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Preparation and properties of high-strength recycled concrete in cold areas

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ABSTRACT: Concrete waste was processed into recycled coarse aggregate (RCA), subsequently used to prepare high-strength (>50 MPa) recycled concrete. The resulting material was tested for mechanical performance (ULS). The recycled concrete was prepared to the required design strength by adjusting the water/cement ratio. Concrete containing 0, 20, 50, 80 and 100% recycled aggregate was prepared and studied for workability, deformability and durability. The ultimate aim of the study was to prepare high-strength recycled concrete apt for use in cold climates as a theoretical and experimental basis for the deployment of recycled high-strength concrete in civil engineering and building construction.

KEYWORDS: Recycled concrete; Water/cement ratio; Durability; Workability; Freeze/thaw resistance

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RESUMEN: *Preparación y propiedades del hormigón reciclado de alta resistencia en zonas frías*. En este estudio se preparó un hormigón de altas resistencias (>50 MPa) utilizando residuos de hormigón como árido grueso reciclado (RCA). El material resultante se ensayó para determinar sus prestaciones mecánicas (ULS). Para adaptarse a los requerimientos resistentes, se ajustó la relación agua/cemento del hormigón reciclado. Se estudió la trabajabilidad, deformabilidad y durabilidad del hormigón con contenidos del 0, 20, 50, 80 y 100% de árido reciclado. El objetivo final del estudio fue preparar hormigón reciclado de altas resistencias apto para su uso en climas fríos como base teórica y experimental para el desarrollo de este tipo de materiales en obra civil y edificación

PALABRAS CLAVE: Hormigón reciclado; Relación agua/cemento; Durabilidad; Trabajabilidad; Resistencia hielo/deshielo

1. INTRODUCTION

Sustained high rates of economic development in recent years, together with rapidly expanding cities and urban renewal, has spurred construction industry growth. That, in turn, has generated vast amounts of construction and demolition waste (C&DW). Recycling such waste is not only imperative to comply with environmental protection legislation, but reduces production costs and affords a solution to the problem of disposing of C&DW (1–2).

Construction waste is presently recycled in primarily three ways. The first is general backfill. In 1995, Japan, with one of the world's highest recycling rates, valorised up to 65% of its C&DW in road construction and as backfill (3). The second is road construction, as in the UK. Also in the UK, more specifically in Watford, England, the Environment Building was built by BRE using 80 000 recycled bricks (4). The third possible use is as coarse and fine aggregate in structural concrete for buildings and road surfacing. Recycled concrete was first researched and used in developed countries, where codes and standards on its regulation have also been published (5–6).

Processing this material first entails crushing and grading. The aggregate so processed is then used in concrete mixes, either wholly partially replacing natural (usually coarse) aggregate. This type of concrete was initially known as recycled aggregate concrete, although the term was later abbreviated to recycled concrete (7–8). While China began to study concrete waste recycling fairly late in the day, the country has recently engaged in more intense research on the subject, as attested to by the literature (9–10). Nonetheless, many issues are still in need of more in-depth study. The properties of high-strength recycled concrete have been the object of relatively few papers and scant experimental data are available. The present study focused on the preparation and properties of high-strength recycled concrete for cold climates with a view to establishing an experimental basis for applying recycled concrete in civil engineering (11).

2. RAW MATERIALS

2.1. Recycled coarse aggregate (RCA)

The origin of the recycled coarse aggregate used in this study was the concrete waste from structures in Harbin (the capital city of Heilongjiang Province in northeastern China, an area with a very cold climate), where it was subject to countless freeze-thaw cycles prior to crushing, grinding, screening and processing. Since the components in the waste concrete were laboratory-processed into RCA, they contained few impurities and no hazardous materials. The resulting aggregate proved to be apt for use in the preparation of high-strength concrete (12). The micro-cracks that appeared on the surface of the aggregate under the heavy pressure applied during processing detracted from the mechanical performance of the material. To ensure the quality of high-strength recycled concrete, only RCA whose abrasion test results are comparable to the findings for natural aggregate should be used. In the present study, abrasion tests were conducted on coarse aggregate sourced from 40-MPa concrete, 60-MPa concrete and concrete of unknown compressive strength, as well as from natural stone. The results are shown in Figure 1.

At 32.1%, the mean abrasion loss in RCA was greater than in the natural material (24.6%). Abrasion loss was 28.5% in 60-MPa concrete aggregate and

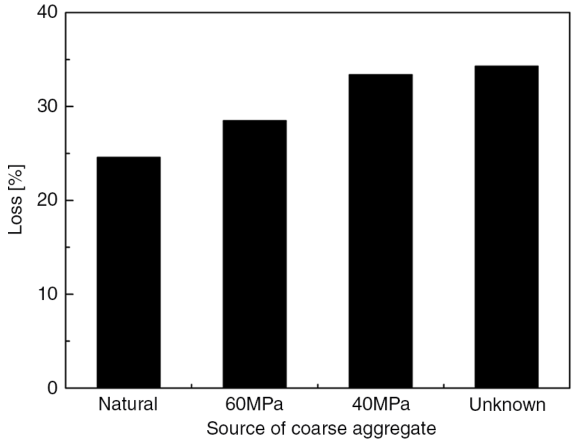

FIGURE 1. Coarse aggregate abrasion resistance.

