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# Properties of Recycled Aggregate Concrete with Various Aggregate to Cement Ratios

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## Abstract
Waste from construction and building demolition work constitutes about 44% of the total amount of waste generated each year in Australia and about 68% in Southeast Queensland (SEQ). The use of recycled aggregate (RA) from concrete waste presents some important environmental and construction engineering issues that need resolution. With poor strength and high water absorption rate, RA is rarely used in high-grade concrete applications; it is only restricted for use in roadwork sub-base, low-grade pavements, retaining walls and footpaths. This paper summarises experimental results on compressive strength, indirect tensile strength and flexural strength of recycled aggregate concrete (RAC) with different aggregate to cement ratios between 3.0 and 6.0 for 30% RA replacement compared with normal aggregate concrete (NAC). Water to cement ratio for all types of concrete is 0.45. The RA samples used are collected from a centralized recycling plant in Southeast Queensland, Australia. All the concrete mixes under investigation achieved at least 35MPa in compressive strength and 3.3MPa in indirect tensile and flexural strength for 28-day curing days. It is also found that the higher the aggregate to cement ratios, the lower the RAC quality. Recommendation for the aggregate to cement ratio for RAC production is about at least 6.0 for general structural concrete.

## Keywords
Aggregate to cement ratio, Compressive strength, Flexural strength, Tensile strength, Recycled aggregate concrete

## 1. Introduction

Construction and demolition (C&D) waste constitutes a large proportion of solid waste: about 70%, 50%, 44% and 29% in Spain, United Kingdom, Australia and USA respectively (Ferguson *et al.*, 1995; Rogoff and Williams, 1994). Waste from C&D sector including metal, concrete, brick, glass, fitting and fixture from demolished or refurbished buildings, wood and wall paneling. Among different types of C&D waste, concrete waste was found the most significant component constituting about 81.8% in Australia (Productivity Commission, 2006). Waste from C&D sites is the major component of the waste stream in Queensland urban centres. On average, C&D waste comprises about 68% of the total municipal solid waste stream in Southeast Queensland (SEQ) (Environmental Protection Agency, 2004). Overall, C&D waste recycling in Queensland is not well established compared with other states in Australia (Environmental Protection Agency, 2007; Kotrayothar *et al.*, 2007).

Recycling, being one of the key strategies in minimisation of waste, offers three benefits (Edwards, 1999). The introduction of recycling in a waste management program mainly offers three benefits. These are softening new material resource demands, reducing transport and production energy costs, and preventing landfill use (Tam and Tam, 2006).

Concrete waste can instead be processed and reused as recycled materials as RA for RAC. RA is crushed from demolished concrete waste including stone particles attached to the old cement mortar as shown in Figure 1. RAC is produced by mixing RA with traditional ingredients, i.e. cement, water, fine aggregate and admixtures. At present, application of RA is limited to road and backfill work, general non-structural construction such as dikes, sidewalks, and curbs and gutters (Bakoss and Ravindrarajah, 1999; Portland Cement Association, 2007; Mulligan, 2002; Solid Waste Management Coordinating Board, 2002; Grubl and Ruhl, 1998; Sobhan and Krizek, 1999). There have been recent indications that RA is slowly becoming recognised as a high-grade construction material as a result of the increasing positive research findings on RA.


**Figure 1: Recycled Aggregate (RA)**

## 2. Objectives and Scope

In general, concrete strength is dependent mainly on the type of cement in the mortar, aggregate strength, water to cement ratio, aggregate to cement ratio, etc (Neville, 1995). Recommendation for the water to cement ratio for RAC production is about 0.4 to 0.45 (Kotrayothar *et al.*, 2009). Aggregate generally constitutes at least 75% of the volume of concrete and can be expected to have an influence on the latter's durability and strength (Gani, 1997). Hence, the selection and proportioning of aggregate should be given full and careful attention. This study attempts to examine the physical and mechanical properties of RAC with different aggregate to cement ratios. Comparisons between RAC and NAC are also provided.

