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## Ways to facilitate the use of recycled aggregate concrete

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**A huge amount of solid waste is generated annually from construction and demolition activities. This has led to the promotion of waste recycling as a major measure to reduce waste and to mitigate the harmful effects of construction activities on the environment. Among these wastes, concrete apports more than half of the total. While recycled concrete waste has been used in low-grade utilisations, high-grade applications are rarely discussed. Although the Hong Kong Special Administrative Region Government has actively been promoting recycling of construction solid waste by issuing technical circulars, specifications and practice notes and setting up a recycling plant to encourage the adoption of recycled aggregate (RA), these measures have not facilitated wide adoption of recycled aggregate concrete (RAC). In fact, the quality of RA and RAC is less than that of virgin material or ordinary concrete and concrete suppliers are thus reluctant to use these materials. Utilising a series of laboratory tests, this paper aims to set out some guidelines to facilitate the use of RAC in the construction industry.**

### 1. INTRODUCTION

Construction and demolition (C&D) wastes—including demolished concrete (foundations, slabs, columns, floors, etc.), bricks and masonry, wood and other materials such as dry wall, glass, insulation, roofing, wire, pipe, rock and soil<sup>1</sup>—constitute a significant component of total generated waste; recycling of these wastes is thus of great importance. As one of the most effective strategies in waste minimisation, recycling offers three main benefits<sup>2–5</sup>

- (a) reduction in demand on new resources
- (b) reduction in transport and production energy costs
- (c) use of waste that would otherwise be landfilled.

Regarding demand for new resources, the extensive extraction of natural resources for building construction as a result of comprehensive building development and redevelopment plans in most metropolises like Hong Kong has violated the principle of sustainability with increasing objections from environmentalists.<sup>6,7</sup> To minimise the use of natural resources and the creation of concrete demolition waste, there is a need to develop long-term action plans on the use of materials and to coordinate the various interests of stakeholders and companies in the construction industry.<sup>8,9</sup> The use of recycled products can reduce the demands for new raw materials; recycled aggregate

(RA) is one of the major construction wastes capable of being recycled and reused.<sup>4,10</sup> Widespread adoption of RA and the production of recycled aggregate concrete (RAC) is to be encouraged and this paper aims to set out some guidelines to facilitate the use of RA and RAC in Hong Kong.

### 2. EFFORTS BY THE HONG KONG GOVERNMENT

Campaigns on waste reduction have been organised by the Hong Kong Special Administrative Region (SAR) Government in recent years. Construction, as one of the most resource-consuming industries,<sup>11–13</sup> has to participate in these campaigns and the use of RA has been strongly advocated as a means of waste minimisation.<sup>9,14–17</sup> To echo this, the Environment, Transport and Works Bureau issued two technical circulars—*Waste Management on Construction Sites*<sup>18</sup> and *Specifications Facilitating the Use of Recycled Aggregate*.<sup>19</sup> The Hong Kong Housing Authority trialled selective demolition in a school project at Lower Ngau Tau Kok Phase 1 Estate, with the Civil Engineering Department setting up a recycling plant to produce RA in Tuen Mun Area 38 and the Buildings Department issuing a practice note on the use of RA in concrete in February 2003.<sup>20</sup> Such measures have aimed to promote the adoption of RA along with standards and practice guidelines for its use. As the government's largest building developer in Hong Kong, the Architectural Services Department has started to examine the possibility of using 20% RA substitution in school construction projects.

### 3. RESEARCH METHODOLOGY

A series of laboratory tests were carried out to assess fresh and hardened concrete properties. Hundreds of mixing trials and concrete cubes were attempted. RA from Tuen Mun Area 38 recycling plant was used in the production of RAC and mixtures of 25, 50, 75 and 100% RA were tested with designated mix proportions according to Buildings Department specifications<sup>20</sup> (see Table 1) with a water/cement ratio of 0.45. Standards used to test the properties of RA and RAC are summarised in Table 2.<sup>21–35</sup> It should be noted that the properties of recycled coarse aggregate and recycled fine aggregate are different. In this study, recycled coarse aggregate was used for the experimental work.

