A Review on the Use of Recycled Aggregate in Concrete in Hong Kong

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ABSTRACT: Hong Kong, which generates a significant amount of construction and demolition (C&D) wastes annually, is a mountainous city with a population of about 6.8 million. Due to the rapid development in this territory in the past two decades, the landfills are estimated to be saturated in 6 to 8 years. Therefore, it is of great importance to find viable ways to recycle these wastes in a scientifically and sustainable manner. This paper reviews the research, applications and specifications of the use of recycled aggregates derived from C&D wastes in concrete. The review covers using recycled aggregates on the properties of the resulting concrete and summarizes RILEM and UK specifications governing the use of recycled aggregate in concrete. A case study on using recycled aggregates in a construction project in Hong Kong is used to illustrate the barriers that must be overcome to facilitate the wider use of recycled aggregates in concrete in Hong Kong.

Keywords: construction and demolition (C&D) waste; recycled aggregate; recycled aggregate concrete

1. INTRODUCTION

Hong Kong, with a population of about 6.8 million and about 2.1 million households has a mountainous landscape. As land is scare in this territory, the most common way to gain additional floor space is by demolishing old buildings and replacing them by high-rise buildings. In 2004, there were over 20 million tones of construction and demolition (C&D) wastes generated in Hong Kong. In the past, the inert portions of these C&D materials, such as rock, concrete and soil, have been beneficially reused as fill materials in forming land for the fast growing perpetual development. However, the increasing awareness on environmental protection by the public has resulted in having most reclamation projects either been deferred or much reduced in scale. This in turn results in a substantial reduction of the public filling capacity to accommodate the surplus of C&D materials. If these materials are not managed properly, it will also accelerate the depletion of the already limited precious landfill resources.

In fact, the quantities of C&D wastes generated in Hong Kong have significantly risen from 13.6 million tons in 1999 to over 20 million tons in 2004 (CEDD, 2006) as shown in Figure 1. It is estimated that this trend will continue. Hong Kong is now facing a crisis on how to accommodate these surplus materials. Apart from putting more efforts in minimizing its generation and the formation of temporary fill banks for temporary accommodation of these materials, recycling is one of the means to alleviate the demand on disposal facilities. Hence, this paper reviews the applications recycled aggregates derived from C&D wastes including crushed concrete rubbles, ceramic tiles and crushed clay bricks in ready-mixed concrete and how the use of these different types of recycled aggregate affects the properties of the resulting concrete. The current specifications of using recycled aggregate in concrete in a few selected countries are summarized. The barriers for a wider use of recycled aggregates in concrete in Hong Kong are illustrated by a case study.

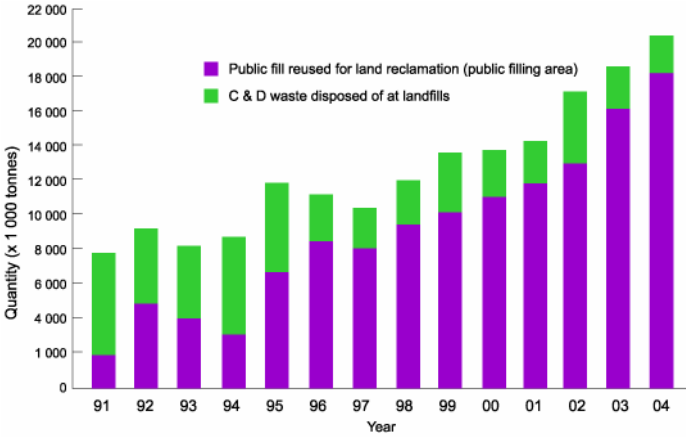

Figure 1. Generation of construction and demolition (C&D) wastes in Hong Kong (CEDD 2006)

2. LITERATURE REVIEW

2.1 *Use of recycled aggregates derived from crushed concrete rubbles in concrete*

