SUSTAINABLE STRUCTURAL MATERIAL COMBINING RECYCLED AGGREGATE AND STEEL FIBRES

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ABSTRACT

Recyclable concrete is now increasingly recognised as a sustainable building material, which could be effectively used in building construction. However, at present, recycled concrete created from recycled aggregate has mainly been used for non-structural and sub-grade applications around the world because companies have long believed that it is inferior to the normal aggregate generation. This research was undertaken with the hypothesis that recycled concrete can be as strong as the normal concrete which is suitable for structural applications when incorporated with steel fibres. Previous research has shown that steel fibre can effectively improve the toughness, shrinkage, and durability characteristics of concrete. Recycled concrete, which is weak in shrinkage properties, can therefore be enhanced by incorporating steel fibres. This paper reports initial experimental results that aims to explore the behaviour of recycled concrete when steel fibre is added. The experiments considered varying steel fibre volumes of about 0%, 30% and 60% with recycled aggregate replacement ratios of about 0%, 30% and 100%. It is found that the more recycled aggregate replacement ratio of the recycled concrete, the lower the compressive strength is. However, the addition of steel fibre can improve the compressive strength of the concrete mixes. The initial experiments reveal the possibility of creating a new material for structural purposes and will thereby contribute to sustainability by resolving environmental issues such as carbon emissions and wasted management. Future research will be carried out to conduct further tests when the material is used in structural members.

Keywords: *Australia; Recycled Aggregate; Recycled Aggregate Concrete; Shrinkage; Steel Fibre.*

1. INTRODUCTION

The global policy attention directed toward climate change and environmental sustainability has created challenges to the Australian construction industry (Manley and Rose, 2012). In particular the industry requires to seek innovative solutions for reducing the impact of constructing and maintaining the built environment on the earth. The structural frame of the building accounts for the highest cost of the building. Using environmentally and economically sustainable materials such as recycled concrete and steel fibres for the building construction would enable effectively respond to industry challenges.

Recycled concrete is now increasingly recognised as a sustainable building material. Recycled aggregate is wasted-crushed concrete consisting of old aggregate and old cement mortar. More than ten million tonnes of concrete waste were generated in South-Eastern Australia annually (Bakoss and Ravindrarajah, 1999; Australian Government: Productivity Commission, 2006; Queensland Government, 2007). Carbon emissions from the generated concrete waste have been considered as an important issue in Australia and around the world. The World Wide Fund for Nature reports that the concrete industry's share of global carbon emissions is about 8%. If recycled concrete is effectively used, the Australian construction industry may be capable of reducing its carbon emissions by up to 90% (World Wide Fund for Nature, 2010).

On the other hand, recycled concrete created from recycled aggregate has mainly been used for non-structural and sub-grade applications around the world because companies have long believed that it is inferior to the normal aggregate generation. Because of this misleading consensus, research on recycled concrete for high-grade structural applications and composite structures has been weak which has not realised its full potential. This project not only creates a new material for composite structural purposes but also resolves carbon emissions and wasted concrete storage problems (Commonwealth Scientific

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and Industrial Research Organisation, 1998; Commonwealth Scientific and Industrial Research Organisation, 2002; Commonwealth Scientific and Industrial Research Organisation, 2006).

Some researchers have compared the behaviour of composite steel-concrete beams using steel fibres and conventional reinforcement (Mookerjee *et al*., 1985; Mirza and Uy, 2009). These researchers have established that the composite steel-concrete beams with steel fibres could sustain higher loads than normal concrete. When steel fibre reinforcement was added to the concrete, the concrete exhibited improved confinement and better bond. Moreover, steel fibres also enhanced the rotational and moment capacity. The combination of steel fibres with a concrete slab not only increases structural stiffness and ductility, but also provides slabs with a fire rating ranging from 60 to 90 minutes (Mookerjee *et al*., 1985; Mirza and Uy, 2009).

