



# Estimation of building-related construction and demolition waste in Shanghai



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## ABSTRACT

One methodology is proposed to estimate the quantification and composition of building-related construction and demolition (C&D) waste in a fast developing region like Shanghai, PR China. The varieties of structure types and building waste intensities due to the requirement of progressive building design and structure codes in different decades are considered in this regional C&D waste estimation study. It is concluded that approximately 13.71 million tons of C&D waste was generated in 2012 in Shanghai, of which more than 80% of this C&D waste was concrete, bricks and blocks. Analysis from this study can be applied to facilitate C&D waste governors and researchers the duty of formulating precise policies and specifications. As a matter of fact, at least a half of the enormous amount of C&D waste could be recycled if implementing proper recycling technologies and measures. The appropriate managements would be economically and environmentally beneficial to Shanghai where the per capita per year output of C&D waste has been as high as 842 kg in 2010.

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## 1. Introduction

As the rapid development of building industry in PR China, huge quantities of construction and demolition (C&D) waste are generated. Along with a speedy increase of Gross Domestic Product (GDP), in the last decade, PR China has been the country with the largest production of C&D waste in the world (Xiao et al., 2012c). However, at present, most of the C&D waste is delivered to suburban or rural areas for simple disposal of landfill. Thus, C&D waste has become an important issue not only for its cost efficiency but also due to its adverse effect on the environment (Trankler et al., 1996). The large amount of C&D waste is a big challenge to the sustainable development of many large countries and regions, including PR China, and has already led to an increasing interest in recycling (Formoso et al., 2002; Tam and Tam, 2006; Xiao et al., 2012a).

In order to promote the sustainability of the building industry, plenty of regulations focusing on reducing or recycling the C&D waste have been carried out in many countries and regions such as the EU countries (Symonds Group Ltd., 1999), the US (USEPA, 2009) and Hong Kong (Hong Kong government, 2005). In recent years, intensive measures to encourage C&D waste reduction and recycling in PR China have also been put forward (China

government, 2005). However, reliable information on the expected quantities of the C&D waste accumulated is important in order to establish reasonable policies as well as to propose alternative solutions. Many organizations and researchers throughout the world have been aware of this issue and focused on the estimation of C&D waste accumulation.

In the US, Franklin Associates (1998) estimated the building-related C&D waste generated was 136 million tons in 1996 and USEPA (2009) concluded the total building-related C&D waste was almost 170 million tons in 2003, with 39% coming from residential and 61% from nonresidential sources. For regions like Florida, Cochran et al. (2007) estimated that approximately 3.75 million tons of building-related C&D waste were generated in 2000, and demonstrated that concrete was the major component of the waste, representing a 56%.

In Europe, Bossink and Brouwers (1996) firstly quantified the waste generation during several residential construction projects in the Netherlands. Researchers in other countries such as Greece (Fatta et al., 2003), Norway (Bergsdal et al., 2007), Portugal (Coelho and de Brito, 2011) and Spain (Solís-Guzmán et al., 2009; Sáez et al., 2012) also took effective efforts to determine C&D waste quantification due to the deficiency of reliable or official data from the local governments. Recently, Llatas (2011) and Mália et al. (2013) also carried out studies to propose C&D indicators to estimate the amount of C&D waste for the EU, since the EU legislation lacked tools to implement C&D waste prevention and recycling measures.

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In Asia, quantification of C&D waste was first noticed in Hong Kong where a series of investigations reported by Poon (1997), Poon et al. (2001, 2004) and Tam et al. (2007) assessed the C&D waste. Seo and Hwang (1999) estimated that the amount of C&D waste in Seoul, the capital city of South Korea, was about 8.63 million tons in the year 1999 and would follow an increasing trend in the later years. The statistics figures were also available in some other countries like Kuwait, Thailand and Israel (Kartam et al., 2004; Kofoworola and Gheewala, 2009; Katz and Baum, 2011). In the mainland of China, Lu et al. (2011) and Li et al. (2013) conducted significant studies separately in Shenzhen city, south part of China. Though the demolition waste was not taken into consideration, both of the investigations presented a waste generation index during construction activity, which was an important factor in calculating the amount of construction waste. The important information cited from the previous researches is summarized and listed in Table 1, which can be used to compare C&D waste generation in different countries or regions.

