Journal of Cleaner Production 133 (2016) 672–680

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Carbon-conditioned recycled aggregate in concrete production

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ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form
10 May 2016
Accepted 1 June 2016
Available online 4 June 2016

Keywords:
Carbon-conditioned recycled aggregate
Recycled concrete

ABSTRACT

This paper investigates the use of carbon-conditioned recycled aggregate (RA^{CO2}) in concrete production. Experimental work is conducted for RA^{CO2} with varying chamber pressure (0 kPa, 75 kPa, 150 kPa), chamber duration (0 min, 30 min, 90 min) and RA^{CO2} replacement percentages (0%, 30%, 100%) for concrete production. Average of three results on compressive, tensile and flexible strength and modulus of elasticity at 28 curing days are compared. The process of carbon-conditioning refers to the pressurised exposure of recycled aggregate to carbon dioxide (CO_2) for a certain period of time before concrete mixing. The entraining of CO_2 assists to facilitate the negative properties of recycled aggregate that produces a deprived final recycled concrete as well as providing a superior calcium carbonate chemical reaction. Carbon-conditioning reduces porosity and water absorbency of recycled aggregate. In addition to improve recycled aggregate quality, CO_2 emissions from the aggregate also help filling openings in the concrete composition, generating an improved bond matrix from the formation of calcium carbonates (Zhan et al., 2014). These two traits assist in enhancing the recycled concrete properties. This paper demonstrates a great potential in the use of RA^{CO2} in improving physical and mechanical properties of recycled concrete and provides insight for effective use of recycled aggregate for concrete production. The effective use of recycled aggregate can reduce the amount of landfill that is utilised for construction and demolition waste.

1. Introduction

Construction and demolition waste is attributed with a large portion of landfill space around the world (Pacheco-Torgal et al., 2013). Recycling construction and demolition waste has been heavily researched in order to discover solutions for reducing landfill space. The use of crushed concrete waste as recycled aggregate serves as a solution with outstanding potential for reducing landfill volume. Conversely, recycled concrete, as it is known, is characterised by a large physical and mechanical shortcomings (Li et al., 2008).

The deficiency of strength exhibited by recycled concrete does not permit it to surpass natural concrete in terms of mainstream practical usage (Kou et al., 2012). To achieve recycled concrete which challenges natural concrete, it must undertake additional strengthening processes. However, supplementary procedures required for improving recycled concrete quality must closely equal practicality and monetary expenditure of natural concrete.

Review on the effects of incorporating recycled aggregate, sourced from construction and demolition waste, on the carbonation behaviour of concrete was conducted (Silva et al., 2015). Various influencing aspects related to the use of recycled aggregate, such as replacement level, size and origin, as well as the influence of curing conditions, use of chemical admixtures and additions on carbonation over a long period of time were identified.

Modification of recycled aggregate by calcium carbonate biodeposition was examined (Grabiec et al., 2012). Calcium chloride was used for precipitation of calcium carbonate, while culture medium consisting of beef extract, peptone and urea was used for cultivation of microorganisms (Grabiec et al., 2012). It was found that the microbial carbonate precipitation peaks at pH 9.5 and increases with higher temperature, bacteria concentration or calcium concentration.

Experiments was also carried out for investigating the possibilities of producing carbonated granulated steel slag concrete in replacing common natural aggregate (Pang et al., 2015). Test results showed that carbonation treatment can significantly improve the strength and volume stability of steel slag aggregate and reduce water absorption, porosity and free calcium oxide.

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http://dx.doi.org/10.1016/j.jclepro.2016.06.007

The process of carbon-conditioning recycled aggregate and recycled concrete proposes an abundance of potential. There are different approaches in carbon-conditioning, for either recycled aggregate or recycled concrete. For carbon-conditioning recycled aggregate, recycled aggregate is first placed in a sealed chamber and at that juncture; it is exposed to carbon dioxide at pressure for a given amount of time. The exposer produces a recycled aggregate which is denser, less porous with a reduced amount of water absorbency (Zhan et al., 2014). The discharge of an amount of CO_2 from the conditioned recycled aggregate also generates a superior bond matrix as a result of an enhanced chemical reaction and a great filling of space within the matrix (Kou et al., 2014). Kou's (Kou et al., 2014) as well as Zhang's (Zhang et al., 2015b) studies also exposed that the carbon-conditioning process has a positive influence on the long-term mechanical properties of recycled concrete, the concrete achieving greater mechanical properties as more time transpired. Unfortunately, due to low pH levels within the cement paste steel reinforcement cannot be applied as the steel becomes susceptible to corrosion. Carbon-conditioning improves recycled aggregate quality and as a consequence, generates a resilient recycled concrete (Zhan et al., 2014).

Properties of carbon-conditioned recycled aggregate and its mortar were also studied (Zhang et al., 2015a). It was found that the carbonation increased the apparent density and reduced both water absorption and crushing value of recycled aggregate. The flowability and compressive strength of the recycled aggregate mortar were lower than those of natural sand mortar. However, the properties of mortar made with CO_2 treated recycled aggregate were very similar to those of natural sand mortar.