## 3. Aggregate Properties

The physical and mechanical properties of RA and natural aggregate (NA) are investigated in accordance with Australian Standard AS 1141 (AS 1141, 1974). Samples of RA from SEQ's centralised recycling plant are collected for the experiment work on RA and RAC in this paper. The properties of RA and NA are shown in Table 1.

**Table 1: Properties of Recycled Aggregate and Natural Aggregate**

| Aggregate Type | Size (mm) | Particle density ($t/m^3$) | Water Absorption (%) | Aggregate crushing value (%) |
|---|---|---|---|---|
| RA | 10 | 2.34 | 5.55 | 22.11 |
| | 20 | 2.42 | 5.23 | 24.64 |
| NA | 10 | 2.68 | 0.61 | 8.34 |
| | 20 | 2.71 | 0.56 | 13.89 |

## 4. Concrete Properties

RAC with aggregate to cement ratios of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0 are covered in this investigation. Water to cement ratio for all types of concrete is 0.45 as recommended from a previous study (Kotrayothar *et al.*, 2009). An Australian Standard mixing approach was used (AS 1012, 1993). Ordinary Portland cement, designated Type GP (General Purpose) and RA replacement of 0% and 30% were adopted noting that 30% is the accepted maximum allowable RA replacement (Yanagi *et al.*, 1993; Topcu, 1997; Masood, 2001; Xiao *et al.*, 2005; Kotrayothar and Tam, 2007). According to AS 1012, the mixing is first charged with about half the coarse aggregate, then the fine aggregate, followed by the cement and finally the remaining coarse aggregate; water is then added after mixing all the solid constituents for two minutes (AS 1012, 1993).

Specimens are cast from each mixture to assess their compressive, tensile and flexural strength according to the Australian Standard(AS 1012, 1993). Each result reported herein is the average of three tests. All specimens were removed from the moulds after 24 hours and then cured in water at room temperature for 28 days. The RAC mix proportions used for experimental work are summarised in Table 2.

**Table 2: Mix Proportions of RAC at Aggregate to Cement Ratios between 3.0 and 6.0 for RA 30% Replacement**

| Material | Mass Required per $1m^3$ (kg) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Aggregate to cement ratio | | | | | | |
| | 3.0 | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
| Cement | 600 | 514.29 | 450 | 400 | 360 | 327.27 | 300 |
| Coarse Aggregate | | | | | | | |
| 10mm | 360 | 360 | 360 | 360 | 360 | 360 | 360 |
| NA | 360 | 360 | 360 | 360 | 360 | 360 | 360 |
| RA | 252 | 252 | 252 | 252 | 252 | 252 | 252 |
| 20mm | 720 | 720 | 720 | 720 | 720 | 720 | 720 |
| NA | 504 | 504 | 504 | 504 | 504 | 504 | 504 |
| RA | 216 | 216 | 216 | 216 | 216 | 216 | 216 |
| Fine Aggregate | 720 | 720 | 720 | 720 | 720 | 720 | 720 |
| Water | 180 | 180 | 180 | 180 | 180 | 180 | 180 |

## 5. Results and Discussion

### 5.1 Fresh Concrete Properties

The workability of concrete which indicated by the corresponding slump value are shown in Table 3. According to some RAC Guideline (Building Department, 2003) suggested a minimum slump of 75mm should be achieved before compaction. Due to the low water to cement ratio and varies aggregate to cement ratios in this experiment, the advised slump value are ignored.

