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Assessing relationships among properties of demolished concrete, recycled aggregate and recycled aggregate concrete using regression analysis

Vivian W.Y. Tam [a,*], K. Wang [b], C.M. Tam [b]

[a] *Griffith School of Engineering, Gold Coast Campus, Griffith University PMB50 Gold Coast Mail Centre, Qld 9726, Australia*
[b] *Department of Building & Construction, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong*

Abstract

Recycled demolished concrete (DC) as recycled aggregate (RA) and recycled aggregate concrete (RAC) is generally suitable for most construction applications. Low-grade applications, including sub-base and roadwork, have been implemented in many countries; however, higher-grade activities are rarely considered. This paper examines relationships among DC characteristics, properties of their RA and strength of their RAC using regression analysis. Ten samples collected from demolition sites are examined. The results show strong correlation among the DC samples, properties of RA and RAC. It should be highlighted that inferior quality of DC will lower the quality of RA and thus their RAC. Prediction of RAC strength is also formulated from the DC characteristics and the RA properties. From that, the RAC performance from DC and RA can be estimated. In addition, RAC design requirements can also be developed at the initial stage of concrete demolition. Recommendations are also given to improve the future concreting practice.
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1. Introduction

Construction debris resulting from construction and demolition (C&D) work constitutes a large proportion of solid waste as shown in Table 1. In the United Kingdom, more than 50% of waste deposited in a typical landfill comes from construction [1]; while about 70 million tonnes of waste are from C&D activities annually [2]. In Australia, about 14 million tonnes of waste have been put into landfill each year, in which about 44% of waste is attributed to the construction industry [3,4]. In the United States of America, about 29% of solid-waste is from construction [5], while in Hong Kong, it is about 38% [6].

Among various types of construction materials, concrete was found to be the most significant element, about 75%, 70%, 40% and 70% collected from construction sites, demolition sites, general civil work and renovation work, respectively (see Table 2).

Because of the fast generation of C&D waste, the Hong Kong government pushed very hard to promote the use of recyclable C&D materials. The Environment, Transport and Works Bureau of the Hong Kong Special Administrative Region (SAR) had issued a technical circular (Ref: 15/2003) on "waste management on construction sites". Various types of materials are sorted before being sent out from construction sites, including all excavated materials, metal, cardboard and paper packaging, plastic, chemical waste and others. The Housing Authority of the Hong Kong SAR has implemented selective demolition methods in school projects at Lower Ngau Tau Kok Phase 1 Estate. Different types of materials are sorted, including timber, steel, florescent tubes, electricity fitting, toilet sets, brick, tiles, finishes, drainage pipes, cables, to improve the recycling rates.

To encourage the adoption of RA, Buildings Department of the Hong Kong SAR issued a practice note for authorised persons and registered structured engineers entitled "Use of RA in concrete" in February 2003 [6] to encourage the adoption of RA in construction activities. The use of RA in concrete is only at its initial stage of implementation. Civil Engineering Department of the Hong Kong SAR is commissioning a pilot recycling

* Corresponding author.
  E-mail addresses: v.tam@griffith.edu.au (V.W.Y. Tam), bctam@cityu.edu.hk (C.M. Tam).

Table 1
Comparison of proportions of construction solid waste [8,56–58]

Country	Proportion of construction waste to total waste (%)	C&D waste recycled (%)
Australia	44	51
Brazil	15	8
Denmark	25–50	80
Finland	14	40
France	25	20–30
Germany	19	40 to 60
Hong Kong	38	No information
Japan	36	65
Italy	30	10
Netherlands	26	75
Norway	30	7
Spain	70	17
United Kingdom	Over 50	40
United States of America	29	25

plant at Tuen Mun Area 38 with a view to supply RA to a number of public work projects earmarked for such purposes. All RA produced needs to fulfill the requirements set by Buildings Department of the Hong Kong SAR.

Although the Hong Kong government has established some guidelines and specifications for construction, the Hong Kong recycling practice is still lagging behind other countries because many recyclable materials are still being dumped as waste. There are many opportunities for the industry to improve waste management and recycling [7] to prolong the landfill life, to minimize transport needs and to reduce primary resource requirements (mineral and energy).

2. Research objectives

This paper focuses on:

- experimenting the characteristics of DC, properties of RA and strength of RAC where samples are collected from demolition sites;
- analyzing the correlation among the characteristics of DC samples, and properties of their RA and RAC by regression analysis;

- formulating relationships among properties of DC, RA and RAC; and
- recommending measures to improve concrete quality for the future concreting activities.

3. Obstacles in the use of demolished concrete waste

A disadvantage of demolished concrete waste is its low density, and as a result its high porosity. Hence, more water is required to ensure full saturation of RA during concrete mixing and it may also require more intensive compaction. Although the RAC applications are only employed for low-grade activities, certain percentages of natural materials can be saved. Most re-utilized waste is considered as roughly broken material processed for low-grade applications. However, demolition techniques generating recycled materials can be controlled to produce end-products suitable for high-grade applications. Currently, only about 4% of this waste is sorted, crushed and graded to be reused as an alternative primary aggregate for road construction [8].