The initial carbon-conditioning process otherwise known as accelerated carbonation is based on the reactions between CO_2 and hydration products of cement in concrete. The preliminary reaction during early hydration precipitates calcium carbonate into pore spaces and densifies the entire microstructure (Xuan et al., 2016). The accelerated carbonation of the concrete is the key to forming a desirable microstructure, which ultimately produces a hardier concrete, unlike a slow and late exposure to concrete which can cause deterioration to occur.

An alternative approach is carbon curing of recycled concrete (Zhan et al., 2013). A CO_2 curing process was adopted to cure concrete blocks made with recycled aggregate. Non-load and load-bearing blocks were prepared and placed in a pressurized 100% CO_2 curing chamber for 6, 12 and 24 h. It was found that the CO_2 cured blocks attaining higher compressive strength and lower drying shrinkage than the corresponding moist cured blocks. It was also found that curing time and amount of recycled aggregate present in the blocks had insignificant effects on the strength gain and CO_2 curing degree.

Carbon-conditioning recycled aggregate is not yet used in the mainstream concrete production. Carbonation is cheaper than other recycling alternatives, seems to generate an appropriate physical and mechanical quality and is practical for commercial use. However, additional research must be conducted. This paper investigates the use of carbon-conditioned recycled aggregate (RA^{CO2}) by varying chamber pressure (0 kPa, 75 kPa, 150 kPa), chamber duration (0 min, 30 min, 90 min) and RA^{CO2} replacement ratio (0%, 30%, 100%) in concrete production. The focus upon both chamber pressure and duration aimed to discover the best medium at which the carbon-conditioning process can be utilised in commercial means. Results on compressive, tensile and flexible strength and modulus of elasticity at 28 curing days are compared.

2. Materials

Recycled aggregate samples collected from a south-eastern Australia centralised recycling plant was adopted for the production of concrete. Particle size distribution is of importance as it affects workability and strength (Neville, 1995). As regards the sample collected was fulfilling the particle size distribution of 10 mm and 20 mm aggregate as stated in Australian standard (see Fig. 1) (AS 1141.11, 2014).

The water absorption of the recycled aggregate sample is about 5.02% for 10 mm and 5.63% for 20 mm with particle density on oven-dried basis of about 1.44 t/m^3 for 10 mm and 1.30 t/m^3 for 20 mm, particle density on saturated and surface-dried basis of about 1.51 t/m^3 for 10 mm and 1.37 t/m^3 for 20 mm, apparent particle density of about 1.55 t/m^3 for 10 mm and 1.40 t/m^3 for 20 mm, aggregate crushing value of about 34%, about 2% contaminant, flakiness index of about 15.12 for 10 mm and 9.78 for 20 mm, and misshapen particle of about 0.88%. The properties of natural aggregate are also compared with the recycled aggregate as shown in Table 1.

2.1. Carbonation chamber

For carbon-conditioning recycled aggregate, a carbonation chamber was designed and built, including a translucent polyvinyl chloride pressure pipe with a screw top lid connecting to a CO_2 tank, brandishing a regulator in controlling pressure. CO_2 was introduced to the chamber for the experimented pressure and duration. Fig. 2 illustrates the carbonation chamber used.

2.2. Experimental design

Ordinary Portland cement, designated Type GP (General Portland) was used for the experimental work. The RA^{CO2} replacement ratios were used at 0%, 30% and 100%, water-to-cement ratios were used at 0.4. The process of carbon-conditioning is a new experimental and prototype process. Pressure on 75 kPa and 150 kPa was nominated. The duration was selected to observe the change in two different durations lower than that of Kou's studies (Kou et al., 2014) for gaining knowledge on the effects of carbon-conditioning in a manageable commercial timeframe. Details of all mixing proportions used for the recycled concrete experimental work and experimental design on RA^{CO2} replacement percentage, chamber duration and chamber pressure are shown in Table 2 and Table 3 respectively.

Each concrete mixture was made up of 9 cylinders and 3 beams in order to gain three samples in each mechanical property test of compression strength, split tensile strength, flexural strength and modulus of elasticity.

The mixing procedure conducted in this paper is based on Australian Standard (AS 1012.2, 2014). The RAC mixing was first charged with about half of natural and recycled coarse aggregate, then with natural fine aggregate, then with cement, and finally with the remaining coarse aggregate. Water was then immediately added after starting the operation for two minutes (AS 1012.2, 2014). It needs to be emphasized that no superplasticizer or additive was added to any concrete mixes in the experimental work. This can ensure that the actual results from the RACO2 replacement percentages, chamber pressure and chamber duration are recorded and analysed.

Three 100 mm-diameter and 200 mm-high concrete cylinders for each mixing proportion were used for conducting compressive strength (AS 1012.9, 2014), split tensile strength (AS 1012.10, 2014) and modulus of elasticity (AS 1012.17, 2014) and three 100 mm-wide, 100 mm-high and 350 mm-length concrete beams for conducting flexural strength (AS 1012.11, 2014) at 28 curing days.

The concrete samples were demoulded after 24 h of mixing and immediately placed in a room with controlled environmental conditions at temperature of 22 ± 2 °C and relative humidity level of 70 ± 2%.