However, the consideration on C&D waste generation amount has been fairly neglected in Shanghai, a big city located in eastern part of PR China. In fact, as a result of past, undeveloped technology and economy, numerous residential or nonresidential buildings in Shanghai that were constructed around 20–30 years ago or before, cannot satisfy the requirements of aseismic performance and accommodate to the rapid urban development. Structure codes in PR China have also been updated several times in the past 30 years, and the demand of urban planning led to massive demolition of old houses, factories and even groups of new constructed buildings in Shanghai. Therefore, there is a pressing

need to understand the generation of both C&D waste in this fast developing region and some further work should be taken to obtain the accurate accumulation of C&D waste generated per year in Shanghai.

The primary purpose of this study is to provide a specific analysis for the quantification and composition of C&D waste in Shanghai, PR China. Some discussion about the waste index per capita per year and lessons for the recycling management in this region will also be offered and introduced. In fact, the proposed estimation methodology will also be practical to evaluate the accumulation of C&D waste for other regions with rapid development.

## 2. Methodology

### 2.1. Approach

Two main methodologies have been used to estimate building-related C&D waste generation in the recent years. One popular method at present is the materials flow (or materials balance) analyses. It calculates the amount of materials that come into service and predicts the amount of those materials come out of service, i.e., C&D waste. The USEPA adopted the materials flow method to characterize municipal solid waste in the US since the late 1960s (USEPA, 2006). Cochran and Townsend (2010) first took advantage of this approach for the C&D waste generation and composition estimation area for the US. For the materials flow analyses, the historical construction material production data of the country or region is needed and data sources inevitably play a significant

**Table 1**  
Previous studies on C&D waste generation in different countries and regions.

Country or region	Year	Types of buildings	Types of waste	C&D waste conclusions
US <sup>a</sup>	1996	Residential and nonresidential	Construction and demolition waste	136 million tons, with 43% coming from residential and 57% from nonresidential
US <sup>b</sup>	2003	Residential and nonresidential	Construction and demolition waste	170 million tons, with 39% coming from residential and 61% from nonresidential sources
Florida in US <sup>c</sup>	2000	Residential and nonresidential	Construction and demolition waste	3.75 million tons and concrete was the major component of the waste representing 56%
Netherlands <sup>d</sup>	1996	Residential	Construction waste	1–10% of the building materials delivered on site becomes waste, with an average of 9%
Greece <sup>e</sup>	2000	Residential and nonresidential	Construction and demolition waste	Exceed 3.9 million tons with about 656 kg per capita
Norway <sup>f</sup>	2002	Residential and nonresidential	Construction and demolition waste	1.256 million tons generated and the major is concrete and bricks, accounting for 67%
Portugal <sup>g</sup>	2008	Residential and nonresidential	Construction and demolition waste	186 kg/person/year, with commercial buildings account for 13% and public works around 15%
Spain <sup>h</sup>	2009	Residential and nonresidential	Construction and demolition waste	New construction: 0.3076 m <sup>3</sup> /m <sup>2</sup> demolition: 1.2676 m <sup>3</sup> /m <sup>2</sup>
Seoul in Korea <sup>i</sup>	1999	Residential and nonresidential	Construction and demolition waste	8.63 million tons in the year 1999 and following an increasing trend
Hong Kong <sup>j</sup>	1998	Residential and nonresidential	Construction and demolition waste	32 710 tons of C&D waste generated per day and waste concrete occupies the most
Shenzhen in Mainland China <sup>k</sup>	2009	Residential and nonresidential	Construction waste	Waste generation rates ranged from 3.275 to 8.791 kg/m <sup>2</sup> and miscellaneous waste, timber, and concrete were the three largest components
Shenzhen in Mainland China <sup>l</sup>	2009	Residential and nonresidential	Construction waste	Waste generation per gross floor area is 40.7 kg/m <sup>2</sup> , and concrete waste is the major contributor, accounting for 43.5%

<sup>a</sup> Franklin Associates (1998).

<sup>b</sup> US Environmental Protection Agency (USEPA) (2009).

<sup>c</sup> Cochran et al. (2007).

<sup>d</sup> Bossink and Brouwers (1996).

<sup>e</sup> Fatta et al. (2003).

<sup>f</sup> Bergsdal et al. (2007).

<sup>g</sup> Coelho and de Brito (2011).

<sup>h</sup> Solís-Guzmán et al. (2009).

<sup>i</sup> Seo and Hwang (1999).

<sup>j</sup> Poon et al. (2001).