4. Materials and methods

Ten samples (Samples 1–10) from 10 demolition sites are collected to investigate their characteristics and properties. Sample 1 is located next to the Victoria Harbour; Samples 2, 6 and 8 are partially located next to open space; and the other samples are located next to residential, commercial, industrial buildings or school areas. A summary of the sample collection locations is schematically shown in Fig. 1. Four DC characteristics are examined: (i) density; (ii) absorptivity; (iii) porosity; and (iv) carbonation depth.

A jaw crusher is used to crush the DC samples into 20 mm and 10 mm aggregate for producing RA and RAC which properties are investigated. Six groups of RA properties: (i) particle size distribution; (ii) particle density; (iii) porosity and absorption; (iv) particle shape; (v) strength and toughness; and (vi) chloride and sulphate contents, and compressive strength of RAC are investigated.

All experimental work is conducted according to British Standards summarized in Table 3. Average results from three tests

Table 2
Composition of construction waste collected in South East New Territories (SENT) landfill [59]

Waste type	Percentage			
	Construction site	Demolition site	General civil work	Renovation work
Metal	4	5	10	5
Wood	5	7	0	5
Plastic	2	3	0	5
Paper	2	2	0	1
Concrete	75	70	40	70
Rock/Rubble	2	1	5	0
Sand/Soil	5	0	40	0
Glass/Tile	3	2	0	10
Others	2	10	5	4
Total	100	100	100	100

Fig. 1. (a) Locations for Samples 1–10. (b) Locations for Samples 1–10.

on each property of DC, RA and RAC are reported in this paper.

5. Results and discussions

Summaries of the characteristics of the DC samples, the properties of their RA and the compressive strength of the RAC are shown in Table 4, Tables 5 and 6, respectively.

To investigate relationships among properties of DC, RA and RAC from the samples, a correlation table is prepared as shown in Table 7 which clearly shows strong correlation among the properties of DC, RA and RAC. The correlation coefficients are measured; some achieved up to 0.995.

Table 3
Standards used for experimental work

Demolished concrete	Standard
Density	
Density	BS 1881: Part 114 [60]
Absorptivity	
Water absorption	BS 812: Part 2 [24]
Porosity	
Mercury intrusion porosimetry (MIP)	Manual of micromeritics poresizer 9320
Carbonation depth	
Fourier transform of infrared spectroscopy (FT-IR)	Manual of FT-IR spectrometer spectrum 1000 (Perkin-Elmer)
Recycled aggregate	
Particle size distribution	
Sieve analysis	BS 882 [22]
Particle density	
Particle density on oven-dried basis	BS 812: Part 2 [24]
Porosity and absorption	
Water absorption	BS 812: Part 2 [24]
Particle shape	
Flakiness index	BS 812: Part 105.1 [28]
Strength and toughness	
Ten percent fine value (TFV)	BS 812: Part 111 [31]
Aggregate impact value (AIV)	BS 812: Part 112 [32]
Chemical composition	
Chloride content	BS 812: Part 117 [61]
Sulphate content	Manual of ion chromatography
Recycled aggregate concrete	
Compressive strength	BS 1881: Part 116 [34]

5.1. Demolished concrete

5.1.1. Density

As cement mortar density of around 1.0–1.6 Mg/m^3 is less than that of natural aggregate particles at around 2.6 Mg/m^3 [9,10], the lower the density of DC samples, the higher the cement mortar content will be. From the results in Table 4, it is found that the variation of density ranges between 2269 kg/m^3 (Sample 8) and 2432 kg/m^3 (Sample 6).

From the results shown in Table 7, it is found that there is a correlation between density and other properties of DC as evidenced by regression equations and R^2 values. A regression equation describes a line or a curve in a two-dimensional or two-variable space defined by the equation $Y = a + b*X$; and R^2 is a regression coefficient describing the correlation of raw data to the line or curve defined by the regression equation, which reflects the accuracy level of the prediction model. Eqs. (1)–(3) show the relationships between density and absorptivity; and porosity, and carbonation depth, respectively.

$$A_{dc} = -0.0265 \, D_{dc} + 67.459 \quad (R^2 \approx 0.6854) \tag{1}$$

Table 4
Summary of results on demolished concrete samples

Sample	Density (in Mg/m^3)	Absorptivity (in %)	Porosity (in %)	Carbonation depth		
				CDI of CO_2	CDI of CO	CDI[a]
1	2.341	3.87	14.40	0.73	0.51	0.62
2	2.425	4.41	13.94	0.86	1.20	1.03
3	2.362	4.14	15.54	1.54	1.50	1.52
4	2.331	6.64	16.00	1.14	1.70	1.42
5	2.321	5.23	16.37	0.86	1.16	1.01
6	2.432	1.98	14.30	0.29	0.53	0.41
7	2.271	8.93	20.41	3.22	3.54	3.38
8	2.269	7.01	17.96	1.86	2.60	2.23
9	2.410	4.93	15.40	0.54	0.36	0.45
10	2.430	3.33	16.25	0.62	0.94	0.78

[a] *Note*: Carbonation depth index (CDI) = $\sum_{n=1}^{4} Q_{Cn} - Q_{C5}/Q_{C5}$, where Q_{Cn} is the quantity of CO or CO_2 of the n-layer of cement paste, Q_{C5} is the quantity of CO or CO_2 of the fifth layer of cement paste and Q_{Cn} should be larger than Q_{C5}.

