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Recycled Aggregate Concrete: Strength Development and Future Perspectives on Steel Fibers and Cost-benefit Analysis

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Abstract
The use of recycled aggregate (RA) in concrete opens possibilities in the ways in which recycled materials can be used for structural applications; indeed, it may be an important breakthrough towards sustainable development. The utilisation of RA is an effective solution to the problem of possessing excess waste materials while simultaneously maintaining satisfactory concrete quality. The utilisation of waste construction materials should be related to the application of quality guarantee systems to achieve suitable product properties. A complete understanding of the characteristics of new materials is, therefore, extremely important so that it is potential in applications can be thoroughly studied. This paper investigates the physical and mechanical properties of recycled aggregate concrete (RAC). The experimental works on RAC from different mix proportions, including replacement ratios of RA from 0%, 30%, 50%, 70% and 100%, are investigated on compressive strength. Further research on steel fibres addition and cost-benefit analysis are also explored.

Keywords
Recycled aggregate, recycled aggregate concrete, strength, steel fibre, cost-benefit analysis, Australia

1. Introduction

The global policy attention directed toward climate change and environmental sustainability has created challenges to the Australian construction industry [1]. 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 a total building. Using environmentally and economically sustainable materials such as recycled concrete for the building construction would enable to respond to industry challenges effectively.

Recyclable concrete is now increasingly recognised as a sustainable building material which could be effectively used. 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 [2-4]. Carbon emissions from the generated concrete waste have been considered important issues 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% [5].

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 has been weak which has not realised its full potential. This proposed project shows that recycled concrete can be as strong as the normal concrete which is suitable for structural applications when incorporated with steel fibres. This not only creates a new material for structural purposes but also resolves carbon emissions and wasted concrete storage problems [6-8].

Some researchers have compared the behaviour of composite steel-concrete beams using steel fibres and conventional reinforcement [9, 10]. These researchers have established that the composite steel-concrete with steel fibres could sustain higher loads than plain 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, they also provide slabs with a fire rating ranging from 60 to 90 minutes. Two aspects are to be considered when steel fibre reinforced concrete is used in concrete beams; ductility and the ability of steel fibre reinforced concrete to resist transverse shear in the reinforced concrete beams [11]. Steel fibres have been replaced with welded wire fabric (WWF) as secondary reinforcement and verified that both deflection and cracks decreased in composite beams [12]. They also demonstrated that it was preferable to use steel fibres rather than synthetic fibres. A slab reinforced with 29.6 kg/m^3 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/m^3 of synthetic fibres failed at a load equivalent to the WWF.

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 sustainable solution to Australian Construction Industry. Therefore, experimental study is much needed as a basis to understand and compare the behaviour of this new material.

Due to the complexity of new designs, the possibilities for cost blowouts are much greater in construction projects. Hence, [13] viewed that cost managers should be engaged in evaluating design options and their effect on construction costs. The lack of such exercise will cause project failures [14]. Hence, it is important not only to analysis the structural suitability, but also the cost effectiveness of this novel design by incorporating techniques such as cost-benefit analysis and further life-cycle cost considerations[15].

In order to go ahead with this new proposal of mixing steel fibres to RAC to improve its structural strength, it is required to examine the physical and mechanical properties of RAC through experiments as presented next.

2. Experimental Design

For investigating the behaviour of RAC, RA samples collected from the south-eastern Australia centralised recycling plant was adopted for the production of concrete. The water absorption of the sample is about 2.68% with particle density of about 2.52 t/m^3 and aggregate crushing value of about 22.31%. Prior to the production of RAC, the RA was pre-soaked to create a saturated surface dried condition, in accordance with the Australian Standard requirement [16]. Ordinary Portland cement, designated Type GP (General Portland) was used for the experimental work. The RA replacement ratios were used at 0%, 30%, 50%, 70% and 100% with a water-to-cement ratio at 0.45 and aggregate-to-cement ratio at 4.5.

3. Recycled Aggregate Concrete Properties

The average results from three tests to measure compressive strength at curing age 7, 28 and 56 days are shown in Table 1. Many researchers have highlighted the reduction of strength with higher substitution of RA [17-24]. The more that RA is incorporated into the production of concrete, the weaker the concrete strength will be. This is because the performance of RA with attached cement mortar and higher porosity is weaker than that of normal aggregate. Based on the experimental results, the strength reduction is up to 34.5%, 28% and 30% for a 100% RA replacement compared to normal aggregate concrete at 7, 28 and 56 days respectively.

Table 1: Compressive strength of RAC

RA replacement ratios	7 days	28 days	56 days
0%	50.84	58.40	64.60
30%	42.40	52.40	56.00
50%	40.73	50.00	55.76
70%	39.76	46.80	53.74
100%	33.30	41.50	45.20

The reduction of concrete strength with the increasing RA replacement ratios can be explained with the carbonation effects from the atmosphere to the RA and RAC. Carbonation in the atmosphere reacts in the presence of moisture with hydrated cement minerals. The reaction of carbonation takes place even for small concentrations such as rural air where carbonation content is about 0.03%. In an unventilated laboratory, this content may rise to above 0.1%. In large cities, it is about 0.3% and in some exceptional cases, it can increase to 1% [25]. The carbonation rate increases when the concentration of carbonation increases, especially with a high water-to-cement ratio. Carbonation occurs when calcium hydroxide [$Ca(OH)_2$ or *CH*] reacts with CO_2 [26]. This reaction has also led to the formation and accumulation of calcium carbonate ($CaCO_3$) as shown in Equation (1) to Equation (4). CO_2 of the $CaCO_3$ is generated (see Equation (5)) during carbonation and *CO* is generated after the generation of the CO_2 as shown in Equation (6) [27].