**Table 3: Workability of Fresh Concrete**

| NAC | | RAC | |
|---|---|---|---|
| Type | Slump (mm) | Type | Slump (mm) |
| AC3RA0 | 5 | AC3RA30 | 5 |
| AC3.5RA0 | 5 | AC3.5RA30 | 5 |
| AC4RA0 | 10 | AC4RA30 | 12 |
| AC4.5RA0 | 15 | AC4.5RA30 | 75 |
| AC5RA0 | 37 | AC5RA30 | 50 |
| AC5.5RA0 | 30 | AC5.5RA30 | 35 |
| AC6RA0 | 25 | AC5.5RA30 | 40 |

### 5.2 Compressive Strength

After 28-days of water curing, the compressive strength values of NAC are generally higher than those of RAC – by 7.95%, 13.15%, 12.24, 0.90%, 9.81%, 13.28% and 14.79% for aggregate to cement ratio of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 respectively. With a ratio 4.5, the 28-day compressive strength of RAC and NAC are similar as shown in Figure 2.

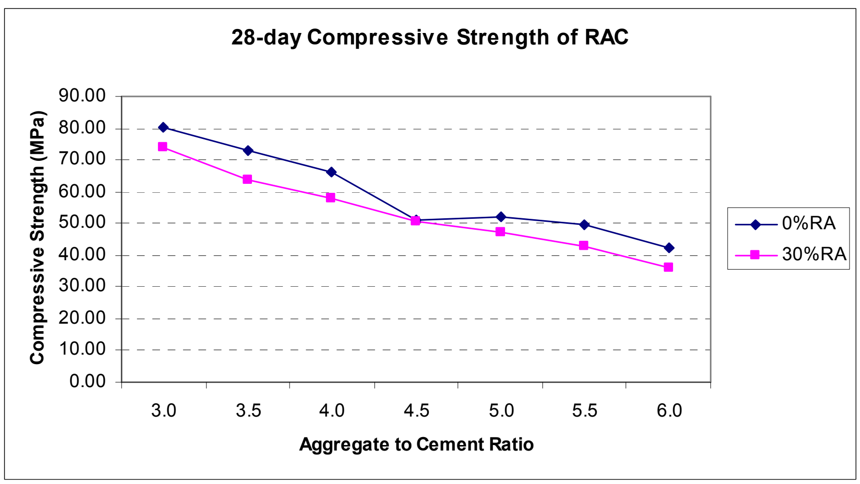


**Figure 2: Compressive Strength of NAC and RAC at 28-day**

### 5. 3 Tensile and Flexural Strengths

The 28-day tensile strength values of NAC are almost higher than RAC except at aggregate to cement ratio 3.0 which is about 2.02% lower than RAC. While the flexural strength values of NAC is higher than RAC of about 10.37%, 16.56%, 4.39%, 30.50 %, 12.31%, 4.77% and 25.00% for aggregate to cement ratio 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0 respectively. The trends of the 28-day tensile strength and flexural strength are similar as shown in Figure 3 and Figure 4.