Table 5
Summary of results on recycled aggregate

| Sample | Particle size distribution | | Density | | Porosity and absorption | | Particle shape | | Strength and toughness | | Chloride and sulphate contents | | |
| | Sieve analysis | | Particle density (Mg/m3) | | Water absorption (%) | | Flakiness index (%) | | TFV (kN) | AIV (%) | Chloride content (%) | | Sulphate content (%) |
	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm			10 mm	20 mm	
1	Pass	Pass	2.16	2.20	5.83	6.89	11.13	9.68	93.89	33	0.0078	0.0089	0.031
2	Pass	Pass	2.22	2.14	6.36	6.40	10.44	10.08	61.36	36	0.0108	0.0091	0.017
3	Pass	Pass	2.20	2.18	7.50	7.35	15.17	8.61	107.42	31	0.0013	0.0019	0.005
4	Pass	Pass	2.20	2.20	6.93	7.25	15.42	7.91	112.82	23	0.0019	0.0019	0.005
5	Pass	Pass	2.15	2.19	7.31	6.82	17.82	12.96	92.09	32	0.0054	0.0061	0.006
6	Pass	Pass	2.25	2.27	5.20	5.77	11.96	9.93	155.53	25	0.0008	0.0025	0.006
7	Pass	Pass	2.11	2.13	8.74	7.30	12.86	5.70	110.18	30	0.0976	0.0902	0.013
8	Pass	Pass	2.10	2.12	8.58	7.99	15.12	9.78	83.48	34	0.0013	0.0014	0.005
9	Pass	Pass	2.21	2.24	6.94	6.11	13.78	12.17	92.87	36	0.0459	0.0352	0.024
10	Pass	Pass	2.20	2.23	6.85	5.95	16.47	9.92	89.91	28	0.0494	0.0430	0.018

$$P_{dc} = -0.0231\,D_{dc} + 70.472 \quad (R^2 \approx 0.5637) \tag{2}$$

$$CDI_{dc} = -0.0115\,D_{dc} + 28.303 \quad (R^2 \approx 0.6121) \tag{3}$$

where D_{dc} is the density of the DC samples (in kg/m^3); A_{dc} the absorptivity of the DC samples (in %); P_{dc} the porosity of the DC samples (in %); and CDI_{dc} the carbonation depth index of the DC samples.

5.1.2. Absorptivity

Cement paste has a relatively higher absorptivity than that of the aggregate. The higher the absorptivity of the DC, the more cement paste attached on the samples will be. Table 4 shows the absorptivity of the 10 DC samples. It is found that Sample 7 has the highest absorptivity of about 8.93% while Sample 6 has the lowest of about 1.98%.

From the results shown in Table 7, there is a correlation between absorptivity and porosity, and carbonation depth as shown in Eqs. (4) and (5), respectively.

$$P_{dc} = 0.8088\,A_{dc} + 11.975 \quad (R^2 \approx 0.7077) \tag{4}$$

$$CDI_{dc} = 0.3984\,A_{dc} - 0.7257 \quad (R^2 \approx 0.7563) \tag{5}$$

5.1.3. Porosity

Porosity of DC is closely related to the content of cement mortar in the samples as explained in Sections 5.1.1 and 5.1.2 [11–17]. The more cement mortar content in the samples, the lower their density, the higher their absorptivity and porosity will be. Experimental results on mercury intrusion porosimetry (MIP) are summarised in Table 4, which is designed to investigate the porosity of the DC samples. Sample 7 has the highest porosity of about 20.41% while Sample 2 has the lowest of about 13.94%.

From the correlation table shown in Table 7, there is a correlation between porosity and carbonation depth of the DC samples as shown in Eq. (6).

$$CDI_{dc} = 0.425\,P_{dc} - 5.5397 \quad (R^2 \approx 0.7957) \tag{6}$$

5.1.4. Carbonation depth

To compare the carbonation depth among the samples, the Fourier transform of infrared spectroscopy (FT-IR) is used. Five layers of cement paste around aggregate are studied (see Fig. 2). Quantities of carbon oxide (CO) and carbon dioxide (CO_2) on each layer are examined. Carbonation depth index (CDI) is used for analysis which is estimated using Eq. (7).

$$\text{Carbonation depth index (CDI)} = \frac{\sum_{n=1}^{4} Q_{Cn} - Q_{C5}}{Q_{C5}} \tag{7}$$

where Q_{Cn} is the quantity of CO or CO_2 of the nth-layer of cement paste, Q_{C5} the quantity of CO or CO_2 of the fifth layer of cement paste and Q_{Cn} should be larger than Q_{C5}.

