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EFFECTS OF ALTERNATIVE AGGREGATES ON CONCRETE STRENGTH

DANIELA IONESCU, JOE PETROLITO, JOHN FORREST, SAMUEL GERMAN, and SAM PINNUCK

Dept of Engineering, La Trobe University, Australia

Worldwide, large quantities of solid waste are generated by construction and demolition (C&D) activities and the car industry. At the same time, the availability of landfill space is diminishing, and most industrialized nations are actively promoting recycling procedures to reduce the amount of waste going to landfill. Governments have also set up regulatory bodies to provide standards and protocols for these procedures. Environmental benefits and reduced concrete production costs are some of the advantages of using recycled materials. Given these worldwide trends, it is essential to consider recycling some of the solid waste from the construction industry and used tires from the car industry to supplement natural aggregates in the production of concrete for the construction industry. This papers discusses the on-going research at La Trobe University on the use of recycled aggregates such as crushed concrete, crushed brick and rubber chips in the production of concrete. The effects of partial or total replacement of normal-weight aggregates with recycled aggregates on the strength of concrete were investigated. Different types and proportions of aggregate replacements were studied to establish which protocols provided the best options. It was found that concrete mixes produced with recycled aggregates produced acceptable concrete with reduced production costs.

Keywords: Construction and demolition waste, Crushed bricks, Crushed masonry, Recycled masonry, Recycled tires, Rubber chips.

1 INTRODUCTION

Concrete is the most preferred construction material for civil infrastructure due to its versatility, strength and durability. However, concrete is not an environmentally friendly material as it requires significant quantities of natural aggregates in its production. Hence, there is an increasing demand and interest in aggregates from non-traditional sources, such as from recycled industrial (scrapped tires) and construction and demolition (C&D) wastes.

In Australia, scrapped tires and C&D waste represent a significant proportion of the solid waste disposed at landfills. In 2010-2011, 32% of the total of 63 million tons of solid waste was C&D waste (Randell *et al.* 2013). The recovery rate of the masonry materials was 66%. During the same period, the Australian car industry produced over 500,000 tons of waste rubber tires, with only 16% of this being recycled (Hyder Consulting 2012). Furthermore, only 3% of the recycled tires are currently used in civil engineering applications, which is well below the rate for other developed countries (Mohammadi *et al.* 2014).

As sustainability is a vital part of the construction industry, the use of recycled aggregates in concrete is one possible solution to reduce the environmental impacts of concrete production. Currently, recycled masonry materials are mainly used in pavement applications (Hyder Consulting 2011). Ionescu (2010) and Cavalline and Weggel (2013) reported that recycled masonry can successfully be used in concrete production as replacements for natural aggregates. Recycled rubber from scrapped tires is mainly used as a partial replacement for sand (Li *et al.* 2014, Mohammadi *et al.* 2014), while rubber chips may be used as a partial replacement of coarse aggregates in concrete production (Somerville *et al.* 2015). The results of an ongoing study into the use of waste products (masonry materials and scrap tires) as either partial or total aggregate replacements in the production of light-weight concrete are reported in this paper.

2 MATERIAL REQUIREMENTS

Neville (2005) reviewed the major properties of aggregates that affect the behavior of fresh and hard concrete, namely strength, hardness, toughness, durability, porosity, volume change, grains shape and texture, chemical reactivity and relative density. Past research into the possible uses of crushed masonry has suggested that crushed concrete and bricks have most of the required properties, and hence they may be used as either partial or total replacements for naturally occurring aggregates in concrete production (Oikonomou 2005, Ionescu 2010, Ionescu *et al.* 2015).

A good concrete mix shows evidence of equal amounts of bond failure and fracturing of the coarse aggregates (Neville 2005). Hence, aggregates that have angular grains with a rough surface texture and a broad gradation produce the minimum void space in the concrete matrix. Proportions of flaky and elongated particles and aggregates with high water absorption should also be avoided (Neville 2005).

3 EXPERIMENTAL PROGRAM

The physical characteristics of the materials used in the study were determined in accordance with relevant Australian Standards (primarily AS 1012, AS 1289, AS 2758). The governing factors were the compliance with current specifications and the feasibility of obtaining an acceptable material.