$Ca(OH)_2 + CO_2$	$\rightarrow CaCO_3 + H_2O$	(1)
Calcium silicate hydrate + CO_2	$\rightarrow$ *various intermediates*	(2)
	$\rightarrow CaCO_3 + SiO_2nH_2O + H_2O$	
Aluminate hydrates + CO_2	$\rightarrow CaCO_3$ + *hydrated alumina*	(3)
Ferrite hydrates + CO_2	$\rightarrow CaCO_3$ + *hydrated alumina and iron oxides*	(4)
$CaCO_3$	$\rightarrow CaO + CO_2$	(5)
$2CO_2$	$\rightarrow 2CO + O_2$	(6)

Carbonation has a deleterious effect on hardened cement paste as it appears to decrease strength and increase porosity [26, 28, 29]. Major controlling factors affecting carbonation concentration are water-to-cement ratios, aggregate porosities, curing and the environment of exposed structures [26]. The carbonation depth is roughly proportional to the square-root of time, doubling between one year and four years, then again doubling between four and ten years; there is probably a further doubling up to 50 years [25]. An extensive survey by Brown [30] found that carbonation depths correlated well with concrete quality but there was no significant relationship with reported exposure conditions. In general, any factors, which may increase concrete permeability, can also increase the carbonation rate, provided that sufficient internal moisture is present. The carbonation reaction rate depends on the moisture content of concrete and relative humidity of the ambient medium [25, 26]. In addition, carbonation depth increases with an increase in water to cement ratio; for example, for a water to cement ratio of about 0.4, the depth is only half of that at about 0.6; for a water to cement ratio of about 0.8, the depth is about 50% greater than at 0.6. A typical depth for a water to cement ratio of about 0.5 after normal exposure for 10 years is between 5 mm and 10 mm [25].

In summary, the experiment results proved that the higher the RA replacement ratios for RAC, the lower the compressive strength. However, it is predicted that the strength development of RAC could be improved by combining it with steel fibres as discussed next.

4. Steel Fibres on Recycled Aggregate Concrete

Fiber reinforcement can effectively improve the toughness, shrinkage, and durability characteristics of RAC. Due to the poor tensile behaviour of RAC the defects occurred. To improve RAC toughness and reducing the size and amount of defects in the RAC is by adding steel fibers to the concrete mix during mixing. In the fracture process of fiber reinforced RAC, fibers bridging the cracks in the matrix can provide resistance to crack propagation and crack opening before being pulled out or stressed to rupture. Preliminarily studies [9, 10, 31, 32] have proved that steel fiber reinforcement can significantly improve the tensile properties of concrete. When fresh concrete harden, the rate of evaporation at the concrete surface is greater than the rate of water migration to the surface which causes plastic cracking. Therefore another application of fiber reinforcement is for the reduction of the shrinkage and shrinkage cracking of concrete associated with hardening and curing. Therefore, it is assumed that the strength reduction of RAC from various RA percentage ratios can be improved with the addition of steel fibres.

5. Cost-benefit Analysis

As argued in this paper, not only the structural feasibility should be tested in this proposed new solution for secondary beams of building structures, but also the economic feasibility. If this option is economically viable and cost effective over other available options the industry practitioners would accept it. Even though there needs to be specific cost studies carried out on the proposed combination after the experimental stage, looking at previous cost comparisons individually carried out for RAC and steel fibers, it is fairly reasonable to presume that the new combination would offer value for its money. The future directions of this research project intend to carry out cost-benefit analysis for the optimum solution that would be identified through the experiments.

For concrete structures, the objective function to be minimized should be the cost, because these structures are made of more than one material. The great majority of papers on cost optimization of concrete structures include the material costs of concrete, steel, and formwork only [33]. Other costs such as the cost of labor, fabrication, placement, and transportation are often ignored.

As the report of Cement Concrete and Aggregates Australia [34] highlighted that there are a number of manufactured and RA readily available in certain localities which have the potential to be used in construction. Tam [35] through a cost-benefit analysis proved that in comparison to the cost on the current practice, the concrete recycling method could result in a huge sum of saving. This is not only in terms of the material costs but also including other costs such as processing and transportation. The transportation costs for the RA is reduced due to the weight of RA is lighter than virgin aggregate and recycling concrete from the demolition projects can save the costs of transporting the concrete to the landfill and the costs of disposal [36]. This shows that there are significant cost-benefits in using RA and RAC. However, the additional costs associated with quality control and for the mix design adjustments (inclusion of steel fibre to RAC) to achieve the same structural strength as concrete need to be considered. Use of steel fibre in place of some reinforcement has proven to be cost effective. However, as Sarma and Adeli [33] highlighted that additional research needs to be done on life-cycle cost optimization of structures where the life-cycle cost of the structure over its lifetime is minimized instead of its initial cost of construction only. Hence, life-cycle costing would be considered in the proposed optimum solution.

6. Conclusion

This paper studied the compressive strength development in relations to RA replacement ratios. Although it is the case that the more the RA is adopted in the production of concrete, the weaker the concrete strength will be. The paper identified that fibre reinforcement can effectively improve the toughness, shrinkage, and durability characteristics of RAC and therefore would ideally suit for structural elements such as secondary beams. Further to the strcutural suitability, it was noted that the economic suitability of such a soltion need to be considered. As a result, future research on steel fibres inclusions and cost-benefit analysis have also been explored. This will bring significant benefits to the industry in effectively use of waste materials and form a closed system for concrete.

7. References

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