CO_2 in the atmosphere reacts in the presence of moisture with hydrated cement minerals. Reaction of CO_2 takes place even at small concentrations such as rural air where CO_2 content is about 0.03%. In an unventilated laboratory, the content may rise to above 0.1%. In large cities, it is about 0.3% and in some exceptional cases, it can increase to 1% [10]. The carbonation rate increases when the concentration of CO_2 increases, especially with a high water to cement ratio. Carbonation takes places when calcium hydroxide [Ca(OH)$_2$ or CH] [18]. The reaction has also led to the formation and accumulation of cal-
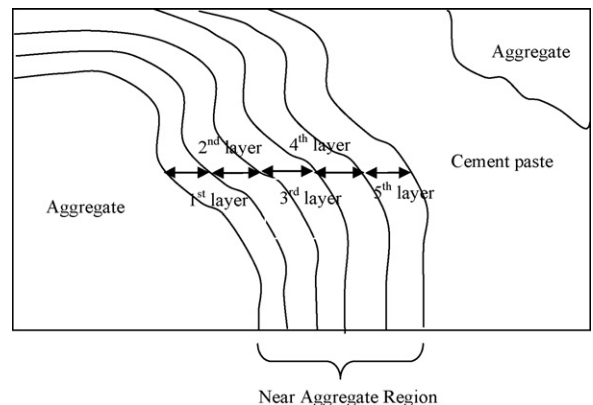

Fig. 2. Five layers of cement sample near aggregate region for Fourier transform infrared spectroscopy examination.

Table 6
Summary of results on recycled aggregate concrete

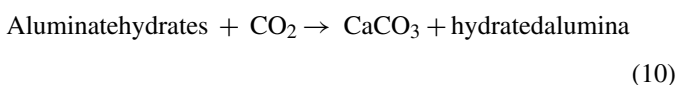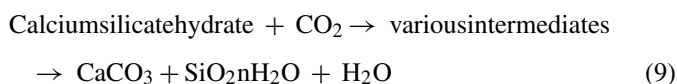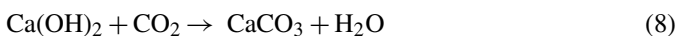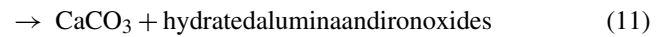| Sample	Test	Compressive strength (in MPa)
1	1	56
	2	54
	3	55
	Average	55
2	1	56
	2	57
	3	56
	Average	56
3	1	53
	2	53
	3	52
	Average	53
4	1	50
	2	51
	3	51
	Average	51
5	1	52
	2	51
	3	51
	Average	52
6	1	65
	2	62
	3	62
	Average	63
7	1	51
	2	50
	3	48
	Average	50
8	1	49
	2	52
	3	50
	Average	50
9	1	58
	2	58
	3	55
	Average	57
10	1	60
	2	57
	3	59
	Average	59

Fig. 3. Comparison of Fourier transform infrared spectroscopy absorbance spectra for Sample 3. (a) First layer of cement paste; (b) second layer of cement paste; (c) third layer of cement paste; (d) fourth layer of cement paste; and (e) fifth layer of cement paste.

$$\text{Ferritehydrates} + CO_2$$
$$\rightarrow CaCO_3 + \text{hydratedaluminaandironoxides} \quad (11)$$

$$CaCO_3 \rightarrow CaO + CO_2 \quad (12)$$

$$2CO_2 \rightarrow 2CO + O_2 \quad (13)$$

Carbonation has a deleterious effect on hardened cement paste as it appears to decrease strength and increase porosity [18–20]. Major controlling factors affecting carbonation concentration are water to cement ratios, aggregate porosities, curing and the environment of exposed structures [18]. The carbonation depth is roughly proportional to the square-root of time, doubling between 1 year and 4 years, then again doubling between 4 years and 10 years; there is probably a further doubling up to 50 years [10]. An extensive survey by Brown [21] found that carbonation depths correlated well with concrete quality but there was no significant relationship with reported exposure conditions. In general, any factors, which increase concrete permeability, can also increase the carbonation rate, provided that necessary internal moisture conditions are present. The carbonation reaction rate depends on the moisture content of concrete and relative humidity of the ambient medium [18,10]. In addition, carbonation depth increases with an increase in water to cement ratio; for example, at a water to cement ratio of about 0.4, the depth is only half of that at about 0.6; at a water to cement ratio of about 0.8, the depth is 50% greater than at about 0.6. A typical depth at a water to cement ratio of about 0.5 after normal exposure for 10 years is between 5 mm and 10 mm [10].

From the FT-IR results, it can be observed that there is a gradual increase in the total absorbance of CO and CO_2 in the samples. An example of the change in gradient is shown in Fig. 3. Theoretically, cement paste far from inner aggregate should be exposed to a higher degree of carbonation. Therefore, the total absorbance of CO and CO_2 should be gradually decreasing from the fifth layer to the first layer of cement paste. However, the results from the samples show that the total absorbance of CO and CO_2 in the near layers to aggregate, such as the first or second layers of cement paste, is higher. From the results shown in Table 4, Sample 7 has the highest CDI of about 3.38 while Sam-

cium carbonate ($CaCO_3$) as shown in Eqs. (8)–(11). CO_2 of the $CaCO_3$ is generated (see Eq. (12)) during carbonation and CO is generated after the generation of the CO_2 as shown in Eq. (13).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (8)$$

$$\text{Calciumsilicatehydrate} + CO_2 \rightarrow \text{variousintermediates}$$
$$\rightarrow CaCO_3 + SiO_2nH_2O + H_2O \quad (9)$$

$$\text{Aluminatehydrates} + CO_2 \rightarrow CaCO_3 + \text{hydratedalumina}$$
$$\quad (10)$$

