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EXPERIMENTAL STUDY ON RECYCLED CONCRETE WITH STEEL FIBERS AS A SUSTAINABLE BUILDING MATERIAL

OLIVIA MIRZA[1], DANE WIGG[2], WON HEE KANG[1], SEPANI SENARATNE[1], VIVIAN TAM[1], and RAKUL RAMESH[1]

[1] *Western Sydney University, Penrith, New South Wales, Australia*
[2]*Western Suburb Concrete, Penrith, New South Wales, Australia*

The global demand for construction aggregate exceeds 26 billion tons per year. With global policy attention directed towards climate change, environmental and economic sustainability, changes are required to the Australian construction industry regarding the extraction of natural resources. In particular, the concrete industry requires seeking innovative, sustainable solutions for reducing the impact of construction and maintenance on the environment. The majority of structures in Australia use reinforced concrete. Therefore, using environmentally and economically sustainable materials such as recycled concrete in construction would preserve natural resources and reduce construction waste and overall costs. There is considerable research available on the use of recycled concrete as a construction material and the use of steel fibers as structural reinforcement has been studied since the 1960's. However, there is very little research on the combination of the two as a construction material for concrete structures. This study focused on secondary beams made of recycled concrete with the incorporation of steel fibers. This combination offers a structurally sound material that will provide a durable and sustainable solution to Australian Construction Industry. Experimental studies were conducted to validate the performance of the new material in a structural application. Based on the results of the study, recommendations for future research and design applications using these materials are made.

Keywords: Recycled aggregate, Steel fiber-reinforced concrete, Sustainability.

1 INTRODUCTION

When concrete structures are brought down either for renovation of demolishing purposes, recycling the used material and deriving aggregates from them is a more sustainable solution than dumping them in landfills for disposal. The importance given to decrease the impact on the environment by a structure has increased the possibility of recycled aggregates (RA) being used as a construction material. According to Yang *et al.* (2008), 8 to 12 billion tons of natural aggregate will be required per year to meet the global construction demands, from 2010. The decrease in overall costs by employing recycled aggregates has pushed more researchers in this direction. Recycled aggregates are produced by crushing old concrete from construction and demolition waste (Etxeberria *et al.* 2007). Their production is similar to natural aggregates (NA).

Ravindrarajah (1996) stated that typically, the properties of RA are inferior to those of NA. This inferiority is mostly due to the residual mortar from the original concrete attached to the RA. As this residual mortar is generally rough and porous, it causes an increase in water absorption and a decrease in particle density. Modulus of elasticity is also reduced while drying shrinkage and creep are increased. But if the water absorption of RA is less, the mechanical properties of the RAC obtained are comparable to that of the control mix (Yang *et al.* 2008, Duan *et al.* 2014).

Steel fibers (SF) have become a common alternative reinforcement material to steel reinforcement bars and there is a vast research already conducted on its properties and cost effectiveness. SF are added to prevent or control cracking and to induce positive effects on post-cracking behavior of the composite, like improving strain capacity and its energy absorption capacity, or toughness. Though fibers with higher aspect ratio are efficient, both increase in the volume as well as aspect ratio of the fibers produce greater post-cracking strength in concrete beams (Michels 2013).

According to Awchat *et al.* (2013), the combination of RA and SF as a solution of both sustainable and effective construction material is scarcely touched upon in previous research. Recycled aggregate concrete on combining with steel fibers is considered to be a viable alternative material which not only provide cheaper solutions but is also efficient in reducing waste and increasing strength. This paper provides an insight into the behavior and performance of steel fiber reinforced recycled aggregate concrete (SFRRAC) used in secondary beams. Experimental studies have been carried out to assess the ultimate capacity of SFRRAC beams subjected to static load, the deflection, the failure mode and the force-deflection relationship.

2 EXPERIMENTAL STUDY

Nine concrete beams were cast, each with different proportions of RA replacement and SF addition. The mix design and replacement ratios are detailed in Table 1. Concrete beams were 3,000 mm long, 600 mm deep and 450 mm wide. Longitudinal reinforcement consisted of 4 N12 deformed bars in compression and 4 N20 deformed bars in tension. These reinforcing bars were tied together with 3 N12 shear ties at 300 mm centers, starting 150mm in from each end. Strain gauges were attached to each of the tension reinforcement bars in three locations, one at each end and one in the center. Strain gauges were attached in order to determine at what point in the loading sequence the tension steel yields and fails. Reinforcement and strain gauge configuration are detailed in Figure 1.

Supports were clamped to prevent any movement prior to testing. The beams were 3,000 mm in length but had an effective length of 2,800 mm. The strain gauges were plugged into the data logger. Two linear position sensors (LP), located underneath the midline of the beam to measure the beams deflection, were also plugged into the data logger. A linear variable differential transformer (LVDT) was fitted to the load machine to measure the stroke of the actuators and to obtain the accurate measurement of deflection.