Poon et al. (2004) showed that the slump of recycled aggregate concrete was dependent on the moisture state of the recycled aggregate. When oven-dry recycled aggregate was used, a high initial slump was observed due to the high amount of water that was used to compensate the high water absorption of the recycled aggregate. Cho and Yeo (2004) found that, due to the high water absorption of the recycled aggregate, a higher slump loss was observed when compared to that of natural aggregate concrete. Dhir et al. (1999) showed that the compressive strength of concrete prepared with 100 % coarse and 50 % fine recycled aggregates was between 20 and 30 % lower than that of the corresponding natural aggregate concrete. However, the reduction in strength can be minimized if the mixing procedure is modified (Otsuki et al. 2003; Tam et al. 2005). Furthermore, Olorunsogo and Padayachee (2002) found that the water sorptivity of concrete prepared with 100 % recycled aggregate was higher than that of natural aggregate concrete at the curing age of 28 days. Abou-Zeid et al. (2005) reported that recycled aggregate concrete exhibited higher water permeability and lower resistance to chloride ion penetration compared to conventional concrete. Salem et al (2003) showed that recycled aggregate concrete had a lower resistance to freezing and thawing compared to natural concrete. Otsuki et al. (2003) reported that the carbonation resistance of recycled aggregate concrete was inferior compared to that of natural aggregate concrete. The drying shrinkage and creep of recycled aggregate concrete were found to be higher than those of natural aggregate concrete (Tavakoli and Soroushian, 1996; Gomez-Soberon, 2003). Furthermore, Park et al. (2005) examined the effective use of recycled aggregate as a constituent in porous concrete used for a sound absorption material. They reported that the optimum Noise Reduction Coefficient (NRC) was achieved when the void ratio and recycled aggregate content were 25 % and 50 % respectively. Dhir et al. (2004) found that for all classes of concrete, 30% replacement of natural aggregate with coarse recycled concrete aggregate had only a modest influence on concrete performance. At higher replacement levels, equal performance to natural aggregate concrete could be achieved at equivalent 28-day strength by appropriate reducing the water-to-cement ratio used. Although the employment of recycled aggregate adversely affects the drying shrinkage and creep of concrete, a number of ways such as the use of fly ash and steam curing (Kou et al. 2005; Poon et al. 2006) have been proposed to mitigate some of these detrimental effects.

2.2 *Use of crushed clay brick in concrete*

Research has been carried out using crushed clay brick in concrete for a number of years. It is known that the use of crushed brick in concrete affects the properties of the resulting concrete to a certain extent depending on the type of brick from which the aggregates are derived. Akhtaruzzaman and Hasnat (1983) first studied the use of crushed brick as a 100 % replacement of coarse natural aggregates in concrete. The resulting concrete had a unit weight between 2000 and 2080 kg/m^3 and a compressive strength between 13.8 and 34.5 MPa. It was found that the tensile strength of the brick concrete was higher than that of normal concrete by about 11 %. However, the modulus of elasticity was 30 % less than that of normal concrete. Khaloo (1994) tried to use crushed clinker (hard burnt) brick as aggregates in concrete. The resulting concrete had a unit weight of about 2100 kg/m^3. The average compressive, tensile and flexural strengths of brick concrete were -7 %, +2 % and +15 % than those of normal concrete. Padmini et al., (2001) who used a fractional factorial experimental design method, studied the relative influence of different parameters on the strength of concrete using low-strength (6-13 MPa) bricks as aggregates. It was found that the strength of brick concrete was most influenced by the cement content, the aggregate conditions (i.e. pre-wet or dry before mixing) and the strength of brick from which the aggregates were derived. Kibriya and Speare (1996) used three different types of brick aggregates to assess their impacts on the strengths and the long-term durability of concrete. The brick concrete had comparable compressive, tensile and flexural strengths to those of normal concrete but the modulus of elasticity was drastically reduced. Furthermore, it was found that the use of brick aggregate significantly increased the shrinkage of concrete at 90 days, and the creep tested at one year was slightly increased as well. de Brito et al. (2005) investigated the use of brick aggregate derived from hollow brick partition walls as a replacement of limestone aggregate in the production of 50 mm thick concrete pavement slabs. They found that the use of brick aggregate decreased the compressive strength and flexural strength of the slabs. Nevertheless, an increase in the abrasion resistance of the slabs was observed as the brick aggregate content increased.

2.3 *Use of ceramic tile in concrete*

The number of study on the use of crushed ceramic tile as a construction material is scarce. Khaloo (1995) investigated the use of crushed tile as a source of coarse aggregate in concrete. The crushed tile had a lower density and a much higher water absorption value compared to those of natural crushed stones. The resulting concrete made with 100 % crushed tile as the coarse aggregate had a lower density and higher compressive (+2%), tensile (+70%) and flexural (+29%) strengths. Ay and Unal (2000) studied the possibility of using ground waste ceramic tile as a cement replacement in concrete. It was found that ground waste tile possessed pozzolanic properties and it was possible to use ground waste tile as a 35 % by weight replacement of cement.