Table 7
Correlation coefficients on demolished concrete, recycled aggregate and recycled aggregate concrete

Correlation			Demolished concrete				Recycled aggregate				Recycled aggregate concrete
			Density	Absorptivity	Porosity	Carbonation depth	Density		Water absorption		Strength
							10 mm	20 mm	10 mm	20 mm	
Demolished concrete	Density		1.000	0.828	0.751	0.782	0.911	0.681	0.753	0.892	0.891
	Absorptivity		0.828	1.000	0.841	0.870	0.768	0.723	0.848	0.722	0.865
	Porosity		0.751	0.841	1.000	0.892	0.790	0.544	0.880	0.557	0.644
	Carbonation depth		0.782	0.870	0.892	1.000	0.744	0.780	0.854	0.726	0.747
Recycled aggregate	Density	10 mm	0.911	0.768	0.790	0.744	1.000	0.721	0.794	0.764	0.787
		20 mm	0.681	0.723	0.544	0.780	0.721	1.000	0.725	0.772	0.787
	Water absorption	10 mm	0.753	0.848	0.880	0.854	0.794	0.725	1.000	0.731	0.806
		20 mm	0.892	0.722	0.557	0.726	0.764	0.772	0.731	1.000	0.911
Recycled aggregate concrete	Strength		0.891	0.865	0.644	0.747	0.787	0.787	0.806	0.911	1.000

ple 6 has the lowest of about 0.41. The CDI difference among various samples is quite large.

In this section, all characteristics of the DC samples are shown to correlate among each other. Therefore, either "density", "absorptivity", "porosity" or "carbonation depth" is enough for describing the characteristics of the DC samples.

5.2. Recycled aggregate

5.2.1. Particle size distribution

Particle size distribution is important in affecting concrete workability [10]. The collected samples all fulfill the particle size distribution of 10 mm and 20 mm aggregate as stated in BS 882 [22] as shown in Table 5. "Pass" in Table 5 means the grading of the aggregate is within the upper and lower boundary requirements as stated in the British Standard for concrete workability.

5.2.2. Particle density

Aggregate particle density is an essential property for concrete mix design and also for calculating concrete volume produced from a certain mass of materials [23], which is a ratio of mass on a given volume to the mass of the same water volume [24]. Particle densities are measured and presented in Table 5.

As discussed in Section 5.1.1, the lower the density, the higher the cement mortar content attached to the RA will be. Samples 7 and 8 have the lowest values of particle density, indicating the highest amount of cement mortar attached to RA in Samples 7 and 8 compared with other samples; while Sample 6 has the highest value of particle density. Furthermore, particle densities of 20 mm aggregate are larger than those of 10 mm aggregate, inferring a higher amount of cement mortar attached to the 10 mm aggregate. This implies that the larger the size of the aggregate, the smaller the percentage of cement mortar attached to its surfaces and the better the aggregate quality will be.

Eq. (14) shows the relationship between density for 10 mm and 20 mm aggregate.

$$D_{ra20} = 0.7311\,D_{ra10} + 0.5961 \quad (R^2 \approx 0.5198) \qquad (14)$$

where D_{ra10} is the particle density for 10 mm aggregate (in % of dry mass); and D_{ra20} the particle density for 20 mm aggregate (in % of dry mass).

Table 7 shows the correlation of particle densities with water absorption rates of the RA samples. Eqs. (15) and (16) show the relationships between particle density and water absorption for 10 mm and 20 mm aggregate, respectively.

$$WA_{ra10} = -18.014\,D_{ra10} + 46.295 \quad (R^2 \approx 0.6304) \qquad (15)$$

$$WA_{ra20} = -11.206\,D_{ra20} + 31.325 \quad (R^2 \approx 0.5956) \qquad (16)$$

where WA_{ra10} is the water absorption rate for 10 mm aggregate (in % of dry mass); and WA_{ra20} the water absorption rate for 20 mm aggregate (in % of dry mass).

Based on Eqs. (15) and (16), the parameters which can be used to measure the particle density exhibit strong correlation to the water absorption values of the RA; for example, when the particle density is obtained, water absorption can be determined at an accuracy of about 60% significance. Savings in time and resources in carrying out all tests can thus be achieved, leading to higher efficiency in adopting RA for new construction work. By reducing the number of RA tests, shorter RA evaluation time can be achieved.

In addition, the particle densities of the RA samples also show relationships with density, absorptivity, porosity, and carbonation depth for the DC samples as shown in Eqs. (17)–(23).

$$D_{dc} = 1182.1\,D_{ra10} - 217.72 \quad (R^2 \approx 0.829) \qquad (17)$$

$$D_{dc} = 872.48\,D_{ra20} + 448.48 \quad (R^2 \approx 0.4644) \qquad (18)$$

$$A_{dc} = -31.844\,D_{ra10} + 74.468 \quad (R^2 \approx 0.5892) \qquad (19)$$

$$A_{dc} = -29.596\,D_{ra20} + 69.863 \quad (R^2 \approx 0.5234) \qquad (20)$$

$$P_{dc} = -31.519\,D_{ra10} + 84.768 \quad (R^2 \approx 0.6245) \qquad (21)$$

$$CDI_{dc} = -14.146\,D_{ra10} + 32.124 \quad (R^2 \approx 0.5541) \qquad (22)$$

$$CDI_{dc} = -14.619\,D_{ra20} + 33.301 \quad (R^2 \approx 0.6085) \qquad (23)$$

5.2.3. Porosity and absorption

Overall aggregate porosity or absorption may depend upon consistent degree of particle porosity or represent an average value for a mixture of variously high and low absorption materials [23]. In this study, water absorption rate is used to assess the porosity and absorption levels of the samples.