<sup>k</sup> Lu et al. (2011).

<sup>l</sup> Li et al. (2013).

role in the accuracy of the results. Furthermore, the time span of the data for materials flow analyses should be longer than the service life time of buildings (usually 30–70 years), so that it can be utilized to estimate the amount of C&D waste. However, unlike the US, the data about construction material production in PR China from the governmental statistics can only be found since 1985 and the time span is shorter than the service time of most buildings. It is therefore very difficult to apply this approach in this study.

Another approach is similar to the waste weight per area method first reported by Yost and Halstead (1996). This method is described and given by Eq. (1) in a simple manner which is based on some measurements of the construction, or demolition activity level in a region (by area of the structure,  $m^2$ ) and the average waste generation per building area ( $\text{tons}/m^2$ ) to determine the waste generation.

$$W = CW + DW = CA \cdot G_c + DA \cdot G_d \quad (1)$$

where  $W$  is the total weight of building-related C&D waste generated during one year ( $\text{tons}/\text{year}$ ),  $CW$  and  $DW$  are the construction weight and demolition waste per year respectively, ( $\text{tons}/\text{year}$ );  $CA$  is the area of buildings constructed or innovated and  $DA$  is the area of buildings demolished per year ( $m^2/\text{year}$ );  $G_c$  and  $G_d$  are the average waste generation per building area during construction and demolition activity ( $\text{tons}/m^2$ ), respectively. This method has been utilized to estimate C&D wastes in the estimations performed by Franklin Associates (1998) and USEPA (2009) for the US, Seo and Hwang (1999) for Seoul, Cochran et al. (2007) for Florida, Coelho and de Brito (2011) for Portugal and so on. After comparing the two described methods, the basic ideology of Yost and Halstead (1996) method is adopted in this investigation to estimate the C&D waste in Shanghai, PR China.

The regional estimation approach adopted in this paper expands upon the common methodology (Yost and Halstead,

1996; Franklin Associates, 1998) by considering the varieties of structure types and building waste intensities due to the requirement of progressive building design and structure codes in different decades. It is well known that Shanghai has been undergoing a rapid development in the last half century, from 1970s to the present. The average waste generation per building area during construction or demolition activity ( $G_c$  and  $G_d$ ) has changed greatly due to the requirement of progressive building design and structure codes, on account of the development of economy and the improvement of construction technology. The methodology proposed in this study can well consider the regional varieties of structure types and building waste intensities in different decades. The methodological framework of the present study is illustrated in Fig. 1.

## 2.2. Demolition waste

In order to evaluate the accumulation of demolition waste with relative accuracy, the regional demolition waste  $DW$  ( $\text{tons}/\text{year}$ ) generation can be estimated using the analytical expressions in Eq. (2), which takes into account the residential or nonresidential buildings, various structure types and building waste intensities due to the requirement of progressive building design and structure codes. In this study, it is assumed that the waste induced by building demolition process is equal to the total amount of building materials consumed during its original construction process.

$$DW = DW_r + DW_{nr} \\ = DA_r \cdot \sum_k F_t \cdot F_{sr} \cdot G_{dr} + DA_{nr} \cdot \sum_k F_t \cdot F_{snr} \cdot G_{dnr} \quad (2)$$

where  $DW_r$  and  $DW_{nr}$  ( $\text{tons}/\text{year}$ ) are the amount of the demolition waste caused by regional residential and nonresidential demolition activity, respectively;  $DA_r$  and  $DA_{nr}$  ( $m^2/\text{year}$ ) are the demolished