### 4. MAJOR FINDINGS

#### 4.1. Potential reduction in RAC quality

The main difference between RA and ordinary aggregate is that RA contains some cement mortar as a result of crushing concrete

Concrete ingredients	Mass: kg
Ordinary Portland cement	100
Fine aggregate	180
20 mm coarse aggregate	180
10 mm coarse aggregate	90

Table 1. Mix proportions

waste.<sup>35</sup> This residual cement mortar changes the concrete properties<sup>37-39</sup> and degrades targets on density, strength, rigidity, deformation and permeability. From the experimental results, significant reductions were found with different proportions of added RA, as shown in Table 3. The reduction percentage can be measured by equation (1).

$$1 \quad [(N_d^r - N_d^{r0}) / N_d^{r0}] \times 100\%$$

where  $N_d^{r0}$  is the result for different RAC properties collected with 0% RA substitution on day  $d$  and  $N_d^r$  is the result for different RAC properties collected with  $r\%$  RA substitution on day  $d$ . RAC thus needs to be used with care and users should fully understand the behaviour of RAC with an appropriate mix design to cater for these weaknesses.

#### 4.2. Classification of RA for various applications

As the quality of RA varies from site to site, it is worth considering the advantages of its production at a centralised recycling plant. Tam<sup>40</sup> attempted to correlate various properties of RA. It was found that there exist some relationships between

Property	Standard
<b>Aggregate</b>	
Sieve analysis	BS 882 <sup>21</sup>
Particle density on oven-dried basis	BS 812: Part 2 <sup>22</sup>
Particle density on saturated and surface-dried basis	BS 812: Part 2 <sup>22</sup>
Apparent particle density	BS 812: Part 2 <sup>22</sup>
Water absorption	BS 812: Part 2 <sup>22</sup>
Moisture content	BS 812: Part 109 <sup>23</sup>
Flakiness index	BS 812: Part 105-1 <sup>24</sup>
Elongation index	BS 812: Part 105-2 <sup>25</sup>
Ten per cent fines value (TFV)	BS 812: Part 111 <sup>26</sup>
Aggregate impact value (AIV)	BS 812: Part 112 <sup>27</sup>
Chloride content	BS 812: Part 117 <sup>28</sup>
Sulphate content	Manual of Alltech Ion Chromatography System ICM-300
<b>Concrete</b>	
Density	Mass/volume
Compressive strength	BS 1881: Part 116 <sup>29</sup>
Flexural strength	BS 1881: Part 118 <sup>30</sup>
Tensile splitting strength	BS 1881: Part 117 <sup>31</sup>
Static modulus of elasticity	BS 1881: Part 121 <sup>32</sup>
Shrinkage	BS 1881: Part 5 <sup>33</sup>
Creep	ASTM C512-02 <sup>34</sup>
Air permeability	Manual of P-6000 Poroscope
Water permeability	Manual of GWT-4170 kit
Chloride permeability	AASHTO T277 <sup>35</sup>