The water absorption of the RA samples 1–10 is varied as shown in Table 5. Sample 7 exhibits the highest water absorption rate at about 8.74%, and Sample 6 has the lowest water absorption rate at about 5.20% for 10 mm aggregate. One of the most obvious attributes between RA and natural aggregate is the higher water absorption rate of RA, which is mainly affected by the amount of cement paste attached on the aggregate surface that describes the soundness of aggregate since porosity of cement mortar is higher than that of aggregate. RA with a higher absorption rate tends to be weaker in strength and resistance to freezing and thawing than normal aggregate [25–27].

Eq. (24) shows the relationship between water absorption values for 10 mm and 20 mm aggregate.

$$WA_{ra20} = 0.4744\,WA_{ra10} + 3.4508 \quad (R^2 \approx 0.5344) \tag{24}$$

The water absorption for the RA samples shows relationships with density, water absorption, porosity, and carbonation depth for the DC samples as shown in Eqs. (25)–(31).

$$D_{dc} = -43.063\,WA_{ra10} + 2661.7 \quad (R^2 \approx 0.5664) \tag{25}$$

$$D_{dc} = -78.657\,WA_{ra20} + 2892.7 \quad (R^2 \approx 0.7958) \tag{26}$$

$$A_{dc} = 1.5503\,WA_{ra10} - 5.8422 \quad (R^2 \approx 0.7189) \tag{27}$$

$$A_{dc} = 2.0337\,WA_{ra20} - 8.7474 \quad (R^2 \approx 0.521) \tag{28}$$

$$P_{dc} = 1.5476\,WA_{ra10} + 5.1867 \quad (R^2 \approx 0.7751) \tag{29}$$

$$CDI_{dc} = 0.715\,WA_{ra10} - 3.7371 \quad (R^2 \approx 0.7287) \tag{30}$$

$$CDI_{dc} = 0.9367\,WA_{ra20} - 5.0688 \quad (R^2 \approx 0.5267) \tag{31}$$

5.2.4. Particle shape

Characteristics and variations of aggregate particle shape can affect workability and strength of concrete [23]. The shape of aggregate particles is best described by two principal parameters: 'sphericity' and 'roundness'. Aggregate particles are classified as flaky when they have the thickness (smaller dimension) of less than about 0.6 of their mean sieve size, for example, a mean sieve size of about 7.5 mm is the mean of two successive sieves of 5 mm and 10 mm [28]. Aggregate particles are classified as elongated when they have a length (greatest dimension) of more than about 1.8 of their mean sieve size [29].

BS 882 [22] provides limits for the flakiness (particle thickness relative to other dimensions). BS 882 [22] limits the flakiness index determined in accordance with BS 812: Part 105:1 [28] to about 50% for uncrushed gravel and about 40% for crushed rock or crushed gravel, with a warning that lower values may be specified for special circumstances such as pavement wearing surfaces. All 10 samples in this study have a flakiness index lower than 40%.

5.2.5. Strength and toughness

It is important that aggregate for making concrete be 'strong' in a general sense [30]. In most cases, inherent aggregate strength is dependent upon aggregate 'toughness', a property broadly analogous to 'impact strength'. In this study, ten percent fine values (TFV) and aggregate impact values (AIV) are used to determine the strength and toughness of the RA samples, respectively.

The TFV measures aggregate resistance in crushing which is applicable to both weak and strong aggregate [31]; a higher value indicates that aggregate is more resistant in crushing [23]. The AIV measures aggregate resistance to sudden shock or impact [32]. A smaller AIV indicates that the aggregate is tougher or more impact resistant than aggregate with a higher AIV [23]. In the 10 samples, Sample 6 has the highest value of TFV and the lowest value of AIV of about 155.53 kN and 25%, respectively; while Sample 2 has the lowest value of TFV and the highest value of AIV of about 61 kN and 36%, respectively as shown in Table 5. The obvious reason for this is that the cement paste attached to the RA directly affects the aggregate strength. The accuracy of more than 50% can be obtained based on the relation between TFV and AIV given by Eq. (32):

$$AIV_{ra} = -0.1317\,TFV_{ra} + 43.96 \quad (R^2 \approx 0.5417) \tag{32}$$

where TFV is the ten percent fine value of aggregate (in kN); and AIV the aggregate impact value (in %).

BS 882 [22] provides limits for the minimum TFV and maximum AIV of about 150 kN and 45%, respectively according to the concrete type in which the aggregate is used. According to British Standard requirements, Samples 6 can be used for structural elements, Samples 4 and 7 for pavement work and other samples confined to non-structural elements.