The loading structure was lowered onto the top of the specimen and roller supports were unclamped during testing. Then the beam was loaded to 100 kN at a rate of 0.02 mm/s and unloaded to 5 kN at the same rate. This cycle was performed three times to ensure that the beam is stable, to take any movement out of the apparatus and to ensure a smooth load-deflection curve. After the three cycles, once the beam was determined to be stable, it was loaded to failure. The load rate was kept at 0.02 mm/s and observations regarding sighting of the first deflection and shear cracks were recorded.

Table 1. Mix proportions of experimental beams.

Beam	Water (L)	Cement (kg)	Sand (kg)	10 mm NA (kg)	10 mm RA (kg)	20 mm NA (kg)	20 mm RA (kg)	Steel Fibre (kg)	RA (%)	Steel Fibre (%)
1	189	630	454	296	0	592	0	0	0	0
2	213	630	454	89	207	177	414	0	30	0
3	223	630	454	0	296	0	592	0	100	0
4	189	630	454	296	0	592	0	9.5	0	0.3
5	213	630	454	89	207	177	414	9.5	30	0.3
6	223	630	454	0	296	0	592	9.5	100	0.3
7	189	630	454	296	0	592	0	18.7	0	0.6
8	213	630	454	89	207	177	414	18.7	30	0.6
9	223	630	454	0	296	0	592	18.7	100	0.6

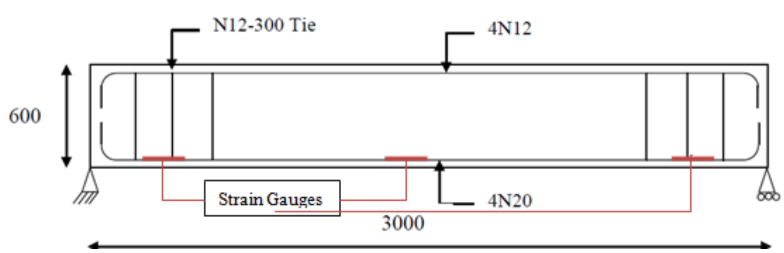

Figure 1. Beam and reinforcement configuration.

Once initial cracking had occurred the load rate was increased to 0.03 mm/s. Any significant observations, such as steel yield, load plateau and concrete failure were recorded with time, stroke and load as a reference. Load rate was increased as necessary and beam was loaded until structural failure or deflection limits were reached. After this, the test data including load, deflection and strain values were analyzed.

3 RESULTS AND DISCUSSION

3.1 Material Testing Results

A comparison of compressive strengths of the different concrete mixes is shown in Table 2. Table 2 shows a consistent decrease in average compressive strength with an increase in RA proportion. These results could be attributed to the increase in mix water for beams with RA included, as shown in Table 1. These results are consistent with research by Ravindrarajah (1996) who suggested that the increased water demand of RA adversely affects concrete strength and durability. The test results showed a consistent reduction in compressive strength of RAC compared with NAC. This decrease in compressive strength is somewhat counteracted by the addition of steel fibers, which can be seen in Beam 8 (30% RA and 0.6% SF) which has an increase in average compressive strength over all other mixes with RA included. When comparing beams with similar RA content, there is also an increase in average compressive strength with an increase in SF content.

Table 2. Compressive test results for nine concrete mixes.

Beam	Mix	Compressive Test Results 28 Day 1	2	3	Ave	Test Day 1	2	3	Ave	Age (days)
1	0-0	52.5	34.3		43.4	52.4	61.8	50.1	54.8	96
2	30-0	40.5	40.6	42.5	41.2	45.8	47.7	44.6	46.0	102
3	100-0	36.6	37.2	33.5	35.8	37.1	37.8	43.8	39.6	104
4	0-0.3	47.0	47.8	61.7	52.2	46.2	53.8	61.9	54.0	106
5	30-0.3	44.5	44.9	46.8	45.4	48.0	43.5	47.4	46.3	110
6	100-0.3	42.1	32.2	32.2	35.5	44.1	42.1	45.9	44.0	112
7	0-0.6	46.2	59.0	54.1	53.1	55.3	57.7	55.0	56.0	120
8	30-0.6	44.2	40.3	53.8	46.1	50.6	60.6	54.2	55.1	125
9	100-0.6	46.1	46.6	44.3	45.7	52.0	52.5	52.9	52.5	127

3.2 Beams Testing Results

Figure 2 shows a comparison of the load-deflection curves of the nine experimental beams. Figure 2 illustrates that there is an increase in stiffness with the addition of SF. Beams with 0.6% SF content (7, 8 and 9) show the greatest stiffness. This is indicated by an increase in gradient of the initial ascending part of the curve. This is caused by the SF ability to prevent the development of micro-cracks for a longer period of time and resist the widening of these cracks once they occur. Conversely there is a decrease in stiffness with an increase in RA replacement. Beams with 100% RA replacement proved to be less stiff than beams with less RA percentage but the same SF content. This can be attributed to the reduction in compressive strength and elastic modulus due to the increase in water demand of RAC mixes. This increase in water demand is caused by the porous nature of the aggregate which is able to absorb more free water from the concrete mix. These results are consistent with the compressive strengths shown in Table 2 inferring that concrete compressive strength had a direct effect on beam stiffness.