33.4% in the material processed from 40-MPa concrete waste. In other words, the higher the pre-crushed concrete strength, the lower the abrasion loss in the aggregate. The highest abrasion loss, 34.3%, was recorded for the waste concrete of unknown strength. That finding was attributed to the fact that it had been in service longest and the initial quality was the lowest. Since abrasion loss was under 50% in the three types of RCA studied (Figure 1), all three were regarded as apt for use in structural concrete (13). The recycled coarse aggregate sourced from crushed 60-MPa concrete was chosen for preparing the high-strength recycled concrete used here, inasmuch as its abrasion loss was lower than the other two types of RCA tested.

The data on physical properties given in Table 1 confirm the higher quality of natural than recycled coarse aggregate.

2.2 Other raw materials

Cement: Swan P·O 42.5 ordinary portland cement supplied by the Yatai Group cement plant at Harbin.
Fine aggregate: natural standardised sand (14) with an apparent density of 2640 kg/m^3.
Natural coarse aggregate: crushed stone, ≤31.5 mm.
Water: runningwater.

3. HIGH-STRENGTH RECYCLED CONCRETE

3.1. Preparation and ultimate limit strength

The natural and recycled aggregate were mixed at replacement ratios of 0, 30, 50, 80 and 100%. Four water/cement (w/c) ratios were used to prepare the concrete: 0.30, 0.35, 0.40 and 0.45. The batching design called for 195 kg/m^3 of water and 1130 kg/m^3 of coarse aggregate, while the fine aggregate content was adjusted in keeping with the w/c ratio. The mix was enhanced with an LQ-polycarboxylate high-range

Table 1. Coarse aggregate properties

Aggregate type	Particle diameter [mm]	Apparent density [kg/m^3]	Water sorptivity [%]	Moisture content [%]	Packing density [kg/m^3]	Crushing index [%]
Crushed stone	5~31.5	2780	0.72	<0.5	1392	10.1
Recycled aggregate	5~31.5	2492	3.87	2.6	1236	15.8

water-reducing admixture dosed at 1 wt% of the cement. The recycled concrete mix was moulded into 150-mm^3 cubic specimens and cured under standard conditions for 28 days, when compressive strength was measured as described in Chinese specification *GB/T50081-2002 Standard for test method of mechanical properties on ordinary concrete* (15). Table 2 lists the concrete batching used and the 28-day compressive strength values for the specimens. As the specimens failed at around 70 MPa in all cases, this was the ultimate limit strength defined for high-strength recycled concrete.

3.2 Design

The design strength established for the recycled concrete studied was 50–70 MPa. The concrete was batched to a design for concrete with natural aggregate (16) compliant with Chinese standard *JGJ 55 - 2000 Mix proportion design of ordinary concrete rules* (17) (Table 2). The graph in Figure 2 plots compressive strength against the w/c ratio in the recycled concrete. Adjusting the w/c ratio during concrete preparation to attain the design strength minimised the effect of the RCA on that parameter. The procedure yielded satisfactory results for the concretes in which the RCA accounted for 50% or less of the total. These trials also showed that in high-strength recycled concrete, the suitable range for the w/c ratio is 0.30 to 0.40.

4. PROPERTIES OF HIGH-STRENGTH RECYCLED CONCRETE

4.1. Workability

Multiple samples taken from different parts of the high-strength recycled concrete were tested for slump 5 minutes after mixing. The graph in Figure 3 relates slump values to the aggregate replacement ratio.

Table 2. Mix proportioning and concrete compressive strength

Water/cement ratio	Replacement ratio of recycled coarse aggregate [%]	Batching [kg/m^3]					28-d compressive strength [MPa]
		Cement	Water	Sand	Coarse aggregate	Recycled coarse aggregate	
0.45	0	433	195	532	1130	0	49.6
	30	433	195	532	791	339	49.3
	50	433	195	532	565	565	50.2
	80	433	195	532	226	904	46.7
	100	433	195	532	0	1130	46.3
0.40	0	488	195	517	1130	0	57.5
	30	488	195	517	791	339	57.1
	50	488	195	517	565	565	57.7
	80	488	195	517	226	904	54.1
	100	488	195	517	0	1130	53.8
0.35	0	557	195	485	1130	0	60.3
	30	557	195	485	791	339	60.0
	50	557	195	485	565	565	60.9
	80	557	195	485	226	904	57.4
	100	557	195	485	0	1130	57.1
0.30	0	650	195	435	1130	0	70.2
	30	650	195	435	791	339	69.8
	50	650	195	435	565	565	70.7
	80	650	195	435	226	904	67.5
	100	650	195	435	0	1130	67.1