3.1 Concrete Aggregate

Considering the economic aspects, it was decided that the recycled masonry aggregates would be used as supplied with no additional crushing, sieving or washing. Materials were supplied by All Stone Quarries (ASQ) in Bendigo, Hymix Quarry in Axedale (HQA) and Tyrecycles in Melbourne. Independent of the material type used as aggregates, coarse and fine fractions combine best for a target Gradation 2 (C&CAA 1976, AS 2758.1 2014). The following aggregate combinations were used:

- HQA coarse basalt and blended washed river sand (B-CA + BWRS-FA)
- ASQ coarse recycled brick and HQA blended washed river sand (Br-CA + BWRS-FA)

- ASQ coarse and fine recycled brick (Br-CA + Br-FA)
- HSQ coarse basalt and ASQ fine recycled brick (B-CA + Br-FA)
- ASQ coarse recycled concrete and HQA blended washed river sand (CC-CA + BWRS-FA)
- ASQ coarse and fine recycled brick (CC-CA + CC-FA)
- HQA coarse basalt with 5%, 10% and 20% replacement by volume with Tyrecycles rubber chips and blended washed river sand (B&XRC + BWRS-FA, where X is 5, 10 and 20, respectively).

Table 1 gives the gradation characteristics of the nine aggregate combinations. Fines (grains < 0.425 mm) were tested for any clay content. A summary of the consistency tests (AS 1289 2005) and the clay and silt contents (AS 1141.33 1997) is given in Table 2. The finer fractions were classified as non-plastic/low plasticity silts. The physical properties of the aggregates were determined in accordance with the relevant specifications (AS 1141.6.1 2000), and they are summarized in Table 3. As expected, recycled brick and concrete (CA and FA) showed significantly higher water absorption rates compared with the currently-used aggregates, and this was accounted for in the mix design. The recycled CA concrete, brick and rubber chips were 18%, 20% and 60%, respectively, lighter than the basalt, whereas the recycled FA concrete and brick were only 4% to 6% lighter than the river sand.

Table 1. Grading characteristics of combined aggregates (after Ionescu *et al.* 2015).

Material	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c
B-CA + BWRS-FA	0.51	3.75	8.20	16.1	3.4
Br-CA + BWRS-FA	0.41	2.90	11.05	27.0	1.9
Br-CA + Br-FA	0.85	5.71	10.34	12.2	3.7
B-CA + Br-FA	0.53	3.60	7.80	14.7	3.1
CC-CA + BWRS-FA	0.26	3.70	11.30	43.5	4.7
CC-CA + CC-FA	0.38	2.65	9.98	26.3	1.9
B&5RC + BWRS-FA	0.32	2.85	8.15	25.5	3.1
B&10RC + BWRS-FA	0.27	2.57	8.05	29.8	3.0
B&20RC + BWRS-FA	0.10	2.02	8.00	80.0	5.1

Table 2. Fine aggregates consistency and silt content characteristics (after Ionescu *et al.* 2015).

Material	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Linear shrinkage (%)	Silt content (%
BWRS-FA	18	14	4	2	6
Br-FA	19	16	3	1	7
CC-FA	19	17	2	2	8

Table 3. Physical properties of aggregates used (after Ionescu *et al.* 2015).

Material type	B-CA	Br-CA	CC-CA	RC-CA	BWRS-FA	Br-FA	CC-FA
Water absorption (%)	2.23	7.00	6.02	0.40	0.60	4.60	3.80
Particle density (SSD) (t/m^3)	2.72	2.20	2.24	1.08	2.61	2.44	2.50

3.2 Concrete Properties

The concrete mixes were based on a characteristic compressive strength of 32 MPa. A 50-mm slump was used (C&CAA 2002), and the aggregates were used in the air-dried condition. The quantities of materials used per 1 m^3 are summarized in Table 4.

Table 4. Average properties for 28 days old concrete (after Ionescu *et al.* 2015).

Mix type \ Parameter	Mix quantities c/w/FA/CA/RC (kg)	Compressive strength (MPa)	Flexural strength (MPa)	Indirect tensile strength (MPa)	Density (kg/m^3)
B-CA + BWRS-FA	370/200/620/1090/0	53.0	5.9	3.5	2400
Br-CA + BWRS-FA	370/216/620/950/0	43.0	5.6	3.3	2240
Br-CA + Br-FA	370/258/530/950/0	41.0	5.9	3.2	2180
B-CA + Br-FA	370/208/530/1090/0	49.5	6.0	3.8	2320
CC-CA + BWRS-FA	370/206/700/1130/0	41.2	4.6	3.2	2280
CC-CA + CC-FA	370/232/610/1190/0	28.9	3.7	2.5	2200
B&5RC + BWRS-FA	370/200/620/1040/19	42.3	5.7	2.8	2380
B&10RC + BWRS-FA	370/190/620/980/38	35.9	5.3	2.4	2330
B&20RC + BWRS-FA	370/180/620/870/76	25.5	4.7	1.9	2250

Note: c = cement, w = water, FA = fine aggregates, CA = coarse aggregates and RC = rubber chips.