Table 2. Standards controlling aggregate and concrete properties

the various properties of RA

$$2 \quad WA_{10} = -23.855SSD_{10} + 63.147 \quad (R^2 = 0.9163)$$

$$3 \quad WA_{20} = -21.387SSD_{20} + 57.04 \quad (R^2 = 0.9603)$$

$$4 \quad MC_{10} = -4.4417SSD_{10} + 11.83 \quad (R^2 = 0.7527)$$

$$5 \quad MC_{20} = -4.1345SSD_{20} + 11.044 \quad (R^2 = 0.7919)$$

$$6 \quad SSD_{10} = 0.014FI_{10} + 2.1644 \quad (R^2 = 0.6832)$$

$$7 \quad SSD_{20} = 0.0139FI_{20} + 2.2232 \quad (R^2 = 0.7857)$$

$$8 \quad WA_{10} = -0.3199FI_{10} + 11.287 \quad (R^2 = 0.5743)$$

$$9 \quad WA_{20} = -0.3088FI_{20} + 9.6472 \quad (R^2 = 0.8188)$$

where  $WA_{10}$  is the water absorption rate for 10 mm aggregate (in units of % of dry mass),  $SSD_{10}$  is the value of particle density based on the SSD basis for 10 mm aggregate (in  $Mg/m^3$ ),  $WA_{20}$  is the water absorption rate for 20 mm aggregate (in % of dry mass),  $MC_{10}$  is the moisture content for 10 mm aggregate (in % of dry mass),  $MC_{20}$  is the moisture content for 20 mm aggregate (in % of dry mass),  $SSD_{20}$  is the value of particle density based on the SSD basis for 20 mm aggregate (in  $Mg/m^3$ ),  $FI_{10}$  is the flakiness index for 10 mm aggregate (in %) and  $FI_{20}$  is the flakiness index for 20 mm aggregate.

Five tests—grain-size qualification, water absorption, 10% fines value, chloride content and sulphate composition—are adequate to describe the quality of RA (see Table 4). These five tests portray RA behaviour and define RAC applications such as structural element, minor structural element, non-structural element, prestressed concrete element, road surface, insulation barrier, base course and embankment and fill. The requirements for various construction applications are shown in Table 5,<sup>21,41,42</sup> which are equally applicable to the use of virgin materials.

#### 4.3. Slump loss of RAC

When using RA to produce RAC, workability needs to be considered. In current practice, if the correct slump cannot be achieved on site, the load of concrete is unacceptable for use, is returned to the batching plant and finally dumped as waste.

Slump loss is loss of consistency in fresh concrete with elapsed time. Slump loss is a normal phenomenon in all concrete because it results from gradual stiffening and setting of hydrated Portland cement paste, which is associated with the formation of hydration products such as ettringite and calcium silicate hydration.<sup>43</sup> Slump loss occurs when the free water from a concrete mixture is

RAC property	RA as a percentage of natural aggregate in the mix: %			
	25	50	75	100
Density reduction <sup>*†</sup> : %	0–1.4	0.12–2.4	0.77–6	1.11–10
Compressive strength reduction <sup>*†</sup> : %	0.3–31.8	1.2–57.8	1.22–54.5	1.49–86.4
Flexural strength reduction <sup>*†</sup> : %	0–10.4	0–8.1	2.39–10.03	8.1–20
Tensile splitting strength reduction <sup>*†</sup> : %	10.6–50.7	12.84	21.40	6–29.95
Modulus of elasticity reduction <sup>*†</sup> : %	6.16–22.7	2.8–30.5	2.27–21.9	1.1–50
Shrinkage increase <sup>‡†</sup> : %	0.4–30.9	0.1–53.4	—	5.9–88
Creep increase <sup>‡†</sup> : %	33.13–47.26	—	—	166.47–215.75
Air permeability reduction <sup>‡†</sup> : %	0–26.47	—	—	0–57.41
Water permeability increase <sup>‡†</sup> : %	0–23.52	—	—	0–28.84
Chloride permeability increase <sup>‡†</sup> : %	0–23.70	—	—	0–30.25

\*Tests conducted at 28 days curing  
\*Tests conducted at 7–56 days curing  
‡Tests conducted at 14–182 days curing  
†Data collected from previous research

Table 3. Reduction of RAC quality with respect to RA ratio

Classification method	Experimental work covered by classification
Grain-size qualification	Grain-size qualification
Water absorption	<ul style="list-style-type: none"> <li>Particle density</li> <li>Water absorption</li> <li>Flakiness index</li> </ul>
TFV	<ul style="list-style-type: none"> <li>TFV</li> <li>Aggregate impact value</li> </ul>
Chloride content	Chloride content
Sulphate content	Sulphate content

Table 4. Classification system used to replace experimental work

removed by hydration reactions, by adsorption on the surfaces of hydration products and by evaporation. RAC has a higher slump loss than normal aggregate concrete due to the high absorptive rate of the cement portion attached to the RA.