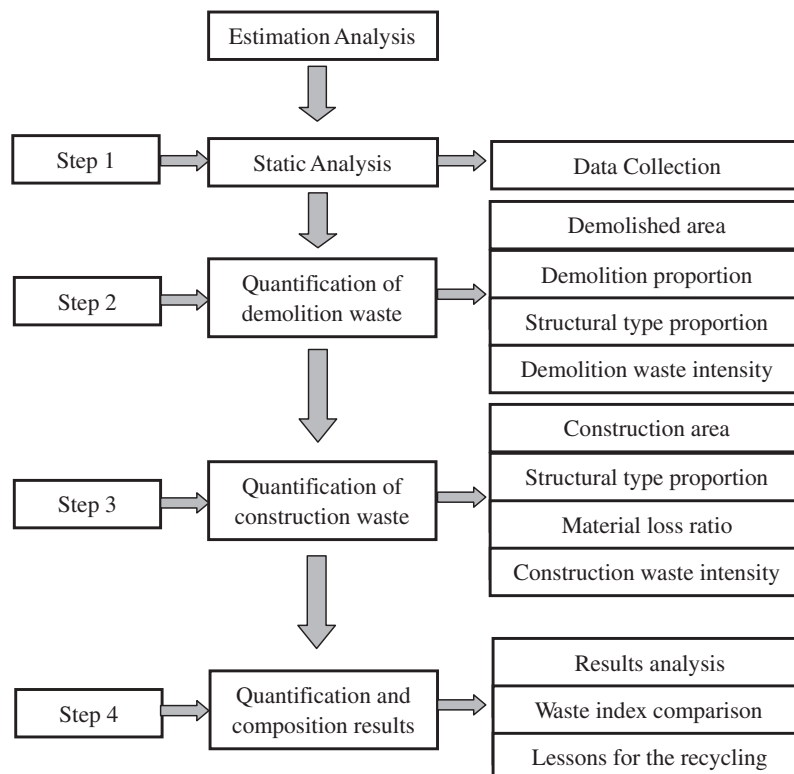


Fig. 1. Methodological framework.

floor area of residential and nonresidential buildings, respectively;  $F_t$  is a proportion value which means the percentage of demolished buildings that were constructed in different decades;  $F_{sr}$  and  $F_{snr}$  are the percentage of a structure type designed in a specific decade, and  $G_{dr}$  and  $G_{dnr}$  are the demolition waste intensity (tons/m<sup>2</sup>) for residential and nonresidential buildings, respectively, also in a specific decade. It must be emphasized that  $F_{sr}$ ,  $F_{snr}$ ,  $G_{dr}$  and  $G_{dnr}$  could be variable in different decades according to the progressive and different building design and structure codes, because of the rapid development in some regions, like Shanghai. However, the various structure types and waste intensities were not taken into account in the previous investigations. Eq. (2) presents the calculation for demolition waste, where  $k$  represents the number of waste materials that should be considered such as steel, concrete, brick or blocks, gypsum.

### 2.3. Construction waste

For the purpose of obtaining available data for the waste production on the construction site per year  $CW$  (tons/year), Eq. (3) presents the equation for predicting waste generation during the construction activities.

$$CW = CW_r + CW_{nr} = CA_r \cdot \sum_k F_{sr} \cdot G_{cr} + CA_{nr} \cdot \sum_k F_{snr} \cdot G_{cnr} \quad (3)$$

Similar to the demolition expressions stated above,  $CW_r$  and  $CW_{nr}$  (tons/year) represents the amount of the construction waste produced by regional residential and nonresidential construction or innovation activity, respectively;  $CA_r$  and  $CA_{nr}$  (m<sup>2</sup>/year) are respectively the construction floor areas of residential and nonresidential buildings including renovation construction activity;  $G_{cr}$  and  $G_{cnr}$  are the construction waste intensities (tons/m<sup>2</sup>) for

residential and nonresidential buildings, respectively. Likewise,  $F_{sr}$  and  $F_{snr}$  are the percentages of different structure types and  $k$  represents the number of waste materials should be regarded to.

## 3. Results and analysis

### 3.1. Data collected and result calculation

Once all of the values in Eqs. (2) and (3) are known, the accumulation of the whole C&D waste generated in the recent years can be calculated according to the sum of  $CW$  and  $DW$ .

For the demolition waste calculation of Shanghai, the data  $DA_r$  and  $DA_{nr}$  (m<sup>2</sup>/year) could be collected from Shanghai statistical yearbook (Shanghai Statistical Bureau, 2013). The data collected from Shanghai Housing Security and Management Bureau shown in Fig. 2 could be used as the average percentage of demolished buildings  $F_t$ . Fig. 2 reflects that most of the demolished buildings in Shanghai were constructed before 1980, while the building constructed between 1980 and 1990 also occupy a rather large portion.

According to Year book of Shanghai Construction (Shanghai Urban Construction and Communications Commission, 2008), the brick-wood structures, brick-concrete structures, reinforcement-concrete structures, steel-frame structures are the most common structure types built in Shanghai during the last half century. The average percentages for these structure types designed and constructed in different decades both for residential and nonresidential buildings, i.e., factors  $F_{sr}$  and  $F_{snr}$ , could be adapted from the Year Book of Shanghai Construction (Shanghai Urban Construction and Communications Commission, 2008). The data listed in Table 2 demonstrates that, for the residential buildings, before the year 2000, most of the structure types were brick-wood structures and brick-concrete structures; however, for the nonresidential buildings, concrete structure has been the major structure type since 1990.