3. SPECIFICATIONS ON THE USE OF RECYCLED AGGREGATE

Recycled aggregate has long been used in the construction industry; however, due to the lack of suitable specifications, its use is being limited to the low-grade applications such as in road sub-base. Undoubtedly, suitable quality of recycled aggregates may be used successfully in higher grade applications such as concrete. Recent international advances in the drafting of specifications provide good guidance on the quality control of recycled aggregate and its respective use in higher grade applications. An overview of the specifications prepared by RILEM and UK, on which the current Hong Kong specifications for the use of recycled aggregates in construction are based are summarized in the following sections.

3.1 *RILEM*

RILEM, an international union of testing and research laboratories for materials and structures, has been actively working to harmonize current European approaches to the specifications of concrete which contains recycled aggregate. In 1994, RILEM released its specifications on the use of coarse recycled aggregate (≥ 4 mm) in concrete (RILEM, 1994). These specifications have three main objectives: 1) to provide guidelines for classifying the coarse recycled aggregate, 2) to identify the fields of application, and 3) to indicate the design values for the types of recycled aggregate.

Three types of recycled aggregate are specified by RILEM and they are summarized in Table 1. Based on the descriptions in Table 1, it is very difficult to assign the aggregate to the correct aggregate types. As a result, RILEM imposed some requirements for the three aggregate types on the basis of the particle density and the impurity content as illustrated in Table 2 .

Table 1 – Descriptions of three types of recycled coarse aggregate (RILEM, 1994)

Type	Description
I	aggregates which are implicitly understood to originate primarily from masonry rubble.
II	aggregates which are implicitly understood to originate primarily from concrete rubble.
III	aggregates which are implicitly understood to consist of a blend of recycled aggregates (maximum 20%) and natural aggregates (mandatory minimum 80%). The maximum content of Type I aggregates in the blend is intended to be 10% (i.e. 50/50 masonry/concrete mixtures may be used for blending with natural aggregate).

The properties of recycled aggregate (i.e. grading, static strength, form index, abrasion value, chloride content, content of swelling clay and frost resistance) are not specified but they should comply with the national or CEN standards. Nevertheless, recycled aggregates listed in Table 2 should not contain any materials which can retard concrete setting by more than 15 % compared to the same concrete made with natural aggregate.

Recycled aggregate, which complies with the specifications in Table 2, can be used in plain and reinforced concrete provided that it meets the strength requirements in Table 3. If reinforced concrete using recycled aggregate is exposed to weather, extra care should be paid to the durability aspect of the reinforced concrete. Additional tests such as ASR expansion test, freeze-thaw test and deicing salt test are necessary.

Table 2 – Classification of recycled aggregate (RILEM, 1994)

Mandatory requirements	Type I	Type II	Type III	Test method
Minimum dry particle density (kg/m^3)	1500	2000	2400	prEN 1097-6
Maximum wt. % with SSD<2200 kg/m^3	--	10	10	
Maximum wt. % with SSD<1800 kg/m^3	10	1	1	prEN 1744-1
Maximum wt. % with SSD<1000 kg/m^3	1	0.5	0.5	
Maximum wt. % of foreign materials (metals, glass, soft material, tar, crushed asphalt etc.)	5	1	1	Test by visual separation as in prEN 933-7
Max. content of metals (% m/m)	1	1	1	Visual
Max. content of organic material (% m/m)	1	0.5	0.5	NEN 5933
Max. content of filler (<0.063 mm) (% m/m)	3	2	2	prEN 933-1
Max. content of sand (<4 mm) (% m/m)	5	5	5	prEN 933-1
Max. content of sulfate (% m/m)	1	1	1	BS 812: part 118

Table 3 - Maximum allowable strength for concrete with various types of recycled aggregate (RILEM, 1994)

	Type I	Type II	Type III
Grade of concrete	C16/20 #	C50/60	No limit

The strength may be increased to C30/37 subject to the condition that the SSD density of the RCA exceeds 2000 kg/m^3.

The design procedures for recycled aggregate concrete are the same as for natural aggregate concrete as stated in prENV 1992-1-1. However, the influence of recycled aggregate on the mechanical properties of reinforced concrete should be included in the design. Due to a lack of experimental data in 1994, RILEM proposed various factors (Table 4) in order to estimate the mechanical properties of reinforced concrete made with recycled aggregate. These factors are applied to the design values for normal aggregate concrete prescribed by prENV 1992-1-1.

