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Mix Design of Recycled Aggregate Concrete Using Packing Density Method

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Abstract

Packing density method is new kind of mix design method, generally used for design normal, high-strength and self-compacting concrete. This method considers the volume and density variation between different types and sizes of aggregate. The adoption of packing density method optimises the particle packing density of concrete by selecting the right amount of various aggregates to fill up the voids between large and small aggregates, which allows a more dense and stiff structure. This paper is devoted to the studies of material and mechanical properties of recycled aggregate concrete using packing density method. This paper considers mix of two different aggregate sizes of 10 and 20mm, 0, 30, 50, 70 and 100% recycled aggregate replacement ratios, and water-cement ratio of 0.35, 0.45 and 0.55. In total of fifteen concrete mix designs are considered. The paper presents the material properties of aggregates which were obtained from the material testing. The mix design method and results of mechanical testing will be discussed. The results show that the packing densities of natural and recycled aggregates are different, and should not be treated in the same way. By using packing density mix design method, recycled aggregated concrete strengths fluctuation can be resolved, and the concretes can have similar strengths consistency, regardless the recycled concrete aggregate replacement ratios. This method minimise the influence of recycled concrete aggregates obtain from various sources with variable quality.

Keywords: Recycled Aggregate Concrete, Packing Density Method, Concrete Mix Design, Recycled Concrete Aggregate.

1. INTRODUCTION

In Australia, about 17 million tonnes of construction waste is landfilled each year, the amount of solid waste has increased over the last few years, hence the landfill space quickly becomes limited (Kotrayothar 2012; Poon, Shui & Lam 2004). Recycling and reuse of concrete waste is necessary from the viewpoints of environmental preservation and effective utilisation of resource, it helps to limit the environmental impact by reducing landfilling and limiting the exploitation of natural resources. Many researchers have tried to promote the use of recycled concrete aggregate (RCA) in conventional concrete, to reduce the use of NA (Rahal 2007; Tam 2005; Xiao, JianZhuang, Li & Poon 2012). However, many studies have shown that concrete mixed with RCA usually have mechanical strength variations compared to those conventional concrete made with NA (Rahal 2007; Singh 2014; Xiao, JianZhuang, Li & Poon 2012). This is mainly due to the method used to obtain the RCA, usually produced through mechanical crushing of old concretes that are obtained from demolished structures (Wagih et al. 2013). The crushing process often involves several stages to achieve desirable shapes and sizes (RILEM 1992). It can result in non-homogeneous and round-shaped property, which hinders their wide use (de Juan & Gutiérrez 2009).

In addition, recycled concrete aggregates have higher water absorption capacity due to the presence of old motor attached to the surface (Huang 2015; Sidorova et al. 2014). The water absorption capacity affects both fresh and hardened properties of recycled aggregate concrete (RAC). In order to obtain the similar workability as conventional concrete, additional quantity of water is required. It would often cause increase of water-cement ratio (*w/c*) and affect the strength of the RAC (Huang et al. 2016;

Wardeh, Ghorbel & Gomart 2015). Moreover, several studies have shown that the porosity of RAC is modified and increased with the RCA replacement ratio, as a result, high porosity can leads to reduce of mechanical strengths (Gomez-Soberon and Kou et al., cited in Wardeh, Ghorbel & Gomart 2015). In addition, the mechanical properties of RAC also depends on other parameters, such as quality of concrete from which RCAs are obtained (Xiao, Jz, Li & Zhang 2005).

In general, the higher the parking density of aggregates, the smaller the voids need to be filled by the cement paste. It also reduces the amount of excess concrete paste, because cement paste has to fill up the voids between aggregates. In other words, minimum voids and maximum density concrete can be generated, with less cement and water required (Raj, Patil & Bhattacharjee 2014). Moisture content and material properties of RCAs are also considered in the mix design, so the amount of water and aggregates can be predict (Wardeh, Ghorbel & Gomart 2015). This paper is devoted to the studies of material and mechanical properties of recycled aggregate concrete using packing density method.

