compressive Strength Test*

The average value recorded from compressive strength tests carried out on specimens cured for 7 days can be seen below in Figure 3. An increasing trend can be witnessed along with the addition of glass aggregate, until the maximum compressive strength (46.5 MPa) was developed at a replacement level of 30%. All mixture proportions containing waste glass to this point exceeded the strength developed by the control, with the 30% glass mix recording a compressive strength 9% higher. These findings support earlier research conducted by Tuncan et al. (2001), where the compressive strength of concrete after 7 days of curing was found to increase with the addition of glass, albeit at lower levels of replacement.

Addition of waste glass beyond the optimum level resulted in a significant reduction to the level of compressive strength developed. At a glass replacement level of 40%, the compressive strength achieved (35.1 MPa) was 17% below the control and 25% below the maximum recorded value.

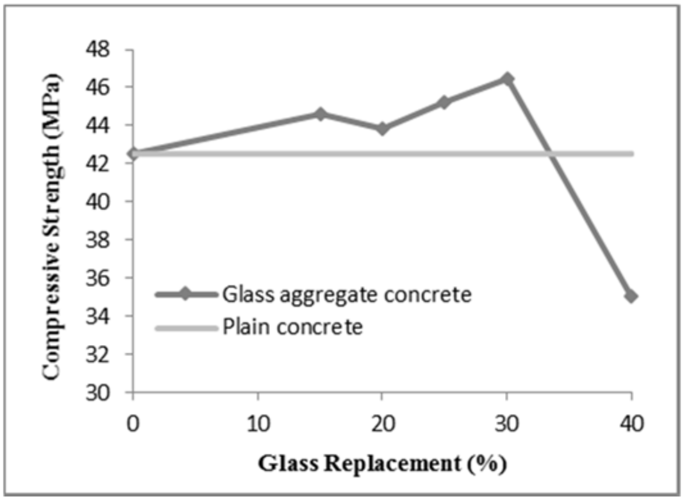

Figure 3. Comparison of the 7 day compressive strength between the control and glass aggregate concrete.

3.4 *28 Day Compressive Strength Test*

The results of compressive strength tests following 28 days of curing can be seen in Figure 4 below. The results closely mirror that of the seven day test, with the compressive strength following an increasing trend with the addition of waste glass up until an optimum percentage of 30%. At this point, the maximum compressive strength developed was 58.5 MPa, 6% higher than that achieved by the control (55.1 MPa). The increase in strength above that of the control may be attributed to the angular nature of the glass aggregate, which has a greater surface area than the naturally rounded sand particles. This increased surface area allows for greater bonding with the cement paste, resulting in a stronger concrete matrix.

The specimen containing 40% waste glass was found to have achieved a compressive strength of 47.2 MPa, 16% lower than that achieved by the control. This concurs with the results obtained from the 7 day test, and it can therefore be concluded that levels of glass replacement in excess of 30% adversely affect the development of compressive strength. Similar findings were obtained by Malik et al. (2013), who found that compressive strength reduced by 8% at a glass replacement percentage of 40% when adopting a similar glass particle distribution as to that adopted in this study. Whilst previous studies have implied that this tendency is a result of reduced adhesion between the glass particles and cement paste (reference), the results from this study suggest that the angular nature of the glass particles may further contribute to the witnessed reduction in strength. It is suggested that where glass aggregate is present in higher proportions, there is insufficient cement paste available within the mix to facilitate bonding with all particles, resulting in the formation of microscopic voids which adversely affect concrete strength.

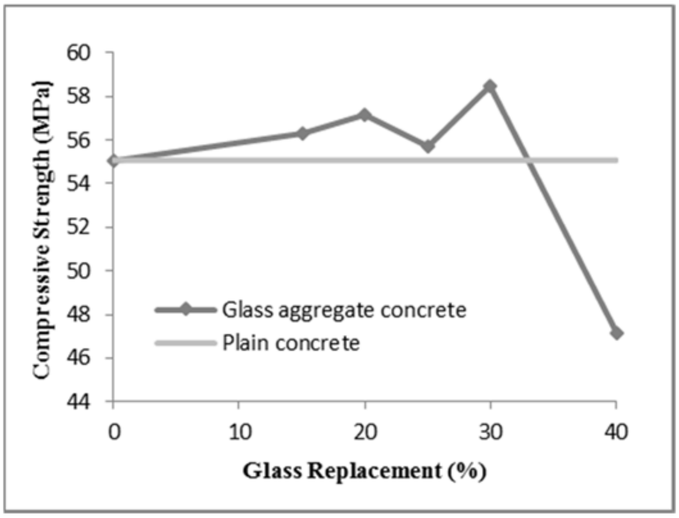

Figure 4. Comparison of the 28 day compressive strength between the control and glass aggregate concrete.

3.5 *Discussions*

The results obtained from compressive strength tests at both 7 and 28 days (Figures 3 and 4) appear to display inconsistent results. After 7 days of testing, compressive strength for the sample containing 20% glass aggregate replacement achieved a compressive strength 1.9% lower than sample containing 15% glass aggregate. Likewise, 28 day compressive strength for specimens containing 25% waste glass was 3.5% lower than that measured for 20% glass replacement. It is noted that only 2 samples were tested at 28 days due to voids being present in the third sample due to insufficient vibration. All values of compressive strength obtained for the samples in question achieved higher compressive strength than the control. As such it is suggested that the discrepancies noted are due to variations in the properties of concrete specimens and as such do not diminish the validity of the identified trend.

Table 5: Maximum variance within sample groups

Maximum variance	Glass replacement percentage					
	0	15	20	25	30	40
MPa	1.45	1.44	2.20	0.06	0.80	1.41
%	2.7	2.6	3.9	0.1	1.4	2.3

Further, the experimental results show unexpectedly high readings of compressive strength development by both the control and samples containing fine glass aggregate. For the control set, the test results indicated that 28 day compressive strength increased 37.7% above the design value of 40MPa. However, as can be seen in Table 5, the discrepancy of test results between samples containing the same percentage glass can be seen to be very small. After careful scrutiny, it was concluded that the increase in compressive strength was due to the high quality of cement rather than experimental or equipment errors. Regardless of the high readings, the results as shown in sections 3.1 to 3.4 are compared between the resulting groups and the control, and therefore the following observations and conclusions can still be drawn.

4 CONCLUSIONS

This experimental study sought to identify the effects of implementing waste glass as a partial replacement for fine aggregate in structural grade concrete. The results obtained demonstrate that doing so can in fact ‘add value’, and in conjunction with environmental legislation focusing on sustainable building development, may act as an incentive for the construction industry to incorporate this waste material into their practices. This would result in a twofold benefit for the environment, reducing the consumption of raw materials and diverting additional waste from landfill. The main findings of the study can be summarised as follows:

1. The workability of concrete followed a decreasing trend with the addition of fine glass aggregate, due to the angular nature of the glass particles. Despite this trend, the concrete was deemed workable and was within the specified tolerance intervals.
2. The optimum percentage replacement of sand with fine glass aggregate was determined to be 30%.
3. Compressive strength was found to increase with the addition of waste glass to the mix up until the optimum level of replacement. This can be attributed to the angular nature of the glass particles facilitating increased bonding with the cement paste.
4. In proportions exceeding 30%, waste glass was found to negatively impact the development of compressive strength. It is suggested that in larger quantities, the angular nature of the glass aggregate reduces available cement paste and leads to the formation of microscopic voids within the concrete matrix.

5 ACKNOWLEDGEMENTS

This work is partially supported by the Australian Research Council (ARC) through Discovery Project program (DP130104332).

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