Table 4 – Factors for evaluating the mechanical properties of various types of recycled aggregate concrete (RILEM, 1994)

Design Values	Type I	Type II	Type III
Tensile Strength (f_t)	1	1	1
Modulus of Elasticity (E)	0.65	0.8	1
Creep Coefficient (ϕ)	1	1	1
Shrinkage (ε)	2	1.5	1

As indicated in Table 4, the mechanical properties of concrete made with Type III recycled aggregate are the same as that of natural aggregate concrete. One may recall that Type III concrete only contains 20 %

recycled aggregate. However, the modulus of elasticity and the shrinkage of concrete made with either Type I or II recycled aggregate are different from those of natural aggregate concrete. RILEM suggested that Type I recycled aggregate concrete has modulus of elasticity and shrinkage values which are 35 % lower and 100 % higher than conventional concrete, respectively. Likewise, Type II recycled aggregate concrete has modulus of elasticity and shrinkage values which are 20 % lower and 50 % higher than conventional concrete, respectively. These modified design values for recycled aggregate concrete agree with the recent investigations which show that modulus of elasticity and shrinkage of recycled aggregate concrete are lower and higher than conventional concrete, respectively.

3.2 *UK*

Although BS 6543 (BSI 1985) “Use of industrial by-products and waste materials in building and civil engineering” provides guideline for the use of recycled materials including recycled aggregate in civil engineering works, they are rarely quoted in contract documents. In order to facilitate the recycling of demolition waste, The Building Research Establishment (BRE) established specific guidance to give full coverage to the use of recycled aggregate in 1998 (BRE, 1998).

In the specifications, recycled aggregate is classified into three classes based on the relative proportions of concrete to brick masonry as shown in Table 5. Class RCA(I) has the lowest quality compared to RCA (II) and RCA (III). It allows mixture to contain as much as 100 % brick or block masonry. The strength, expressed as a ten percent fines value, is approximately 70 kN. RAC(II) has the best quality among the three classes. It contains at least 90 % crushed concrete and its strength (i.e. 10 % fines value) is greater than 100 kN. Finally, RAC(III) can be considered a blend of concrete and masonry. The required strength is the same as RAC(I) but its quality is better than that of RCA(I) due to a higher content of crushed concrete. The impurity content is also specified for the three classes of recycled aggregate as shown in Table 6. It is evident that the impurity content for each class of recycled aggregate varies with the intended applications of the recycled aggregate.

Table 5 – Classes of recycled aggregate in UK (BRE, 1998)

Class	Origin	Brick content by weight	Strength (by 10% fines test)	Relative Quality
RCA (I)	Brickwork	0 – 100%	70 kN	Lowest
RCA (II)	Concrete	0 – 10%	> 100 kN	Highest
RCA (III)	Concrete and brick	0 – 50%	70 kN	Moderate

Although recycled aggregate of Classes RCA(I), (II) or (III) can be used in concrete, the quality and grading of the recycled aggregate have to meet the requirements as specified in BS 882 (BSI 1992). For the aggregate, which fails to comply with the grading requirements in BS 882 (BSI 1992), may still be used in concrete provided that the quality of the aggregate is in compliance with BS 5328 (BSI 1997) and trial mixes indicate that concrete of suitable quality can be produced. However, recycled aggregate, which has particle size less than 5 mm, is not recommended for the use in concrete because it would cause an increase in the water content and contain a high level of contamination. Nevertheless, a 10 % replacement of natural sand by recycled fine aggregate is permitted in some situations where a high degree of control exists. (i.e. fines from reclaimed product at a precast concrete works)

After all, BRE (1998) recommends a maximum grade for concrete using different Classes of recycled aggregates as follows :

RCA (I):dry density < 2000 kg/m^3	C20
RCA (I):dry density > 2000 kg/m^3	C35
RCA (II):	C50
20% RCA(III) + 80% natural aggregate	no limit

In order to control the quality of the concrete, BRE also limits the variations of the dry density of the aggregate. The variations should be ±1 % and ±5 % for Class RCA (II) and for Classes RCA (I) and (III), respectively.

Table 6 – Maximum recommended levels of impurity (by weight) in Britian (BRE, 1998)

	Use in	Use in road	Hardcore,

	concrete as coarse aggregate	construction	fill or granular material
Asphalt and tar	Included in limit for other foreign material	10% in RCA (I) 5% in RCA (II) 10% in RCA (III)	10%
Wood	1% in RCA (I) 0.5% in RCA (II) 2.5% in RCA (III)	Sub-base: 1% Capping layer: 2%	2%
Glass	Included in limit for other foreign material	Contents above 5% to be documented	Contents above 5% to be documented
Other foreign material (e.g. metals, plastic, clay)	5% in RCA (I) 1% in RCA (II) 5% in RCA (III)	1%	1%
Sulfates	Concrete and CBM: 1% acid-soluble SO_3		

In 2002, BS 8500-2 (BSI 2002) published requirements for using coarse recycled aggregate in concrete. Based on the composition of the recycled aggregate, recycled aggregate is divided into two classes: namely recycled concrete aggregate (RCA, comprising > 95% crushed concrete) and recycled aggregate (RA, comprising < 95% crushed concrete) and the corresponding composition requirements for each of the classes are summarized in Table 7.