Table 3 demonstrates that the beam's ultimate concrete capacity is positively affected by the addition of SF. This is due to the ability of the SF to carry a load across widening cracks in the concrete which contributes to the tensile resistance of the beam. Beams with the highest percentage of SF (0.6%) achieved the highest ultimate capacity. As expected, the beams with 0.3% SF carried the next highest ultimate load. An increase in RA replacement ratio caused a decrease in ultimate capacity. The reduction in concrete compressive strength could be due to the amount of weak bond areas between the residual mortar and NA and also between the residual mortar and the new paste (Ravindrarajah 1996). This is somewhat counteracted by the addition of SF as the beam with 0.6% SF content and 100% RA replacement (Beam 9) outperformed beams with less SF and RA content. The beams with zero SF were the lowest performing specimens.

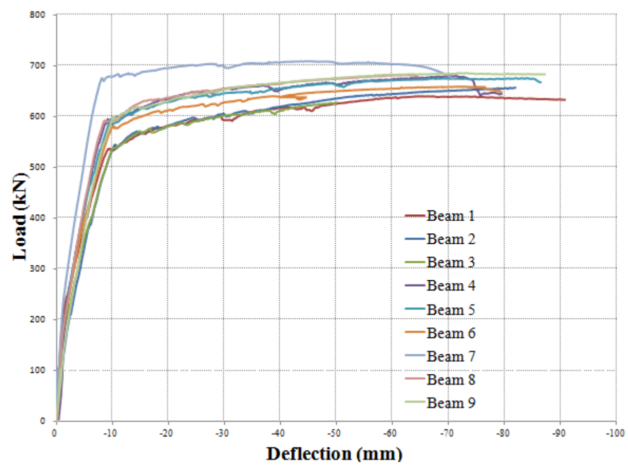

Figure 2. Comparison of load-deflection relationships for all mixes.

Table 3. Ultimate concrete capacity for all beams.

Ultimate Concrete Capacity		
Beam	Mix	Load (kN)
7	0-0.6	680
9	100-0.6	600
5	30-0.3	600
8	30-0.6	590
4	0-0.3	590
6	100-0.3	580
2	30-0	550
3	100-0	540
1	0-0	535

Table 4. Initial cracking of beams (visual experimental observation).

Beam	Mix Proportion RA-SF (%)	1st Deflection Crack (kN)	1st Shear Crack (kN)
1	0-0	200	500
2	30-0	200	350
3	100-0	200	400
4	0-0.3	200	400
5	30-0.3	200	450
6	100-0.3	153	350
7	0-0.6	250	390
8	30-0.6	180	400
9	100-0.6	180	400

There is no clear indication of the effects of SF and RA on the ductility of specimens, as the reinforcing steel is the controlling factor in the ductility of the concrete beams. It is observed from the results that 0% RA is more ductile than 30% and 100% RA when no SF were added, 30% RA is more ductile than 0% and 100%

when 0.3% SF is used and 100% RA is more ductile than 0% and 30% RA when specimens have 0.6% SF content.

Visual observations made on initial cracking of beams are listed in Table 4. The replacement of NA with RA has only a slight effect on the appearance of the first deflection crack in some beams, although these observations are not consistent enough to draw any conclusions. The use of RA has an effect on the appearance of the first shear crack although it is not proportional to the replacement ratio.

4 CONCLUSIONS

This research concluded that:

1. The experimental results show that an increase in RA replacement corresponds to a decrease in concrete compressive strength, elastic modulus, stiffness or flexural rigidity and ultimate capacity.
2. The increase in RA content increased the number of visible shear and deflection cracks throughout the experiment.
3. Contrarily, concrete compressive strength is marginally improved with the addition and subsequent increase in SF content.
4. Experimental results also show overall improvements in elastic modulus with the increase to 0.6% SF content.
5. The flexural test results indicate that an increase in SF content corresponded to an increase in ultimate capacity, stiffness and post-crack ductility of the beams.
6. Shear cracking is moderately reduced with the inclusion of 0.3% SF, however this cracking is more significantly reduced when the SF volume is increased to 0.6%.
7. Overall, the experimental results showed that addition of 0.6% SF with 30% RA replacement is a structurally effective combination. A sustainable solution can be obtained with the ability to replace NA with RA in structural applications.

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