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Time-dependent and long-term mechanical properties of concretes incorporating different grades of coarse recycled concrete aggregates

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ABSTRACT

It is now accepted that replacement of natural aggregates in concrete with recycled concrete aggregates obtained from construction and demolition waste is a promising technology to conserve natural resources and reduce the environmental impact of concrete. This paper presents a study on long-term properties of concretes manufactured with recycled aggregates of different parent concrete strengths. A total of six batches of recycled aggregate concretes (RACs) were manufactured. Tests were undertaken to establish the long-term compressive strength, elastic modulus, splitting tensile strength, workability, drying shrinkage, and creep of each batch. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) characterizations were performed to explain the mechanisms behind the observed time-dependent and mechanical properties of RACs. Test parameters comprised the replacement ratio and parent concrete strength of the recycled aggregates used in the preparation of the new concrete mixes. The results indicate that the parent concrete strength of the recycled aggregates significantly affects the time-dependent and long-term mechanical properties of RACs. It is shown that concrete mixes containing lower strength recycled concrete aggregates develop lower mechanical properties and higher shrinkage strain and creep deformation compared to mixes prepared with higher strength recycled concrete aggregates. Normal-strength RAC mixes containing higher strength recycled concrete aggregates develop slightly lower splitting tensile strength at all curing ages but similar compressive strength and elastic modulus in longer term (i.e. over 90 days) compared to those of the control mix. It is also shown that high-strength RACs, prepared with full replacement of natural aggregates with recycled concrete aggregates having a higher parent concrete strength, exhibit time-dependent and long-term mechanical properties that are similar to or better than those of companion natural aggregate concretes.

1. Introduction

In recent decades, the increased use of concrete has resulted in excessive consumption of natural aggregates [1,2], which constitute approximately 70% of the total volume in a concrete mix [3]. The use of construction and demolition (C&D) wastes, which are conventionally disposed of in landfills at a significant cost, in concrete has recently received significant attention, as this technology enables conservation of non-renewable natural resources while also significantly reducing the environmental impact of both concrete and C&D waste [4,5]. Within this context, recycled concrete aggregate, which is obtained from demolished concrete structures, has been considered as an alternative material to natural aggregate in the production of structural concretes. Although recycled aggregate concrete (RAC), which is produced from partial or full substitution of natural aggregates by recycled concrete aggregates, has significant economic and environmental benefits [6–8], its use has so far been limited in construction industry because of the concerns regarding the inferior quality of recycled aggregate compared to that of natural aggregate [9].

Over the past three decades, a large number of studies have been conducted to understand the performance of RAC containing coarse recycled concrete aggregates [10]. The review of the existing literature on RACs shows that most of the existing studies were concerned with the short-term behavior and only a limited number of studies have been reported to date on the long-term behavior of RACs [11–22]. It has been shown that the strength of the parent concrete (the concrete from which recycled aggregates are derived) affects the long-term behavior of RACs [18,21]. Therefore, understanding the mechanisms behind the effect of the parent concrete strength on the long-term behavior of RACs is of significant interest. Moreover, although the popularity of high-strength concretes in the construction industry has been on a steady incline [23–25], only one study (i.e. [18]) has been reported to date on the time-dependent and long-term mechanical properties of high-strength RACs with different parent concrete strengths, which focused on RAC

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mixes containing fly ash. Therefore, there are currently no studies on the long-term behavior of conventional high-strength RACs prepared with recycled aggregates having different parent concrete strengths. Moreover, the creep behavior, a highly important time-dependent property, of high-strength RACs and microstructure of RAC mixes with different parent concrete strengths have not yet been investigated. Therefore, it is clear that additional studies are required to better understand the effect of the parent concrete strength on the time-dependent and long-term mechanical properties of high-strength RACs and mechanisms behind the observed test results.

This paper presents an experimental study conducted to address the research gaps outlined above by investigating the variation of physical, mechanical, and time-dependent properties of normal- and high-strength RACs with the parent concrete strength of coarse recycled aggregates. The paper initially provides a summary of the experimental program, including material properties, specimen properties, and testing procedures, which is followed by the results of the experimental program. A detailed discussion together with microstructural analysis of different mixes using scanning electron micrographs (SEM) and energy-dispersive X-ray spectroscopy (EDX) at 28 days curing is subsequently presented to explain the mechanisms behind the test results.