According to the guidelines, coarse recycled concrete aggregate can be used in concrete with a strength class not greater than C40/50 and is limited to the exposure classes as indicated in Table 8. The guidelines give provisions for the use of recycled concrete aggregate in concrete with other exposure classes provided that it is demonstrated that the resulting concrete is suitable for the intended applications.

Table 7 – Requirements of coarse recycled concrete aggregate and recycled aggregate specified by BS 8500-2 (BSI 2002)

Property	Recycled concrete aggregate[1,2]	Recycled aggregate
Max. masonry content, %	5	100
Max. fines, %	5	3
Max. lightweight material (density < 1000 kg/m^3), %	0.5	1.0
Maximum asphalt, %	5.0	10.0
Max. other foreign materials, %	1.0	1.0
Max. acid-soluble sulfates, SO_3	1.0	-[3]

[1] Where the material to be used is obtained by crushing hardened concrete of known composition that has not been contaminated by use, the only requirements are those for grading and maximum fines

[2] The provisions for recycled concrete aggregate may be applied to mixtures of natural coarse aggregate blended with the listed constituents.

[3] The appropriate limit needs to be determined on a case-by-case basis

Table 8 – Limitations on the use of coarse recycled concrete aggregate in concrete with different exposure classes (BSI 2002)

Description		Severity of exposure →			
X0	No risk of corrosion or attack	X0	-	-	-
XC	Corrosion induced by carbonation	XC-1	XC-2	XC-3	XC-4
XD	Corrosion induced by chlorides	*	*	*	*
XS	Corrosion induced by chlorides (seawater)	*	*	*	*
XF	Freeze/thaw attack	XF-1	*	*	*
DC	Sulfate attack	DC-1	*	*	*

*The guidelines give provisions for the use of recycled concrete aggregate in concrete with other exposure classes provided that it is demonstrated that the resulting concrete is suitable for the intended applications

On the other hand, due to the potential variation in the composition of lower quality recycled aggregate (RA) , BS 8500-2 states that the use of recycled aggregate should be assessed on a case-by-case basis with regard to the sulfate content, chloride content, alkali content and the potential alkali-aggregate reactivity of the recycled aggregate. This requirement hinders the wider use of recycled aggregates in ready-mixed concrete in the UK.

3.3 *Hong Kong*

In order to facilitate the use of recycled aggregate, Hong Kong has recently published specifications for using recycled aggregate in concrete. However, Hong Kong only allows using recycled aggregate as a 100 % replacement and a 20 % replacement of natural coarse aggregate (WTBC 2002). In the meantime, other replacement levels are not specified.

The concrete strength is specified at 20 MPa and it can be used in benches, stools, planter walls, concrete mass walls and other minor concrete structures. The specification requirements for recycled aggregate are listed in Table 9. Similar to other countries, recycled fine aggregate is not permitted. The grading of coarse and fine aggregates should be within the limits prescribed by BS 882 (BSI 1992) as shown in Table 10. Furthermore, the mix proportions should comply with the following proportions:

Ordinary Portland Cement:	100 kg
Fine Aggregate:	180 kg
20 mm Recycled Coarse Aggregate:	180 kg
10 mm Recycled Coarse Aggregate:	90 kg

In order to maintain the same workability, recycled aggregates have to be thoroughly wetted prior to mixing and the resulting concrete should have a slump of 75 mm. To ensure the quality of concrete, 4 concrete cubes must be cast on each concreting day, 2 for crushing tests at 7 days and another 2 at 28 days. The strength of the cube must be at least 14 and 20 MPa at 7 and 28 days, respectively. On the other hand, concrete with 20 % recycled aggregate should have a compressive strength between 25 and 35 MPa and it can be used for general concrete application except in water retaining structures.
Table 9 should be cited to illustrate the specification requirements for the recycled aggregate and both coarse and fine aggregates must satisfy the grading limits as shown in Table 10.