Two aspects are to be considered when steel fibre reinforced concrete is used in concrete beams; shear stud resistance and ductility and the ability of steel fibre reinforced concrete to resist transverse shear in the slabs adjacent to the shear studs (Robery, 2002). Steel fibres have been replaced with welded wire fabric (WWF) as secondary reinforcement and verified that both deflection and cracks decreased in composite beams (Roberts-Wollmann *et al*., 2004). They also demonstrated that it was preferable to use steel fibres rather than synthetic fibres. A slab reinforced with 29.6 kg/m3 of steel fibres had a higher ultimate strength (18%) than a slab reinforced with WWF. Using steel fibres also resulted in a higher ultimate capacity. The researchers also showed that the composite beam reinforced with 0.9 kg/m3 of synthetic fibres failed at a load equivalent to the WWF (Roberts-Wollmann *et al*., 2004).

Generally, concrete which is weak in tension because of its low fracture strength is to resist predominantly compressive actions and the use of steel reinforcement is to resist predominantly tensile actions. Similarly, it is believed that recycled concrete with incorporation of steel fibres will offer a structurally sound material that is not only more cost effective, but also provide a reliable and sustainable solution to Australian Construction Industry. In line with this, this research will be expanded to include a reliability test and a cost benefit analysis.

In terms of reliability, the design codes in most countries including Australian Standards (OHBDC, 1983; ASHTO, 1994; Eurocode 3, 2002) have adopted the Load and Resistance Factor Design (LRFD) format (Faber and Sorensen, 2002). This format aims at achieving a relatively consistent reliability level in structural design through the appropriate introduction of safety margins. Under this format, the novel design should be used in structural design after careful verification of their mechanical strength prediction models and the associated safety margins (capacity factors), which should be determined based on a sufficient number of strength test results and rigorously measured uncertainties.

In terms of cost-benefits, although there is lack of cost information on this novel design, several previous studies showed the economic, environmental and social advantages of using recycled concrete against normal concrete. For example, it would reduce the need to use normal concrete and natural resources; avoid accidental collapses that would happen by unlimited use of sand and gravel from the river systems; reduce the need to treat construction and demolition waste before dumping; and save landfill spaces and life (Tam, 2008). On the other hand, use of steel fibre to strengthen concrete reinforcement structures is seen as a cost effective option that increase the durability and reliability of the structural design (Wang *et al*., 2000). The long-life span enabled by steel fibre would mean less operational costs. A proper cost-benefit analysis (CBA) would consider these benefits in evaluating feasibility of the new proposal.

All in all, this research is believed to be the first fundamental and comprehensive study of composite steel-concrete beams utilising recycled aggregate and steel fibres. It integrates the disciplines of civil, structural engineering and construction management, and employs computational techniques to gain a fundamental understanding composite steel-concrete beam utilising recycled aggregate and steel fibres. This investigation will improve the performance of composite beams while achieving sustainability and reliability. This paper examines the initial experimental results on the compressive strength of concrete cylinders with varied percentages of recycled aggregate and steel fibre.

2. EXPERIMENTAL STUDIES

Normal and recycled aggregate samples collected from south-eastern Australia centralised recycling plant were used for investigating the properties of recycled concrete. Table 1 summaries the water absorption and standards used for the normal and recycled aggregate samples.

Table 1: Water Absorption and Standards Used for the Normal and Recycled Aggregate Samples

Samples	Water Absorption (%)	Standards Used
10mm normal aggregate	1.2	(AS 1141.6.1, 1995)
10mm recycled aggregate	5.9	(AS 1141.6.1, 1995)
20mm normal aggregate	0.7	(AS 1141.6.1, 1995)
20mm recycled aggregate	4.3	(AS 1141.6.1, 1995)

A comprehensive set of experiments which considers a different steel fibre volume of about 0%, 3% and 6% with recycled aggregate replacement ratios of about 0%, 30% and 100% were examined. Details of all mix designs used for the recycled concrete experimental work are shown in Table 2. In total, nine mixes were conducted.