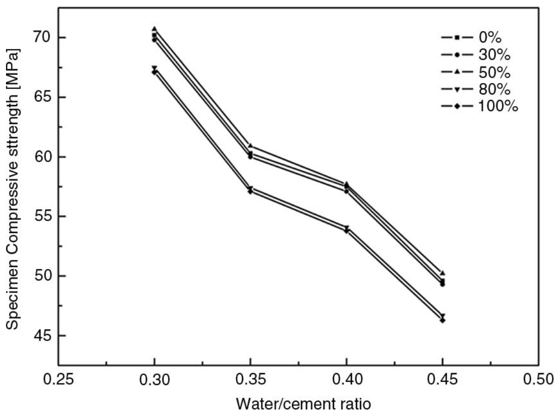

FIGURE 2. Water/cement ratio vs recycled concrete strength.

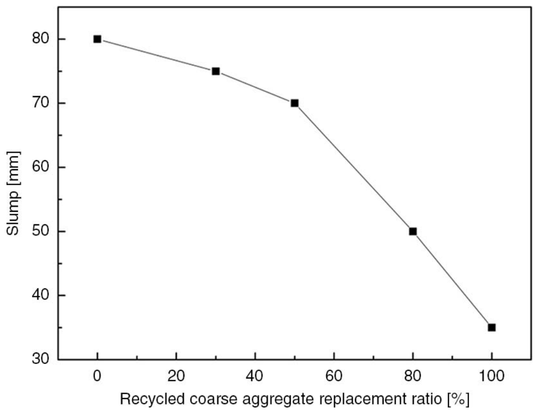

FIGURE 3. Recycled coarse aggregate replacement ratio versus slump.

Concrete slump gradually declined with rising replacement ratio, very significantly when the natural aggregate was wholly replaced by the recycled material.

The explanation for that finding is that the recycled coarse aggregate surface was rougher and more cracked than the crushed stone surface, inducing higher water absorption in the former. The absorption of much of the mixing water by the RCA reduced the amount actually available for mixing per se. The result was greater friction during mixing and pouring and consequently a smaller slump.

Workability of high-strength recycled concrete can be improved by adopting two measures. During processing, the cement mortar attached to the recycled coarse aggregate should be removed to reduce absorption and impurities. Workability can also be enhanced by blending a suitable dose of water-reducing admixture with the other components.

4.2. Deformability

Cylindrical specimens 100 mm in diameter by 300 mm high were tested for creep. The 28-day specimens were compressed on a test frame at a constant pressure equal to 40% of the compressive strength of the cubic specimens. Shrinkage was tested on prismatic specimens measuring 75-mm square by 300 mm deep, stored at ambient temperature and 55% relative humidity. Specimen shrinkage was determined with an unrestrained method, described, like the procedure for measuring creep, in Chinese standard *GB/T 50082-2009 Standard for test methods of long-term performance and durability of ordinary concrete* (18). The elastic modulus, creep and shrinkage values recorded are given in Table 3.

TABLE 3. Creep and shrinkage in high-strength recycled concrete

Replacement ratio of recycled coarse aggregate [%]	Elastic Modulus [10^4MPa]			Creep		Shrinkage [10^{-6}]	
	Design strength [MPa]						
	50	60	70	50	60	60	70
0	2.73	2.85	3.01	1.02	0.69	705	756
30	2.72	2.83	2.96	1.03	0.71	715	768
50	2.62	2.71	2.84	1.19	0.87	755	779
80	2.56	2.65	2.75	1.47	0.92	763	792
100	2.48	2.57	2.68	1.76	0.96	772	805

Although the elastic moduli for the concretes with 0 and 30% RCA were nearly identical, at higher replacement ratios the values declined steadily. Shrinkage and creep were also affected by the replacement ratio, for two reasons. Firstly, the downward adjustment to the w/c ratio to ensure the concretes prepared would attain the design strength raised shrinkage and creep in the resulting material. Secondly, the mortar clinging to the RCA also intensified creep and shrinkage.

4.3. Durability

Durability in a material is its ability to remain intact in the long run. The greater the durability, the longer the service life of the material at issue. The cement mortar attached to the RCA studied increased its void ratio and water sorptivity substantially, inducing the formation of micro-cracks on the surface of the aggregate, with the concomitant impact on concrete durability.