The values used for  $G_{dr}$  and  $G_{dnr}$  (tons/m<sup>2</sup>) for either residential or nonresidential demolition components correspond to the average values and are presented in Table 3. These statistics for each kind of materials are determined from the Building Construction Handbook from the 1st edition to the 5th edition (1980; 1988; 1997; 2003; 2012). The serial handbooks have been published for more than 30 years and have owned a high credibility in PR China, indicating the construction level at any specific time. According to the two investigations by other two Chinese researchers (Lu et al., 2011; Li et al., 2013), the amount of mortar used in the building construction process, only occupies a very little proportion, about 2–4% in China. Furthermore, during the demolition process, the mortar is usually combined with or attached to the concrete and it is hard to separate them on-site. So in this study, the amount of mortar is considered within the amount of waste concrete. It can be inferred from Table 3 that the amount of construction materials used for each kind of structure type has changed during the last half century. Taking the steel consumed in residential brick-concrete buildings as an example, an average value of

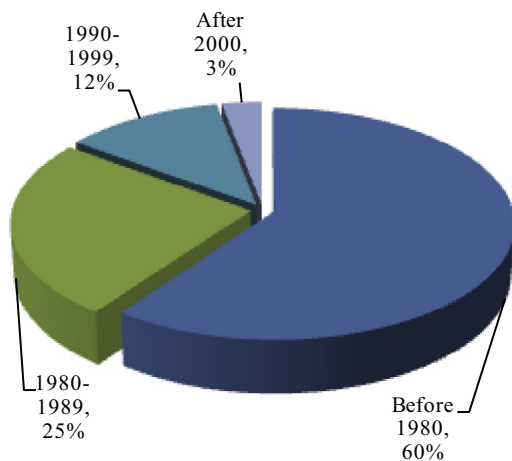


Fig. 2. Proportion of demolished buildings constructed in different decades.

Table 2  
Proportion of various structure types designed in different decades.

Structure type	Before 1980		1980–1989		1990–1999		After 2000	
	Residential	Non-residential	Residential	Non-residential	Residential	Non-residential	Residential	Non-residential
Brick-wood	56%	0%	0%	0%	0%	0%	0%	0%
Brick-concrete	44%	44%	98%	37%	92%	30%	7%	0%
Concrete	0%	56%	2%	60%	8%	60%	93%	80%
Steel-frame	0%	0%	0%	3%	0%	10%	0%	20%

Data source: Shanghai Urban Construction and Communications Commission (2008).

**Table 3**Average waste intensity of demolished buildings (Unit: kg/m<sup>2</sup>).

Structure type	Usage	Ages	Steel	Wood	Concrete	Brick or block	Gypsum
Brick-wood	Residential	Before 1980	1.9	35.0	–	771.3	43.8
Brick-concrete	Residential	Before 1980	9.0	28.1	439.2	676.4	47.5
		1980–1999	17.5	26.2	715.6	672.2	31.5
		After 2000	53.6	27.5	791.3	683.3	30.2
	Non residential	Before 1980	11.5	17.7	529.2	603.3	24.5
		1980–1999	28.0	23.6	875.6	631.9	21.0
Concrete	Residential	1980–1989	38.2	23.4	924.5	317.0	19.2
		1990–1999	39.0	21.6	1012.4	329.2	24.0
		After 2000	79.0	21.2	1115.5	342.7	18.3
	Non residential	Before 1980	32.3	20.7	591.7	403.7	16.8
		1980–1989	37.1	24.5	987.5	401.6	14.3
		1990–1999	41.0	22.4	1185.7	394.9	17.5
		After 2000	109.8	22.1	1252.4	382.1	16.2
Steel	Non residential	After 1990	196.7	32.4	1245.7	131.7	–

Data source: Building Construction Handbook-1st edition (1980), Building Construction Handbook-2nd edition (1988), Building Construction Handbook-3rd edition (1997), Building Construction Handbook-4th edition (2003).

**Table 4**

Data for variable used in Eq. (2) for demolition waste estimation in 2012.