5.2.6. Chloride and sulphate contents

It is important to keep RA chloride and sulphate contents below a certain level. RA chloride contamination derived from marine structures or similarly exposed structural element is of concern which can lead to corrosion of steel reinforcement. However, for most RA samples (Samples 1–6 and 8–10), chloride ion contents are low and within the limit of standards of under 0.05%. Nevertheless, Sample 7 falls beyond the limit with the chloride contents of about 0.10% and 0.09% for 10 mm and 20 mm aggregate, respectively as shown in Table 5. From further investigation of Sample 7, some shell (from fine marine aggregates) contents were found. One of the major reasons comes from the use of marine water or stream water in concrete mixing during the drought period in the 1960s, which was banned since 1970s. This could have increased the chloride content in the sample.

Occurrence of sulphate-based products such as gypsum as contaminants in DC is common. Consideration must be given to use sulphate-resisting cement in situations where gypsum contamination is suspected [33]. In addition, gypsum plaster is seldom used in Hong Kong where lime plaster is more common. In fact, the highest sulphate content recorded is about 0.03% for Sample 1, which still falls within the standard of 1% as shown

Table 8
Mix proportions and design requirements for RAC

Mix proportions	
Ordinary Portland cement (kg)	100
Fine aggregate (kg)	180
20 mm coarse aggregate (kg)	180
10 mm coarse aggregate (kg)	90
Water (kg)	45
Design requirements	
Workability	Recycled coarse aggregates have to be thoroughly wetted before being used. The concrete shall have a slump of 75 mm when it is ready to be compacted to its final position. All mixes are within 65–85 mm slump.
The minimum concrete cube strength at 7 days (MPa)	14
The minimum concrete cube strength at 28 days (MPa)	20

in Table 5. Therefore, sulphate content contamination is not a major problem for RA in Hong Kong.

Eq. (33) shows a strong relationship between the chloride content for 10 mm and 20 mm aggregate with the correlation coefficient of about 99.5%.

$$C_{ra20} = 0.8691\,C_{ra10} + 0.0001 \quad (R^2 \approx 0.9949) \tag{33}$$

where C_{ra10} is the chloride content for 10 mm aggregate; and C_{ra20} the chloride content for 20 mm aggregate.

Furthermore, Eqs. (17)–(23) and (25)–(31) show strong correlation among the properties of the DC samples and their RA properties. It can be concluded that the lower the quality of DC samples, the lower the quality of their RA will be. Although most construction and demolition sites will not measure the quality of DC before crushing it to create RA, it may be important to measure the behaviour of DC to provide a pre-requisite consideration for their RA applications. This can save time and cost for the production of inferior quality RA and ensure that high quality RA is produced for higher-grade concrete applications.

5.3. Recycled aggregate concrete

To verify the above results, compressive strengths of 100 mm cubes made from the 10 samples were measured according to BS 1881: Part 116 [34]. According to Buildings Department's requirements [6], mix proportions and design requirements for RAC are stated in Table 8. All the samples have achieved the required requirements. The average and the individual results of three cubes of each sample are tabulated in Table 6. Since limited samples are collected from the various demolition sites, samples verified by the concrete cubes are used as the base. The results show that the compressive strength of RAC made from Sample 6 has reached about 63 MPa. The lowest strength was recorded for Samples 7 and 8 with values of about 50 MPa.

From the correlation results showed in Table 7, the compressive strength for the RAC samples show relationships with density, absorptivity, porosity, and carbonation depth of the DC

samples as shown in Eqs. (34)–(37).

$$D_{dc} = 13.219\,S_{rac} + 1637.4 \quad (R^2 \approx 0.7942) \tag{34}$$

$$A_{dc} = -0.4102\,S_{rac} + 27.442 \quad (R^2 \approx 0.7489) \tag{35}$$

$$P_{dc} = -0.2935\,S_{rac} + 32.085 \quad (R^2 \approx 0.415) \tag{36}$$

$$CDI_{dc} = -0.1621\,S_{rac} + 10.137 \quad (R^2 \approx 0.5576) \tag{37}$$

where S_{rac} is the compressive strength of RAC (in MPa).

Eqs. (38) and (41) show relationships between the strength of the RAC samples and the properties of their RA.

$$D_{ra10} = 0.009\,S_{rac} + 1.6891 \quad (R^2 \approx 0.6191) \tag{38}$$

$$D_{ra20} = 0.0091\,S_{rac} + 1.6924 \quad (R^2 \approx 0.6187) \tag{39}$$

$$WA_{ra10} = -0.2088\,S_{rac} + 18.426 \quad (R^2 \approx 0.6489) \tag{40}$$

$$WA_{ra20} = -0.1533\,S_{rac} + 15.154 \quad (R^2 \approx 0.8305) \tag{41}$$

Eqs. (1)–(41) highlight that there are correlations among properties of the DC samples, their RA properties, and the compressive strength of RAC. It is clear that the inferior quality of the DC can lower the quality of their RA and RAC. One of the major problems in lowering the quality of DC, RA and RAC is cement mortar attached on the samples. With large pores and voids commonly occur around aggregate for most samples (see Fig. 4), this creates a weak link between aggregate and old cement mortar and limits their concrete applications [35].