Table 2: Recycled Concrete Mix Designs Used for the Experimental Work

Mix	0-0	30-0	100-0	0-30	30-30	100-30	0-60	30-60	100-60
Cement (kg)	700	700	700	700	700	700	700	700	700
20mm normal aggregate (kg)	657	197	-	657	197	-	657	197	-
20mm recycled aggregate (kg)	-	460	657	-	460	657	-	460	657
10mm normal aggregate (kg)	329	99	-	329	99	-	329	99	-
10mm recycled aggregate (kg)	-	230	329	-	230	329	-	230	329
Coarse sand (kg)	310	310	310	310	310	310	310	310	310
Fine sand (kg)	100	100	100	100	100	100	100	100	100
Water (kg)	245	245	245	245	245	245	245	245	245
Superplastizer (litres)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Retarder (litres)	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Steel fibre (kg)	0	0	0	11	11	11	21	21	21

The recycled concrete mixing was first charged with about half of coarse aggregate, then with fine aggregate, then with cement, and finally with the remaining coarse aggregate. Water was then immediately added after starting the operation for two minutes according to the Australian Standard (AS1012, 1993).

The 28-day compressive strength from the different mix designs for the recycled concrete were conducted based on Australian Standard (AS 1012.9, 1999). The average of the three samples of the 28-day compressive strength tests was calculated.

3. RESULTS AND DISCUSSIONS

This is the first time that composite steel-concrete beams utilising recycled aggregate and steel fibres are studied. Recycling of concrete waste as aggregate that is suitable for non-structural concrete applications is emerging as a commercially viable and technically feasible operation. The concrete industry at present globally consumes 8 to 12 billion tons of natural aggregate annually (Heeralal *et al*., 2009). This could cause large scale destruction of the environment. Utilisation of recycled aggregate can minimise the environmental impact and slowdown the huge consumption of natural resources used for concrete applications.

Researcher (Paskova and Meyer, 1994; Ong *et al*., 1997) had undertaken several studies on the effect of steel fibres on normal concrete but they did not consider the combination of composite steel-concrete utilising recycled aggregate and steel fibres. Common applications of reinforced concrete with steel fibres include paving applications such as in airports, highways, bridge decks and industrial floors (Spadea and Bencardino, 1997). By adding the steel fibres, it endures significant cyclic loading during their service life. This argument was not only agreed by the researchers (Subramaniam *et al*., 1999; Cachim *et al*., 2000), but they also proved that steel fibres distributed in the concrete delay the growth of cracks thus improve the ductility of the matrix. Therefore, implementing recycled concrete with steel fibres in the composite steel-concrete beams has a great potential.

The ability of steel fibres in improving the properties of concrete depends on the bond characteristics, aspect ratio of the fibres, surface friction and tensile strength of the fibres. Therefore, all of this will be undertaken in this research herein. Flexural failure is one of the principal modes of failure to be considered in the design of beams subjected to bending loading. The flexural criterion is the most important factor in the design of beam structures. The criterion is used to predict failure and is normally investigated through material testing and full scale beams test in laboratory.

3.1. MATERIAL STRENGTHS

Table 3 summaries the slump test results for the experimental work. It is ranged from 130mm to 240mm for the nine mixes. As the same amount of superplasteriser and retarder are added for each mix for controlling the consistent among the mixes, slight variations on slump test results are acceptable.

Table 3: Slump Test Results for the Experimental Work

Mix	Slump (mm)
0-0	220
30-0	190
100-0	160
0-30	220
30-30	200
100-30	150
0-60	240
30-60	130
100-60	170

Table 4 summaries the compressive strength test results for the experimental work. It is not surprised to find that the more recycled aggregate replacement ratio of the recycled concrete, the lower the compressive strength is. It relates to the attachment of old cement mortar on the recycled aggregate, which is the main source in reducing the concrete performance. For example, 43.40MPa is recorded for 0% recycled aggregate replacement ratio while 41.2MPa for 30% recycled aggregate replacement ratio and 35.77MPa for 100% recycled aggregate replacement ratio with no steel fibre added in the concrete mixes. Similar results can also found on 30% and 60% steel fibres added in the concrete mixes. With 30% steel fibre added in the concrete mixes, 52.17MPa is recorded for 0% recycled aggregate replacement ratio while 45.4MPa for 30% recycled aggregate replacement ratio and 35.50MPa for 100%

recycled aggregate replacement ratio. In addition, with 60% steel fibre added in the concrete mixes, 53.1MPa is recorded for 0% recycled aggregate replacement ratio while 46.1MPa for 30% recycled aggregate replacement ratio and 46.35MPa for 100% recycled aggregate replacement ratio.