Table 9 – Specification requirements for recycled aggregate in Hong Kong (WTBC 2002)

Requirements	Limit	Test Method
Min. dry particle density (kg/m^3)	2000	BS 812 : Part 2
Max. water absorption	10 %	BS 812 : Part 2
Max. content of wood and other material less dense than water	0.5 %	Manual sorting in accordance with BRE Digest 43
Max. content of other foreign materials (eg. Metals, plastics, clay lumps, asphalt, glass, tar. …)	1 %	
Max. fines#	4%	BS 812 : Section 103.1
Max. content of sand (< 4 mm)	5 %	BS 812: Section 103.1
Max. sulphate content	1 %	BS 812: Part 118
Flakiness index*	40 %	BS 812: Section 105.1
10 % fines value	100 kN	BS 812: Part 111
Grading	Table 3 of BS 882:1992	
Max. chloride content@	Table 7 of BS 882 – 0.05 % by mass of chloride ion of combined aggregate	

Filler (<0.063 mm) should be less than 2 % in RILEM specification. BS 882 specifies that fines passing 75 μm sieve should be less than 4 %. The latter is easier to satisfy.
* BS 882 states that flakiness index should not exceed 40 % for crushed rock or crushed gravel.
@ BRE Digest 43 recommends to determine acid soluble chloride rather than water soluble chloride.

Table 10 - Grading limit for coarse and fine aggregates in accordance with BS 882 (BSI 1992)

BS Test Sieve (mm)	Coarse Aggregate		BS Test Sieve	Fine Aggregate
	20 mm	10 mm		Grading M
37.5	100	-	5.00 mm	-
20.0	85-100	-	2.36 mm	65-100
14.0	0-70	100	1.18 mm	45-100
10.0	0-25	85-100	600 µm	25-80
5.0	0-5	0-25	300 µm	5-48
2.36	-	0-5	150 µm	-

4. CASE STUDY – THE PRODUCTION AND USE OF RECYCLED AGGREGATE IN CONCRETE PRODUCTION IN HONG KONG

In mid-July 2003, the HKSAR Government established a pilot C&D materials recycling facility in Tuen Mun to produce recycled aggregates for use in government projects and for research and development works [CEDD, 2006]. The plant had a designed handling capacity of 2,400 tonnes per day. The processing procedure for recycled aggregate comprised the following processes: 1) a vibrating feeder/grizzly for sorting the hard portions from the inert C&D materials which were suitable for subsequent recycling; 2) a jaw crusher (primary crusher) for reducing the sorted materials to sizes of 200 mm or smaller which could be handled by the secondary crushers; 3) a magnetic separator, manual picking gallery and air separator for removal of impurities before the materials were fed into the secondary crusher; 4) cone crushers (secondary crusher) for processing the clean materials into sizes smaller than 40mm; 5) vibratory screens for separating the crushed recycled aggregates into different sizes; and 6) storage compartment for temporary storage for recycled aggregates. The facility was able to produce Grade 200 rockfill and recycled aggregates of various sizes, ranging from 40 mm, 20 mm and 10 mm coarse aggregates to fine aggregates (< 5 mm) for different applications.

Due to the varying sources of the incoming materials, a prudent quality control approach was adopted by the recycling plant. Only suitable materials (e.g. crushed rocks, concrete) were processed at the plant. Bricks and tiles were generally not allowed. The produced recycled aggregates were sampled and tested daily. From July 2003 to June 2005, the facility produced approximately 540,000 tonnes of recycled aggregates with consistent high quality which meets the specification requirements (Table 16). But the facility was decommissioned in June 2005 as it was concluded that without other complementary policy measures (see below) the production of recycled aggregates from C&D waste in Hong Kong would not be economically viable. The produced recycled aggregates were used in over 110 government's public works projects (Figure 2). Despite the very stringent quality control measures implemented, it can be noticed that only a few percentages of the produced recycled aggregates was used for high grade concrete production and the majority of the recycled materials were used in low grade applications such as general fills.

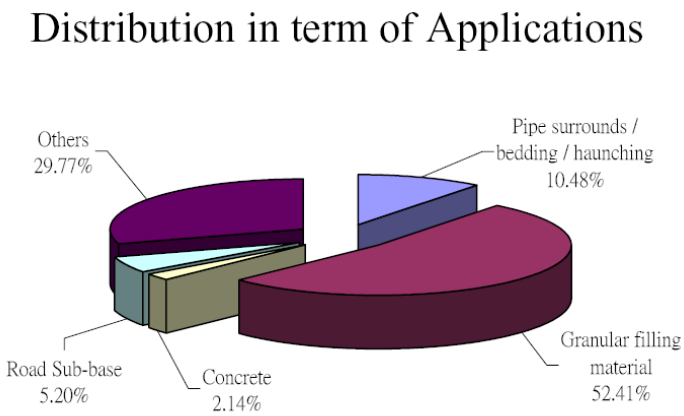

Figure 2 . Distribution of the use of recycled aggregates in Hong Kong (CEDD 2006)