Experimentation confirmed this phenomenon.<sup>40</sup> For normal aggregate concrete, slump loss is not significant during the first 2 h of placing time, but becomes more important (with around 50 mm loss or more) when the concrete placing time is up to 5 h. For RAC, the slump loss during the first 2 h is around 30 mm or more and can reach 70 mm or even up to 150 mm when the placing time is prolonged.

Although RAC has a higher slump loss, the loss can be reduced if the RA is pre-soaked to a fully saturated condition. The following two procedures are thus recommended when using RAC.

- RA should be fully pre-soaked for at least 24 h before use to obtain the fully saturated condition.
- The slump loss for RAC should be considered beforehand and allowed for in the design mix.

## 5. COMPARISON OF GOVERNMENT PRACTICE NOTES AND RECOMMENDED GUIDELINES

Although the Hong Kong Government Buildings Department issued a practice note on the use of recycled aggregate in concrete in February 2003,<sup>20</sup> the information provided is not sufficiently comprehensive for construction professionals to avoid all the uncertainties in the adoption of RAC. Table 6 compares the differences between the requirements of the current government practice note and recommended guidelines.

## 6. CONCLUSION

In recent years, the Hong Kong SAR Government has promoted the adoption of RA and RAC with the issuance of technical circulars, specifications and practice notes and the construction of a recycling plant to produce RA. However, these measures do not provide sufficient background information and knowledge on RAC to allow practitioners to avoid all the uncertainties in RAC use. With the poor quality associated with RA and RAC, concrete

Property	Structural element	Minor structural element	Non-structural element	Prestressed concrete element	Road surface	Insulation barrier	Base course	Embankment and fill
Grain-size qualification	Ref. 21	Ref. 21	Ref. 21	Ref. 21	Ref. 41	Ref. 21	Ref. 42	Ref. 42
Maximum water absorption: %	5*	10	10	10	10	10	10	10
Minimum TFV <sup>24</sup> : kN	150	100	50	100	100	100	50	50
Maximum chloride content <sup>26</sup> : %	0.05	0.05	1	0.015	0.05	0.05	0.05	0.05
Maximum sulphate content: %	1	1	1	1	1	1	1	1

\*This standard measurement is based on the result of experiments undertaken by the authors

Table 5. Requirements for various construction applications

	Government practice note	Recommended guidelines
Tests required for classification system	<ul style="list-style-type: none"> <li>• Particle density</li> <li>• Water absorption</li> <li>• Content of wood and other materials</li> <li>• Content of other foreign materials</li> <li>• Fines particles</li> <li>• Content of sand</li> <li>• Content of sulphate</li> <li>• Flakiness index</li> <li>• TFV</li> <li>• Grading</li> <li>• Chloride content</li> </ul>	<ul style="list-style-type: none"> <li>• Grading</li> <li>• Water absorption</li> <li>• TFV</li> <li>• Chloride content</li> <li>• Sulphate content</li> </ul>
Slump requirement	Min. 75 mm	Min. 75 mm but higher slump recommended for RAC made from water-sprayed RA in contrast to fully soaked RA
Slump loss	—	To consider the effects of slump loss for RAC (both for fully soaked or water-sprayed RA)
Mix proportioning	Designated mix only	Allow for designed mix
Quality of RAC	—	Highlight changes in quality of RAC in different proportions of RA
Percentage of RA to replace natural aggregate	20% for structural and 100% for non-structural elements	From 0–100%
Types of RAC application	Structural and non-structural	Structural, minor-structural, non-structural, pre-stressed concrete, road surface, insulation barrier, base course, and embankment and fill

Table 6. Comparison between the Government practice note<sup>18</sup> and recommended guidelines for RAC

suppliers lack confidence to use these materials. This paper has recommended some guidelines in the use of RAC and has

- (a) highlighted potential reductions in RAC quality
- (b) classified RA for various construction applications
- (c) alerted users to possible extra slump loss in the use of RAC.

A comparison table between the current Government practice note and recommended guidelines is provided for easy reference.

#### ACKNOWLEDGEMENTS

The work described in this paper was fully supported by a grant from the Housing Authority Research Fund of the Hong Kong Special Administrative Region, China (Project Ref. No. 9460004).

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