Table 4: Compressive Strength Test Results for the Experimental Work

Mix	Compressive strength (MPa)				
	Test 1	**Test 2**	**Test 3**	**Average**	**Coefficient of Variation**
0-0	52.5	34.3	-	43.40	0.2965
30-0	40.5	40.6	42.5	41.20	0.0274
100-0	36.6	37.2	33.5	35.77	0.0555
0-30	47.0	47.8	61.7	52.17	0.1584
30-30	44.5	44.9	46.8	45.40	0.0271
100-30	42.1	32.2	32.2	35.50	0.1610
0-60	46.2	59.0	54.1	53.10	0.1216
30-60	44.2	40.3	53.8	46.10	0.1507
100-60	46.1	46.6	-	46.35	0.0076

The additions of steel fibre are aimed to improve the recycled concrete properties. From the experiment results, it is found that the addition of steel fibre can improve the compressive strength of the concrete mixes. With the additions of steel fibre, all concrete mixes with 60% volume of steel fibre found to improve the compressive strength results while the additions of 30% volume of steel fibre found to be slightly improve the compressive strength results with the same recycled aggregate replacement ratios. For example, 43.40MPa is recorded for 0% steel fibre volume while 52.17MPa for 30% steel fibre volume and 53.1MPa for 60% steel fibre volume with no recycled aggregate added in the concrete mixes. Similar results can also found on 30% and 100% recycled aggregate replacement ratios in the concrete mixes. With the 30% recycled aggregate replacement ratio, 41.2MPa is recorded for 0% steel fibre volume while 45.4MPa for 30% steel fibre volume and 46.1MPa for 60% steel fibre volume. With the 100% recycled aggregate replacement ratio, 35.77MPa is recorded for 0% steel fibre volume while 35.5MPa for 30% steel fibre volume and 46.35MPa for 100% steel fibre volume.

It should be highlighted that the additions of 60% steel fibre volume for the recycled concrete mix can improve the compressive strength of recycled concrete. Further research is required to investigate whether further additions of steel fibre volume can further improve the performance of recycled concrete.

3.2. *STATISTICAL ESTIMATION OF DESIGN STRENGTH*

To confirm the structural use of the proposed composite steel-concrete beams with recycled aggregate and steel fibres, the design strengths of the proposed composites are calculated and compared based on the reported initial test results, as a preliminary study. The design strength of a material is defined by the characteristic strength divided by a partial factor and is calculated using the following equation (AS 5104, 2005):

$$f_{cd} = f_{cm} \exp(-\mathrm{k_d} \mathrm{V}_{f'_c} - 0.5 \mathrm{V}^2_{f'_c}) \qquad \text{(Eq: 01)}$$

where f_{cd} = design compressive strength of concrete, f_{cm} = mean measured compressive strength of concrete; $\mathrm{k_d}$ = the fractile factor corresponding to the target reliability index β considering the uncertainties from a number of test data N using a t-distribution; and $V_{f'_c}$ = the coefficient of variation of the characteristic compressive strength f'_c.

Here, the target reliability index is taken as 3.04, by multiplying the target reliability β_t = 3.8 suggested for ultimate limit-state design and the First Order Reliability Method (FORM) sensitivity factor when resistance is taken as 0.8 (EN 1990, 2002).

Using Eq: 01, the design strength of the three representative mix cases are calculated: (i) no recycled aggregate replacement and no steel fibre, (ii) 30% recycled aggregate replacement and no steel fibre, and (iii) 30% recycled aggregate replacement and 60% steel fibres. The design strength of case (i) is calculated based on = 0.10 (AS 3600, 2009), and no uncertainty due to an insufficient number of data is considered because its design strength has already been confirmed by many test results. However, the design strengths of cases (ii) and (iii) are calculated based only on the reported test results because there are no further test results. In these cases, is taken as 0.11, which is estimated by averaging the coefficient of variations for all mix cases, based on the assumption that the coefficient of variation is constant for varying mean measured strengths. The coefficient of variations for each mix case is calculated in Table 4, and the calculation results of the design strengths are reported in Table 5.