2. MATERIALS

Cement Australia® Builders Cement (Type GB) was used in the mix. It is a fly ash blended Portland cement in conformity with the requirements of AS 3972 for general purpose and blended cements. The specific gravity of Builders Cement is 3.11, and its compressive strength after 28 days is 46 MPa. The fine aggregate sand is air dried and passed through a 3.55 mm sieve. And two natural and recycled concrete coarse aggregates of size 10 and 20 mm were used. Natural aggregates were from Penrith Sand and Soil, and RCAs were from a retreatment of demolition materials. Bulk density, specific gravity and absorption tests were carried out according to ASTM C127 for coarse aggregate and ASTM C128 for fine aggregate, the test results are shown in Table 1. The high range water reducing admixture, a liquid based superplasticizer, was used to increase the workability of concrete.

Table 1. Bulk density, specific gravity and absorption of aggregates

Materials	**Bulk density** (g/cm^3)	**Bulk specific gravity**	**Absorption** (%)
1.Fine Sand	1.552	2.683	0.2
2.NA 10 mm	1.518	2.829	1.48
3.NA 20 mm	1.555	2.875	0.91
4.RCA 10 mm	1.310	2.337	4.73
5.RCA 20 mm	1.256	2.276	5.16

3. PACKING DENSITY MIX METHOD

The packing density of aggregate mixture is defined as the solid volume in a unit total volume. The aim of obtaining packing density is to predict the amount of aggregates used in the mixture, and to minimise porosity and reduce amount of cement used in the concrete (Raj, Patil & Bhattacharjee 2014; Wardeh, Ghorbel & Gomart 2015). The values of bulk density of aggregates mixture were first determined by backfill of natural and/or recycled concrete coarse aggregates and fine aggregate sand, with different proportions into an empty mould, using Equation 1 (Raj, Patil & Bhattacharjee 2014). The coarse aggregates 20 mm (CA20) and 10 mm (CA10) were mixed in 60:40 by mass. The coarse aggregate (CA) and fine aggregate sand (FA) were mixed in 64:36 by mass. The ratio of aggregates mixture of CA20, CA10 and FA are 38.4:25.6:36 by mass. The mixture proportions was from IS-10262 (2009) Concrete Mix Proportioning-Guidelines, for Mix Design M-40 Grade concrete. A total of five aggregates mixtures of 0 (NA), 30, 50 70 and 100% are tested, and the test results are shown in Table 2.

$$Mixture\ bulk\ density\ (Maximum) = \frac{Mass\ of\ aggregates\ mixture}{Volume\ of\ mould} \quad (1)$$

Table 2. Maximum aggregates mixture bulk density

RCA replacement	**Mixture of aggregates**	**Weight fraction** (Aggregates mixture ratio)	**Mixture bulk density** (g/cm^3)
0% RCA	NA20:NA10:FA	38.4: 25.6: 36	2.169
30% RCA	NA20:RCA20:NA10:RCA10:FA	26.88: 11.52: 17.92: 7.68: 36	2.123
50% RCA	NA20:RCA20:NA10:RCA10:FA	19.2: 19.2: 12.8: 12.8: 36	2.065
70% RCA	NA20:RCA20:NA10:RCA10:FA	11.52: 26.88: 7.68: 17.92: 36	2.015
100% RCA	RCA20:RCA10:FA	38.4: 25.6: 36	1.973

The packing density of individual aggregate in the mixture is determined from its maximum bulk density and individual aggregate bulk specific gravity, using Equation 2 (Raj, Patil & Bhattacharjee 2014). The voids content of aggregates mixture is determined from its total packing density, using Equation 3. Assume the excess paste content for concrete is 30%, based on the results from Raj, Patil and Bhattacharjee (2014) IS1199-1959 flow table tests. The paste content for concrete and volume of aggregates are determined using Equation 4 and 5. The solid volume of aggregate is determined from individual aggregate weight fraction and bulk specific gravity in the mixture, using Equation 6. The weight of aggregate in the mixture is determined using Equation 7 (Raj, Patil & Bhattacharjee 2014), and all results are shown in Table 3.