The existence of pores and voids near aggregate region of the samples can be explained by the following six major issues [18,36–41,42–55]:

(a) inadequate concrete mixing time creating large pores;
(b) coarse aggregate trapping some voids underneath as shown in Fig. 5;
(c) expansion and shrinkage of aggregate lying under the surface of concrete;
(d) inappropriate water to cement ratio, either too dry or too wet causing the formation of pores;
(e) moisture content in the environment affecting the water content of aggregate and thus pore generation; and
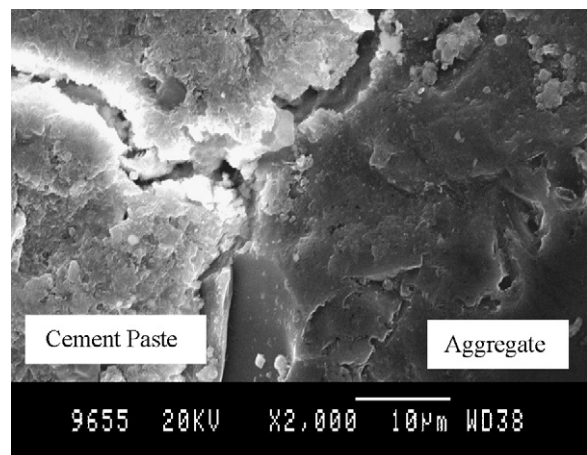

Fig. 4. Scanning electron microcopy image on the interfacial transition zone.

Table 9
Causes and examples of building waste on site [62,63]

| Building waste	Causes of building waste on site	Examples
Site management and practice	Lack of a quality management system aimed at waste minimization	Lack of waste management plan
	Untidy construction sites	Waste materials are not segregated from useful materials
	Poor handling	Breakage, damage, losses
	Over-sized foundations and other elements	Over design leads to excess excavation and cut-offs
	Inadequate protection to finished work	Finished concrete staircases are not protected by boarding
	Limited visibility on site resulting in damage	Inadequate lighting in covered storage area
	Poor storage	Pallet is not used to protect cement bags from contamination by ground water
	Poor workmanship	Poor workmanship of formwork
	Waste generation inherited with traditional construction method	Timber formwork, wet trade
Delivery of products	Over-ordering	Over ordering of concrete becomes waste
	Method of packaging	Inadequate protection to the materials
	Method of transport	Materials drop from forklift
	Inadequate data regarding time and method of delivery	Lack of records concerning materials delivery
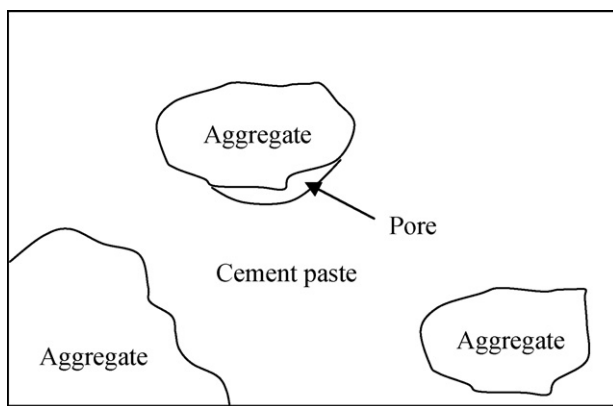
Fig. 5. Schematic diagram showing formation of pores under aggregate during concreting.

(f) alkali-aggregate reaction, such as alkali-silica reaction, alkali-silicate reaction and alkali-carbonate reaction, may lower concrete quality. As alkalis are derived from the cement itself, sodium or potassium can contribute to the reaction provided that the alkali can move into pore solution of concrete and creates the necessary hydroxyl ion.

As buildings would have normally serviced for many years before demolition, the properties and behaviour of concrete would obviously be affected during the service life. However, one of the major factors for the inferior quality of concrete waste is resulted from the poor workmanship and lack of supervision during concreting activities (see Table 9). Therefore, the construction industry should provide measures; including training and on-site supervision to reduce these problems in the future and thus improving DC, RA and RAC quality for higher-grade applications.

6. Conclusion

In this paper, 10 demolished concrete (DC) samples have been collected to investigate the correlation among the char-acteristics of DC, properties of recycled aggregate (RA) and recycled aggregate concrete (RAC). Four properties of the DC samples: (i) density; (ii) absorptivity; (iii) porosity; and (iv) carbonation depth; six properties of their RA: (i) particle size distribution; (ii) particle density; (iii) porosity and absorption; (iv) particle shape; (v) strength and toughness; and (vi) chemical and sulphate contents; and compressive strength of RAC, are examined. From the results, it is clear that there are correlations among the characteristics of the DC samples, and their RA and RAC. It is shown that the inferior quality of DC can lower the quality of their RA and RAC. It is important to measure the characteristics of DC to provide a pre-requisite consideration for their RA and RAC applications. This can save time and cost for the production of inferior quality RA and ensure that high quality RA is produced for higher-grade concrete applications. RAC design requirements can also be developed at the initial concrete demolition stage. Recommendations are also given to improve the future concreting practice.

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