Table 5: Design Strengths

Mix	Design Strengths (MPa)
0-0	31.86
30-0	28.05
30-60	31.39

From these calculation results, it should firstly be noted that the mix design with 30% recycled aggregate replacement with no steel fibres shows slightly lower design strength than that of the normal concrete. This is due to the slightly lower mean measured compressive strength and the uncertainty created from the insufficient number of data collected. The result can be improved by collecting more experimental data, but based on the reported initial test results, the 30% recycled aggregate replacement cannot replace normal concrete in structural design. Second, it should also be noted that the strength reduction by the use of 30% recycled aggregate replacement can be overcome by adding 60% steel fibres as shown in Table 5 where the design strength of cases (i) and (iii) are very close to each other. This indicates that mix case (iii) can be used in a real design to replace normal concrete even based on the current limited number of test results. As more experimental data are collected, the design strengths may increase as the uncertainties from the insufficient number of data are reduced.

3.3 COST-BENEFIT ANALYSIS

It is not only important to analyse the structural suitability and reliability of the novel design, but also the cost effectiveness. The novel design may not be attracted if it is not financially feasible. By carrying out a CBA, this research aims not only to evaluate the immediate economic benefits of the novel design, but also identify the environmental and social benefits to prove the sustainability effects of the design. CBA had gained popularity in evaluating feasibility of new designs that carry significant environmental advantages.

Cost effectiveness of using recycled concrete as a material over normal concrete has been proved by using CBA (Tam, 2008). However, there are no studies that had looked into the cost effectiveness of a structural member when utilising sustainable material such as recycled concrete with steel fibre. Altun and Aktas (2013) explained that steel fibre can be mixed together with concrete for partial or full replacement of traditional steel work decreasing labour intensive hours, delivery, storage and the need for continuous inspections thus saving time and money. Full replacement of traditional steel also decreases cost on steel reinforcement which is one of the most expensive component in structural elements. Therefore, by adding steel fibre (60% -21kg) to recycled aggregate concrete which is very less expensive to reinforcement (generally $3 per kilogram), there will not be a significant cost increase even in the initial costs. When the economic benefits of RAA are considered along the lifecycle costs significant benefits are predicted for this option. Hence, a CBA is underway for this study by comparing the two options (1) Composite beams with normal concrete, and (2) Composite beams with optimal combination of recycled concrete and steel fibre (30-60). Cost data will be gathered from published resources and in-depth interviews with industry practitioners. The following steps will be considered in the analysis.

- Step 1 is to quantify and estimate all initial (direct and indirect) costs, such as material, labour, equipment, transportation and overhead costs or benefits.
- Step 2 is to decide appropriate discount rates, and identify operating costs such as maintenance and repair costs.
- Step 3 is to identify environmental costs and benefits such as savings on construction waste (waste treatment charges; dumping charges, landfill space costs, transportation costs, air pollution costs, gas emission costs, energy consumption costs, noise pollution costs); and, savings on use of natural resources.
- Step 4 is to identify social costs and benefits such as reduction of accidental collapses with unlimited use of sand and gravel from river systems and threat to lives.
- Step 5 is to find the best option in terms of cost effectiveness will be identified based on economic costs (initial and operating as identified in Steps 1 and 2) and the identified environmental and social costs and benefits (as identified in Steps 3 and 4).

It is expected the results will show the significant economic benefits when the costs across a life span are considered for recycled option against the normal concrete option.

4. CONCLUSIONS

This paper examined the initial experimental results on the compressive strength of concrete cylinders with varied percentages of recycled aggregate and steel fibre. The experiments considered varying steel fibre volumes of about 0%, 30% and 60% with recycled aggregate replacement ratios of about 0%, 30% and 100%. It is found that the more recycled aggregate replacement ratio of the recycled concrete, the lower the compressive strength is. However, the addition of steel fibre can improve the compressive strength of the concrete mixes. This should be highlighted that the additions of 60% steel fibre volume for the recycled concrete mix can improve the recycled concrete compressive strength. In addition, a statistical analysis was carried out to estimate the design strengths of the proposed mix cases. Although a small number of test results are considered, the calculation results showed that, by adding 60% steel fibres to recycled concrete with 30% recycled aggregate replacement, the design strength of the recycled concrete becomes similar to that of normal concrete and can therefore be used in structural design. Further research is required to investigate whether further additions of steel fibre volume can further improve the performance of recycled concrete. On the whole, this research will bring significant benefits to the industry by effectively using waste materials and forming a closed system for concrete.

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