$$Packing\ density = \frac{Maximum\ mixture\ bulk\ density \times weight\ fraction}{Individual\ bulk\ specific\ gravity\ of\ aggregate} \times \frac{1}{100} \tag{2}$$

$$Voids\ content = 1 - total\ packing\ density\ of\ the\ mixture \tag{3}$$

$$Paste\ content = Voids\ content \times (1 + \frac{excess\ paste\ content\ \%}{100}) \tag{4}$$

$$Volume\ of\ aggregates = 1 - paste\ content \tag{5}$$

$$Solid\ volume\ of\ aggregate = \frac{Indvidual\ aggregate\ weight\ fraction}{Individual\ bulk\ specific\ gravity\ of\ aggregate} \tag{6}$$

$$Weight\ of\ aggregate = \frac{Volume\ of\ aggregates}{Total\ solid\ volume\ of\ aggregates} \times \text{weight fraction} \times \frac{1000}{100} \tag{7}$$

Three water-cement ratios 0.35, 0.45 and 0.55 were considered in the mix design. The total paste of concrete is determined by the specific gravity of cement and water-cement ratio (w/c), using Equation 8. The total paste for 0.35, 0.45 and 0.55 w/c is 0.6715c, 0.7715c and 0.8715c. The cement content of the concrete is determined by paste content and total paste, using Equation 9, and then calculated the water content of the concrete, using Equation 10 (Raj, Patil & Bhattacharjee 2014). All results are shown in Table 4.

$$Total\ paste = C + W = (\frac{1}{Specific\ gravity\ of\ cement} + \frac{w/c}{1}) \times c \tag{8}$$

$$Cement\ content = \frac{Paste\ content}{Total\ paste} \times 1000 \tag{9}$$

$$Water\ content = paste\ content \times w/c \tag{10}$$

Table 3. Packing density and weight of aggregates

RCA replacement	Materials	Packing density	Voids content	Paste content	Volume of aggregates (cm^3)	Solid volume of aggregate (cm^3)	Weight of aggregate (kg/m^3)
0% RCA	Fine Sand	0.2910	-	-	-	0.1342	713.62
	NA 10 mm	0.1963	-	-	-	0.0905	507.46
	NA 20 mm	0.2897	-	-	-	0.1336	761.19
	RCA 10 mm	-	-	-	-	-	-
	RCA 20 mm	-	-	-	-	-	-
	Total	0.7770	0.2230	0.2899	0.7101	0.3582	1982.28
30% RAC	Fine Sand	0.2848	-	-	-	0.1342	704.96
	NA 10 mm	0.1344	-	-	-	0.0633	350.91
	NA 20 mm	0.1984	-	-	-	0.0935	526.37
	RCA 10 mm	0.0698	-	-	-	0.0329	150.39
	RCA 20 mm	0.1074	-	-	-	0.0506	225.59
	Total	0.7949	0.2051	0.2667	0.7333	0.3745	1958.22
50% RAC	Fine Sand	0.2770	-	-	-	0.1342	686.05
	NA 10 mm	0.0934	-	-	-	0.0452	243.93
	NA 20 mm	0.1379	-	-	-	0.0668	365.89
	RCA 10 mm	0.1131	-	-	-	0.0548	243.93
	RCA 20 mm	0.1742	-	-	-	0.0844	365.89
	Total	0.7956	0.2044	0.2657	0.7343	0.3853	1905.68
70% RAC	Fine Sand	0.2704	-	-	-	0.1342	670.64
	NA 10 mm	0.0547	-	-	-	0.0271	143.07
	NA 20 mm	0.0808	-	-	-	0.0401	214.61
	RCA 10 mm	0.1545	-	-	-	0.0767	333.83
	RCA 20 mm	0.2380	-	-	-	0.1181	500.75
	Total	0.7985	0.2015	0.2620	0.7380	0.3962	1862.90
100% RAC	Fine Sand	0.2648	-	-	-	0.1342	661.62
	NA 10 mm	-	-	-	-	-	-
	NA 20 mm	-	-	-	-	-	-
	RCA 10 mm	0.2162	-	-	-	0.1095	470.48
	RCA 20 mm	0.3329	-	-	-	0.1687	705.73
	Total	0.8138	0.1862	0.2420	0.7580	0.4124	1837.83