3.2.1 *Density*

The concrete specimens were water cured prior to testing. The average density of concrete at 28 days is given in Table 4. The alternative aggregates produced a slightly lower density concrete. The Br-CA + Br-FA combination caused the highest reduction in density (9%), followed by the CC-CA + CC-FA, Br-CA + BWRS-FA, CC-CA + BWRS-FA and B-CA + Br-FA combinations, with density reductions of 8%, 7%, 5% and 3%, respectively. The rubberized concrete had a density reduction of 1%, 3% and 6%, for a replacement by volume of 5%, 10% and 20%, respectively.

3.2.2 *Compressive strength*

Concrete produced with alternate aggregates resulted in a consistently lower compressive strength, with reductions between 6% and 52%. Concrete produced with recycled brick resulted in slightly better concrete than that produced with recycled concrete. The replacement of basalt and river sand with recycled brick (CA + FA) gave a 23% reduction in strength, whereas the replacement by recycled concrete (CA + FA) gave a 45% reduction in strength. This is believed to be due to the large percentage of dust (grains < 0.075 mm) present in CC-FA. The partial replacement of coarse aggregates with recycled masonry caused a reduction in strength of 19% and 22% for crushed brick and crushed concrete, respectively. The partial replacement of fine aggregates with crushed brick caused only a 6% reduction in strength.

The reduction in the strength of rubberized concrete increased with the percentage of aggregate replacement. The strength reduced by 20%, 32% and 52% for replacements of 5%, 10% and 20%, respectively. These results are attributed to a lesser bond between the cement paste and rubber chips.

3.2.3 *Flexural strength*

The 28-day flexural strengths are summarized in Table 4. The trends observed for the compressive strength were also observed for the flexural strength. Concrete produced with alternate aggregates resulted in strengths between 3% and 37% lower than that of the control batch. The effects of total and partial replacements of CA and FA were more critical for concrete produced with crushed concrete, which caused a 22% to 37% strength reduction, as opposed to only a 5% strength reduction for concrete produced with recycled bricks. These results are attributed to the presence of more dust (grains < 0.075 mm) in CC-FA. The partial replacement of aggregates (e.g., only FA) with crushed brick caused a slight improvement in the strength, which is perhaps due to the rough texture of crushed brick compared to river sand.

The rubberized concrete showed reductions in strength of 3%, 10% and 20%, respectively, when the percent of basalt replacement varied from 5% to 20%. The presence of rubber chips slowed the fracture propagation, and the two fragments of the failed test beams remained attached by the rubber chips.

3.2.4 *Indirect tensile strength*

As shown in Table 4, the use of alternate aggregates resulted in lower indirect tensile strengths with reductions between 6% and 46%. Concrete produced with recycled brick performed better (only 6% to 9% strength reduction) than that produced with crushed concrete (9% to 29% reduction in strength). Partial replacement of aggregates (e.g., only FA) with crushed brick caused an 8% improvement in the strength, which is believed to be due to the rougher grain surfaces of crushed brick.

The rubberized concrete showed reductions in strength of 20%, 31% and 46%, respectively, when the percent of basalt replacement varied from 5% to 20%. These results do not follow the trends observed for the flexural strength, although they are consistent with the trends observed for the compressive strength.

4 CONCLUSIONS

The effects of alternate aggregates for concrete production were discussed in this paper. The use of crushed brick CA and FA resulted in the lowest density concrete, and the strength of the concrete was reduced as well. Similar outcomes were obtained when the concrete was produced with coarse and fine recycled concrete aggregates. Partial replacement of natural aggregates also caused reductions in the concrete strength, although the resulting strengths were acceptable. Rubberized concrete resulted in significant strength reductions, although the flexural strength was less affected by the rubber chips.

Further investigation is required to evaluate the effects of alternate aggregates on the elastic properties and durability of concrete. In addition, research into methods of improving the overall properties of concrete with alternate aggregates without greatly affecting the production costs.

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