2. Test program

2.1. Materials

2.1.1. Natural and recycled concrete aggregates

The natural aggregates (crushed basalt) were sourced from McLaren Vale Quarry in Fleurieu Peninsula in South Australia. The natural sand having a 2-mm maximum nominal size was obtained from Price Pit in Yorke Peninsula and used as the fine aggregate in all concrete mixes. Three different recycled concrete aggregates with parent concrete strength of 20, 40, and 110 MPa were used to study the influence of lower and higher parent concrete strength recycled aggregates on the properties of RACs. In the production of the recycled aggregates, three different concrete mixes with three target 28-day strengths of 20, 40, and 110 MPa were prepared in the Concrete Materials Laboratory of the University of Adelaide using the same crushed basalt as the coarse aggregate. Once the parent concretes attained their 28-day strengths, they were crushed using a jaw crusher, such that the particle size distribution of the resulting aggregates would be similar to that of the natural coarse aggregates (refer to Fig. 1). The crushed recycled aggregates were subsequently added to the RAC mixes when they were approximately 56 days old.

The physical properties of natural and recycled aggregates are shown in Table 1. The attached mortar content, which is a measure of the percentage (by weight) of attached mortar in the recycled coarse aggregates, was determined as described in Ref. [26].

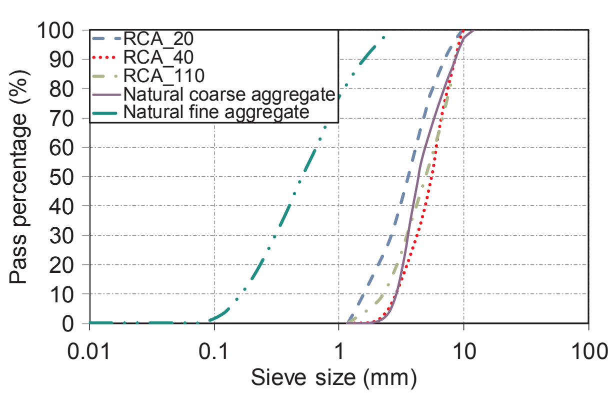

Fig. 1. Sieving test results of coarse and fine aggregates: Particle Size Distribution (PSD). RCA_20, RCA_40, and RCA_110 are recycled coarse aggregates with a 28-day parent concrete strength of 20, 40, and 110 MPa, respectively.

Table 1
Properties of coarse and fine aggregates.

Aggregate type	Maximum size (mm)	Specific gravity (OD)	Water absorption (%)	Fineness modulus	Attached mortar content (%)
NCA	9.5	2.60	2.0	5.4	–
RCA_20	10.0	2.16	6.8	5.1	53
RCA_40	10.0	2.24	5.9	5.9	48
RCA_110	10.0	2.36	5.0	5.7	42
Sand	2.0	2.60	0.4	2.3	–

OD: Oven dry.
NCA: Natural coarse aggregate.
RCA_20: Recycled coarse aggregate with 28-day parent concrete strength of 20 MPa.
RCA_40: Recycled coarse aggregate with 28-day parent concrete strength of 40 MPa.
RCA_110: Recycled coarse aggregate with 28-day parent concrete strength of 110 MPa.

Table 2
Chemical composition of cementitious materials.

Compounds	Ordinary Portland cement (%)	Silica fume (%)
SiO_2	21.4	92.5
$ZrO_2 + HfO_2$	–	5.50
Al_2O_3	5.55	0.35
Fe_2O_3	3.46	0.40
P_2O_5	–	0.30
CaO	64	0.03
MgO	1.86	–
SO_3	1.42	0.90
K_2O	0.54	0.02
Na_2O	0.26	0.02

2.1.2. Cement and pozzolanic admixture

The chemical composition of the ordinary Portland cement and silica fume used in this study are shown in Table 2. The Blaine fineness of the ordinary Portland cement and silica fume was 330 and 18,000 m^2/kg, respectively.

2.2. Test specimens

Six unique batches of concrete were prepared, which included: two control batches of natural aggregate concrete and four batches of RAC. The control mixes were designed as normal- and high-strength concrete (NSC and HSC) mixes with a 28-day compressive strength of 40 and 80 MPa, respectively. A series of tests including: the workability, compressive strength, modulus of elasticity, splitting tensile strength, drying shrinkage, and creep were undertaken on each batch to evaluate the properties of fresh and hardened concrete. Two types of specimens were manufactured for testing, including: prisms and cylinders. The compressive strength and modulus of elasticity of the concretes were established by the compression tests using cylinder specimens with a 100 mm diameter and 200 mm height. The splitting tensile strength tests were conducted on the same size cylinder specimens. 75 × 75 × 285 mm prism specimens were used to monitor the drying shrinkages of the concrete. The creep tests were performed on 100 × 200 mm cylinders. The test parameters included: replacement ratio of natural aggregates with recycled coarse aggregate (*RCA%*) and parent concrete strength of recycled aggregates. In each test, three nominally identical specimens were used for each unique specimen configuration.

2.3. Mix design, specimen preparation, and designation

Table 3 shows the mix proportions of different concrete batches used in this study. Normal- and high-strength RAC mixes were prepared with 50% and 100% *RCA%* (as the volume replacement of natural