Table 4. Cement and water contents

RCA replacement	Cement content (kg/m^3)			Water content (kg/m^3)		
	0.35 w/c	**0.45 w/c**	**0.55 w/c**	**0.35 w/c**	**0.45 w/c**	**0.55 w/c**
0% RCA	431.69	375.74	332.63	151.09	169.08	182.95
30% RCA	397.08	345.61	305.96	138.98	155.53	168.28
50% RCA	395.66	344.37	304.86	138.48	154.97	167.67
70% RCA	390.15	339.58	300.62	136.55	152.81	165.34
100% RCA	360.36	313.66	277.67	126.13	141.15	152.72

4. MIX METHOD AND CONCRETE PROPORTIONS

All 20 and 10 mm natural and recycled concrete aggregates was soaked in water for 12 hours, then air dried till the saturated-surface-dry (SSD), to reduce the effect of water absorption and increase the workability of RCAs without change the water-cement ratio in concrete. Fine sand was air dried and passed through 3.35 mm sieve. Pre-wetted drum concrete mixer was used to mix the concretes, the sand and aggregates were dry-mixed for 5 minutes before the cement and water was added. The liquid-based superplasticizer was first dissolved in water, and then the solution was proportionally split into two parts that were added into the mixture at different time. The concrete was poured into three 100 x 100 x 400 mm prisms and twelve 100 x 200 mm cylinders steel moulds. The concrete specimens were demolded a day after pouring and were cured in a room temperature. A total of fifteen concretes were produced, includes five different RCA replacement ratios of 0, 30, 50, 70 and 100, with three different water-cement ratios of 0.35, 0.45 and 0.55. The mix proportions are shown in Table 5.

Table 5. Mix proportions in 1 m^3

0.35 w/c (kg/m^3)	**Mix 1** **0% RCA**	**Mix 2** **30% RCA**	**Mix 3** **50% RCA**	**Mix 4** **70% RCA**	**Mix 5** **100% RCA**
Type GB Cement	431.69	397.08	395.66	390.15	360.36
Water	151.09	138.98	138.48	136.55	126.13
Fine Sand	713.62	704.96	686.05	670.64	661.62
NA 10mm	507.46	350.91	243.93	143.07	-
NA 20mm	761.19	526.37	365.89	214.61	-
RCA 10mm	-	150.39	243.93	333.83	470.48
RCA 20mm	-	225.59	365.89	500.75	705.73
Superplasticizer	2.75	2.75	2.75	2.75	2.75
0.45 w/c (kg/m^3)	**Mix 6** **0% RCA**	**Mix 7** **30% RCA**	**Mix 8** **50% RCA**	**Mix 9** **70% RCA**	**Mix 10** **100% RCA**
Type GB Cement	375.74	345.61	344.37	339.58	313.66
Water	169.08	155.53	154.97	152.81	141.15
Fine Sand	713.62	704.96	686.05	670.64	661.62
NA 10mm	507.46	350.91	243.93	143.07	-
NA 20mm	761.19	526.37	365.89	214.61	-
RCA 10mm	-	150.39	243.93	333.83	470.48
RCA 20mm	-	225.59	365.89	500.75	705.73
Superplasticizer	2.75	2.75	2.75	2.75	2.75
0.55 w/c (kg/m^3)	**Mix 11** **0% RCA**	**Mix 12** **30% RCA**	**Mix 13** **50% RCA**	**Mix 14** **70% RCA**	**Mix 15** **100% RCA**
Type GB Cement	332.63	305.96	304.86	300.62	277.67
Water	182.95	168.28	167.67	165.34	152.72
Fine Sand	713.62	704.96	686.05	670.64	661.62
NA 10mm	507.46	350.91	243.93	143.07	-
NA 20mm	761.19	526.37	365.89	214.61	-
RCA 10mm	-	150.39	243.93	333.83	470.48
RCA 20mm	-	225.59	365.89	500.75	705.73
Superplasticizer	2.75	2.75	2.75	2.75	2.75

5. RESULTS AND DISCUSSION

Table 6 shows the compressive strength (f_c') of fifteen concretes. The concrete cylinders were tested after 28 days, and the testing procedure was according to AS 1012.14. The compressive strength of recycled aggregate concrete with same water-cement ratio the test results show the strength fluctuation between different RCA replacement ratios are small. The small fluctuations are due to the reduction in cement concentration of the cement paste and porosity variations between aggregates (Wardeh, Ghorbel & Gomart 2015). Overall, 50% RCA recycled aggregate concretes has higher compressive strength.