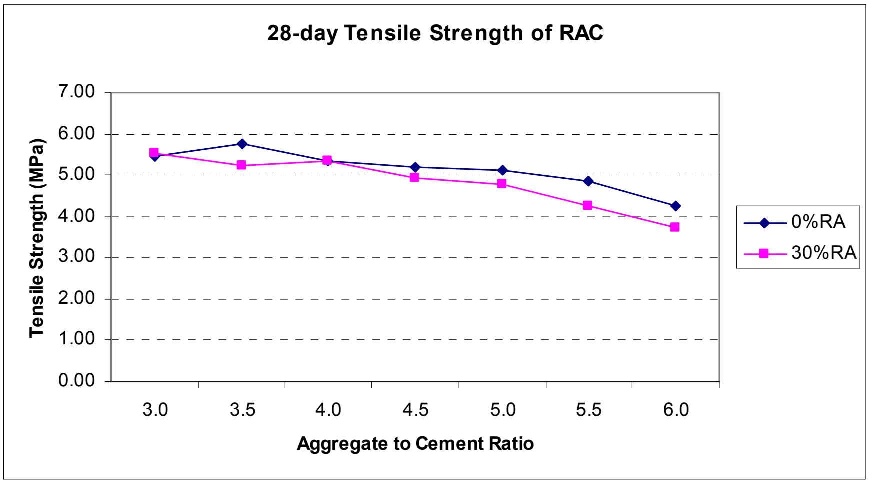


**Figure 3: Tensile Strength of NAC and RAC at 28-day**

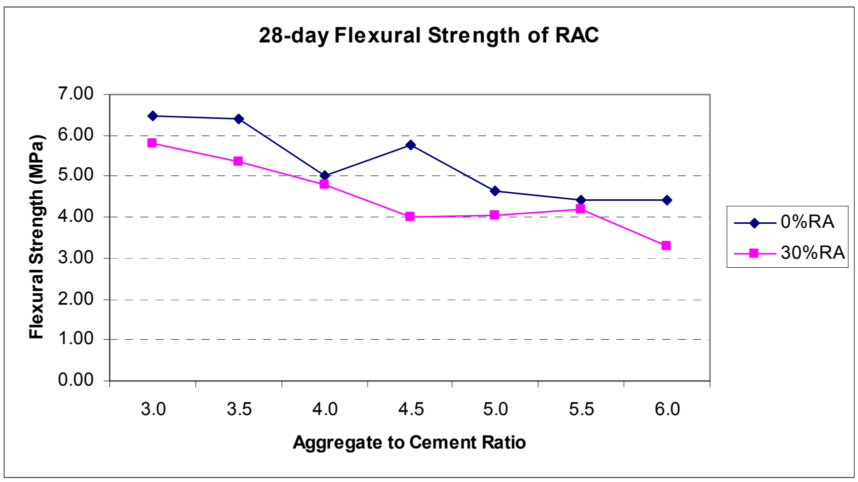


**Figure 4: Flexural Strength of NAC and RAC at 28-day**

The trends clearly indicate that the optimum aggregate to cement ratio which provides the highest mechanical strength of NAC at aggregate to cement ratio 3.0 and 3.5 of about 80.40MPa and 6.46MPa for compressive and flexural strength and 5.44MPa for tensile strength at aggregate to cement ratio 3.0. While the highest 28-day strengths of RAC are 74.01MPa, 5.55MPa and 5.79MPa for compressive, tensile and flexural strength at aggregate to cement ratio 3.0. Density of NAC and RAC are also at aggregate to cement ratio 3.0 which are 2,503 kg/m$^3$ and 2,460 kg/m$^3$ respectively.

## 6. Conclusion

This paper investigates RAC with aggregate to cement ratios of between 3.0 and 6.0. Physical and mechanical properties of the concrete including workability, density, as well as compressive, tensile and flexural strength are examined. The following conclusions have been reached based on the present study.

1. The increasing of aggregate to cement ratios lead to the higher slump values of RAC and NAC.
2. The compressive, tensile and flexural strength values of NAC are higher than RAC of for all aggregate to cement ratios from 3.0 to 6.0 at the 28-days of water curing. All strength values of both NAC and RAC decrease while the aggregate to cement ratios increase from 3.0 to 6.0.
3. The 28-days compressive strength value is higher than 35MPa at aggregate to cement ratio of 6.0 for NAC and RAC.
4. The tensile strength of concrete at 28-days of water curing is higher 3.5MPa for both NAC and RAC at aggregate to cement ratio of 6.0.
5. The flexural strength of NAC and RAC at 28-days is higher than 3.3MPa at aggregate to cement ratio of 6.0.

It can be concluded that RAC made with 30% of RA replacement as an aggregate to cement ratio 6.0 and a water to cement ratio of 0.45 can use for general structural concrete applications where the compressive strength of concrete of 35MPa is required.

For further research on RAC behaviour, mixes with higher aggregate to cement ratios and different percentages of RA replacement should be tested. Additional physical and mechanical properties and the durability of RAC including modulus of elasticity, drying shrinkage and creep should also be included in the study.

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