4.3.1. Freeze-thaw resistance

These tests were conducted on 50-MPa high-strength recycled concrete with an RCA replacement ratio of 100%. Further to the specifications in Chinese standard *DL/T 5150-2001 Hydraulic concrete experiment rules* (19), concrete specimens were fully submerged in water during accelerated (3-hour) freeze-thaw testing. Recycled concrete strength is graphed against the number of freeze-thaw cycles in Figure 4.

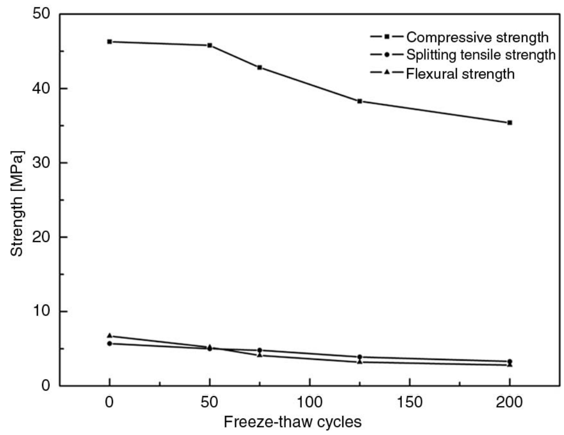

FIGURE 4. Recycled concrete strength vs number of freeze-thaw cycles.

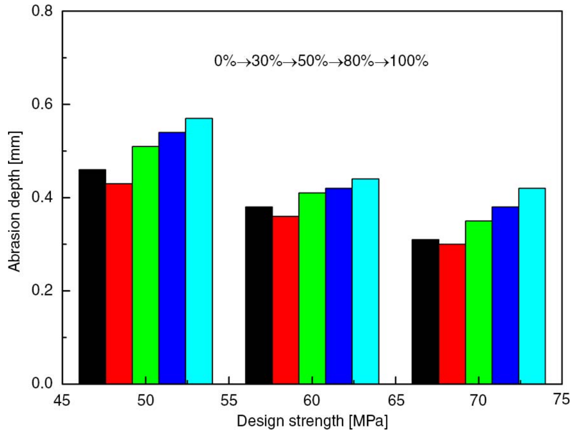

FIGURE 5. Design strength vs abrasion depth.

As the figure shows, as the number of freeze-thaw cycles rose, compressive, splitting tensile and flexural strength declined in cubic specimens made with high-strength concrete containing 100% RCA. The decline in splitting tensile and flexural strength was particularly steep: the latter dropped by 40% after just 50 cycles and after 125 the specimen had lost its bearing capacity entirely.

The reasons were again found to lie in the rough surface and sharp corners and edges on the RCA, along with its high void ratio induced by the presence of cement mortar clinging to the surface. The resulting high porosity in the concrete, in conjunction with its high water sorptivity, determined the presence of water in many of the pores. As the temperature fell, the water began to freeze, first in the larger and then in the smaller pores. The freezing-induced expansion in the smaller pores was restrained by the ice that had formed in the larger pores (20), generating pressure that was initially alleviated by the unclogged pores in the recycled concrete. Since this same process took place in the RCA itself, however, the number of empty pores declined. The hydrostatic pressure on the pore walls generated high tensile stress, which would in all likelihood have equalled concrete tensile strength. The result was intense micro-cracking on the surface of the recycled concrete components, causing severe damage to the specimens.

4.3.2. Abrasion resistance

Concrete specimens with design strengths of 50, 60 and 70 MPa were tested for abrasion resistance on an apparatus described in the literature (21) and further to the specifications in Chinese standard *DL/T 5150-2001 Hydraulic concrete experiment rules* (19). Design strength is graphed against abrasion depth in Figure 5.

Figure 5 shows that the RCA replacement ratio scantly affected the abrasion resistance of high-strength recycled concrete. Abrasion resistance was similar at any given design strength, irrespective of whether the aggregate replacement ratio was 0, 30, 50, 80 or 100%.

5. CONCLUSIONS

- As abrasion loss was under 50% in the three types of recycled coarse aggregate studied, all were judged apt for practical use.
- RCA reduced concrete workability, with slump values declining with higher replacement ratios.
- At replacement ratios of up to 30%, RCA had no effect on recycled concrete strength. With increasing ratios, however, strength tended downward.
- At a replacement ratio of 50%, the 28-day compressive strength of the recycled concrete studied was slightly higher than the value observed for concrete containing natural aggregate.
- The present findings showed that RCA can be used to prepare all manner of high-strength concretes whose compressive strength, elastic modulus and other characteristics are standard-compliant. The RCA content in high-strength recycled concrete impacted shrinkage and creep.
- High-strength recycled and natural concretes with the same design strength exhibited similar freeze-thaw and abrasion resistance. RCA sourced from precast concrete components may, then, be suitable for high-strength concrete. Nonetheless, further testing on RCA from other sources would be required to test that inference.

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