Table 6. Compressive strength (f'_c) of recycled aggregate concretes

No. of mix	w/c	RCA%	Reading 1 (MPa)	Reading 2 (MPa)	Reading 4 (MPa)	Average (MPa)
Mix 1	0.35	0	40.20	46.72	45.63	44.18
Mix 2		20	37.55	34.21	38.25	36.67
Mix 3		50	51.27	46.62	51.65	49.85
Mix 4		70	45.26	43.32	43.14	43.91
Mix 5		100	35.52	39.33	40.35	38.40
Mix 6	0.45	0	37.87	35.01	29.71	34.19
Mix 7		20	32.74	28.78	30.81	30.77
Mix 8		50	35.65	33.22	35.54	34.80
Mix 9		70	30.51	28.93	30.81	30.08
Mix 10		100	29.39	26.15	27.34	27.62
Mix 11	0.55	0	18.69	19.33	19.21	19.08
Mix 12		20	14.97	16.94	19.42	17.11
Mix 13		50	20.11	21.57	22.95	21.55
Mix 14		70	14.23	19.10	16.86	16.73
Mix 15		100	14.01	13.64	13.96	13.87

The flexural tensile strength ($f'_{ct.f}$) of fifteen recycled aggregates are show in Table 7. The concrete prisms were tested after 28 days, and the testing procedure was according to AS 1012.11. It is possible to conclude that the tensile strength variations of recycled aggregate concrete with different RCA replacement ratios are very small, so the tensile strength fluctuations are insignificant.

Table 7. Flexural tensile strength ($f'_{ct.f}$) of recycled aggregate concretes

No. of mix	w/c	RCA%	Reading 1 (MPa)	Reading 2 (MPa)	Reading 4 (MPa)	Average (MPa)
Mix 1	0.35	0	4.38	4.26	4.09	4.24
Mix 2		20	4.78	3.52	4.06	4.12
Mix 3		50	4.06	4.45	5.16	4.56
Mix 4		70	3.79	5.04	4.31	4.38
Mix 5		100	4.24	4.38	5.06	4.56
Mix 6	0.45	0	3	3.61	3.99	3.53
Mix 7		20	-	4.03	3.69	3.86
Mix 8		50	4.7	4.04	3.57	4.10
Mix 9		70	3.74	3.43	3.81	3.66
Mix 10		100	3.23	3.62	-	3.43
Mix 11	0.55	0	2.88	2.9	2.77	2.85
Mix 12		20	2.57	2.79	3.04	2.80
Mix 13		50	3.01	-	2.84	2.93
Mix 14		70	2.47	2.79	2.47	2.58
Mix 15		100	2.51	2.8	2.56	2.62

6. CONCLUSION

In this paper, the packing density method was used to design the recycled aggregate concretes. A total of fifteen concretes with five RCA replacement ratios of 0, 30, 50 70 and 100% and three water-cement ratios of 0.35, 0.45 and 0.55 were produced, it considered 10 and 20 mm of two size natural and recycled concrete aggregates. From the material test results, found that the natural and recycled concrete aggregates have different density, volume and absorption, hence it should not be considered the same. Unlike the absolute volume method, it considered the individual aggregate as well as the overall mixture density and volume changes. Moisture content and water absorption of aggregates are also being considered in the design. From the mechanical testing results, adoption of packing density method can solve the recycled aggregate concrete strengths fluctuation and minimise the influence of recycled concrete aggregates obtain from various sources with variable quality. Irrespective the RCA replacement ratio, the building can maintain the consistency of the strength of the entire structure.

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