Hong Kong Wetland Park is located at the north-western part of Hong Kong and is near the border between Hong Kong and Shenzhen of the Mainland. Completed in early 2006, the Park has a 10,000 m^2 visitor center comprising exhibition galleries, Audio-visual theatres, souvenir shops, cafes, children play areas, classrooms and a resources center. In the project, recycled aggregate was employed to replace part of the virgin aggregate in the majority of the concrete used. In total, about 140,000 m^3 of concrete was produced for this project. The concrete grades used were C10, C20 and C35. The designed slump was 100 mm but in some cases, 75 mm slump concrete was also used.

Based on the specifications, the replacement levels of recycled coarse aggregate were 100 % and 20 % for concrete grades C20 (or below) and C25 to C35 respectively. Because of the limited experience in using recycled aggregates in concrete in Hong Kong, at the beginning of the project, the cement contents for the concrete mixes were deliberately increased by around 4% to compensate for the higher initial free water content required by the recycled aggregates so as to maintain a similar water/cement ratio.

The statistical results listed in Table 11show that the average 28-day cube strength and the standard deviation of recycled aggregate concrete used in the project were about the same as those of ordinary concrete. The similar standard deviations show that the quality of concrete using recycled aggregates can also be controlled to a similar stability as that of ordinary concrete.

Table 11 - Statistical results of recycled and natural aggregate concretes (Fong et al 2004)

Concrete Grade	Slump (mm)	RA (%)	Cement (kg/m^3)	w/c	28 day Cube Strength (MPa)	S. D. for running 40 samples
C35	100	20	395	0.466	47.3	2.8
C35	100	0	380	0.473	48.2	4.1
C35	75	20	380	0.468	47.1	4.8
C35	75	0	365	0.479	45.8	4.5
C30	75	20	360	0.486	44.7	4.4
C30	75	0	345	0.507	42.1	4.7
C20	75	100	300	0.607	31.4	5.0
C20	75	0	290	0.603	32.8	4.4

In Hong Kong, most concrete batching plants were originally designed and built for concrete production with virgin aggregates only. In order to accommodate the recycled coarse aggregate, additional storage compartments had to be installed with all the necessary feeding and batching accessories. Also, as the water absorption rate of recycled aggregates was much higher than that of virgin aggregates, and to avoid excessive slump loss, the recycled aggregates were required to be pre-wetted both at the stockpiles of the recycling plant and by sprinkling water mist on the recycled aggregates during unloading at the receiving hopper at the batching plant before feeding to the overhead bin. The moisture content in the recycled aggregate was then compensated during the mix design. Chemical admixtures that would facilitate good workability retention were also added. But soft materials such as old cement mortar that were originally adhered to the old aggregates were quite easily broken off during mixing of the concrete which further contributed to the slump loss. The slump of the concrete produced therefore tended to be rather unstable, although the performance could still be controlled within the limits of acceptance. Also, the rate of slump loss was high which meant the workable time of the concrete was also reduced. As such, when recycled aggregates are used in ready mixed concrete production, it is advisable to adopt a higher initial design workability to compensate for the higher anticipated slump loss.

Feedback from contractors of this project was that concrete containing 20% recycled aggregates was little different from normal concrete (Li et al 2006). No crack that could be attributed to shrinkage was observed and carbonation test revealed no traceable carbonation depth over the first two years period.

5. BARRIERS AGAINST THE USE OF RECYCLED AGGREGATE IN HONG KONG

In spite of the successful case described above, the deployment of recycled aggregate in concrete is still scare in Hong Kong. The following barriers have been identified to hinder the use of recycled aggregate in Hong Kong (Fong 2003):

- Cheap means of disposal of C&D waste in landfills or reclamation sites and no imposition of aggregate tax.
- Low price and wide availability of natural crushed rock as compared to recycled aggregate.
- No policy to strictly require designers and contractors to use a suitable portion of recycled aggregates in their projects.
- Instable supply of quality recycled aggregate.
- Lack of knowledge about the performance of recycled aggregate in the local construction industry.
- Low incentives on on-site waste separation rendering higher costs for production of recycled aggregate.
- Conservatism and reluctance of the local professionals.
- Conservative specifications of civil engineering work which limit the use of recycled products.

6. RECOMMENDATION

In order to eradicate some of the barriers (i.e. conservative specifications) that hinder the use of recycled aggregate in Hong Kong, a comparison has been made between the specifications in Hong Kong and in other countries which reveals that the scope of the specifications in Hong Kong for recycled aggregate seems to be too narrow. It only allows two types of recycled aggregate in the production of Portland cement concrete. The first type consists of 100 % recycled aggregate and the second type is blended with 80 % natural aggregate and 20 % recycled aggregate. Furthermore, it strictly prohibits using recycled aggregate with a density less than 2000 kg/m^3 (i.e. recycled masonry aggregate) in concrete. In contrast, other specifications such as RILEM and UK permit using recycled aggregate with a density less than 2000 kg/m^3. Moreover, the literature review in this paper shows that using recycled masonry aggregates such as crushed brick results in similar properties as recycled aggregate derived from crushed concrete. One of the experiments even shows that concrete using crushed clinker brick as aggregate has a better tensile strength than that of conventional concrete (Khaloo 1994). Likewise, research studies have also proven that at least 30 % natural coarse aggregate can be replaced by recycled coarse aggregate without compromising the strength of the resulting concrete (Dhir et al. 1999).

Also, given the current specification in Hong Kong that 100% replacement of natural aggregates by recycled aggregates can only be used for Grade 20 or below concrete, which is probably based on the idea that most non-structural concrete would be Grade 20 or lower, there is a need to review whether a higher percentage replacement level is allowed for non-structural concrete application where the specified concrete strength grade is higher than C20 (e.g. C30 concrete is specified in Hong Kong for U channels, precast road kerbs and dividers). This can greatly increase the possible use of recycled aggregate in concrete without compromising the durability of the concrete produced.

On the basis of the discussion above, it is recommended that the recycled aggregate should be classified into three types as shown in Table 12 in Hong Kong. The first type (Type 1) consists of 100 % recycled coarse aggregate with a minimum dry density of 2000 kg/m^3. The second type (Type 2) consists of 30 % recycled coarse aggregate with a minimum dry density of 2000 kg/m^3. Finally, Type 3 consists of 20 % recycled coarse aggregate with a minimum dry density of 1700 kg/m^3. The corresponding concrete grades for Types 1, 2 and 3 recycled aggregate are <25, 45 and 35 MPa, respectively. The recommended classification of recycled aggregate not only can facilitate the use of recycled aggregate in various concreting projects in Hong Kong, it also can increase the use of other inert C&D waste such as clay brick or ceramic tile.

Table 12 – Recommended classification of recycled aggregate for concrete in Hong Kong

Requirement	**Type 1**	**Type 2**	**Type 3**
Min. dry particle density (kg/m^3)	2000	2000	1700
Max. water absorption	10	10	15
Max. content of wood and other material less dense than water	0.5 %	0.5 %	0.5 %
Max. content of other foreign materials (eg. Metals, plastics, asphalt, glass, tar. …)	1 %	1 %	1 %
Max. fines	4 %	4 %	4 %
Max. content of sand (< 4 mm)	5 %	5 %	5 %
Max. sulphate content	1 %	1 %	1 %
Flakiness index	40 %	40 %	40 %
10 % fines value	100 kN	100 kN	80 kN
Grading	BS 882:1992	BS 882:1992	BS 882:1992
Max. chloride content	BS 882 – 0.05 % by mass of chloride ion of combined aggregate	BS 882 – 0.05 % by mass of chloride ion of combined aggregate	BS 882 – 0.05 % by mass of chloride ion of combined aggregate

7. CONCLUSIONS

The reuse of recycled materials derived from construction and demolition waste is growing all over the world. Many governments have already implemented policies aiming at reducing the use of primary resources and increasing reuse and recycling. One of the ways of reducing the use of natural resources and meeting the challenges of sustainability in construction is the use of recycled aggregates derived from construction and demolition waste in new construction.

Research and experimental works on the use of recycled aggregate for different civil engineering applications have been conducted in many parts of the world and it is proven that concrete with acceptable quality could also be achieved with recycled aggregate. A number of countries have also modified their specifications to make provisions for the use of recycled aggregate in different construction works.

But there are still a lot of barriers limiting the use of recycled aggregates, particularly in concrete. To overcome these barriers, appropriate policy measures should be adopted by governments to promote the use of concrete products made with recycled aggregates particularly in government projects. It is also suggested that opportunities should be searched in the precast industry about the use of recycled aggregates as it is easier to ensure quality in the end products due to the presence of an existing quality assurance system. Such a scheme can be implemented first for the production of non-structural products such as partition walls, road dividers, bridge fencing, noise barriers, and paving blocks etc. as the use of which would receive less resistance from engineers who are still quite skeptical about the use of recycled materials in structural applications.

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