$DW_r$	$F_t$		Before 1980	1980-1989	1990-1999	After 2000
			60%	25%	12%	3%
	$F_{sr}$	Brick-Wood	56%	0%	0%	0%
Brick-Concrete		44%	98%	92%	7%	
Concrete		0%	2%	8%	93%	
Steel-Frame		0%	0%	0%	0%	
$DW_{nr}$	$F_t$		Before 1980	1980-1989	1990-1999	After 2000
			60%	25%	12%	3%
	$F_{snr}$	Brick-Wood	0%	0%	0%	0%
		Brick-Concrete	44%	37%	30%	0%
		Concrete	56%	60%	60%	80%
		Steel-Frame	0%	3%	10%	20%

$0.90 \times 10^{-2}$  tons/m<sup>2</sup> was used before the year 1980, however, this data has been updated to  $5.36 \times 10^{-2}$  tons/m<sup>2</sup> after the year 2000.

Table 4 presents the demolition waste estimation process of Shanghai as an example. It summarizes the data for variable used in Eq. (2) which could be found in Fig. 2 and Table 2.

In the construction waste calculation case of Shanghai, the data from Shanghai statistical yearbook (Shanghai Statistical Bureau, 2013) can also be used to obtain the annual construction area including the renovation construction activity,  $CA_r$  and  $CA_{nr}$  (m<sup>2</sup>/year). The structure type percentages  $F_{sr}$  and  $F_{snr}$  have the same meaning as the demolition estimation stated above and have already been summarized in Table 2. As the construction waste quantification has only been measured during the years 2000–2012 in this investigation, no building age differentiation was considered. Due to the fact that the values in Table 3 were acquired based on the estimation of the total amount of building materials consumed in construction, the values used for  $G_{cr}$  and  $G_{cnr}$  (tons/m<sup>2</sup>) could be calculated according to Table 3 by inducing a material loss ratio, that is, as described in Eq. (4), the percentage of materials discarded or broken to the total input materials on-site.

$$\begin{aligned} G_{cr} &= \alpha \cdot G_{dr} \\ G_{cnr} &= \alpha \cdot G_{dnr} \end{aligned} \quad (4)$$

The material loss ratio  $\alpha$  which determined from the 5th edition (2012) of the Building Construction Handbook employed in this study is very close to the values proposed by Lu et al. (2011) and Li et al. (2013), whose investigations were mainly on the construction waste generation index in the city area of China. The compar-

isons between the material loss ratios are listed in Table 5. Table 6 also presents the construction waste estimation process of Shanghai as an example.

### 3.2. Quantification of C&D waste

Fig. 3 summarizes the estimation for building-related C&D waste generation from both the construction activity and demolition activity in Shanghai from 2000 to 2012. First of all, from the view of proportion for the construction waste and demolition waste separately, it is reflected that the percentage of demolition waste to the total C&D waste production was always larger than 50% during the period of 2000–2010, that is, the amount of demolition waste was larger than that of construction waste. Particularly, in the year 2006, the percentage of demolition waste to the total C&D waste production reached the maximum value 77%. However, since the year 2010, this trend changed conversely owing to the increase proportion of construction waste. The percentage of construction waste to the total C&D waste production arrived to 70% in 2012.

In fact, it is known that the World Expo was held in Shanghai 2010, and the huge quantities of demolition waste that were generated in Shanghai during that period. Due to the urban planning, thousands of building sites for the following years were required, such as the 5.28 square kilometer Expo site and the Hongqiao Comprehensive Transportation Hub. Meanwhile, with the booming real estate industry, a generous amount of old houses and factories in the city were demolished before 2007. Thus, the demolition waste in those years was increasing year by year. This phenomenon was very much alike to the waste stream generated in 2004 Olympic Games host city Athens, Greece (Fatta et al., 2003), also a fast developing city. Nevertheless, in such a continuously developing city, after 2008, no immense city expansion was expected in Shanghai as the development area of the city has almost reached its limits. The proportion of old buildings that did not meet with the current building codes was dropping and the area of the demolished buildings was also reducing. However, according to the government statistics, the construction activity still maintained a stable level in the recent years, leading to an increase of C&D waste proportion.

From the view point of total waste quantification, it is indicated from Fig. 3 that the C&D waste generation in Shanghai roughly increased from 2000 to 2006, and then decreased in the period from 2007 to 2012. Combined with above analysis on the proportion of construction and demolition waste, it can be found that the



**Table 5**

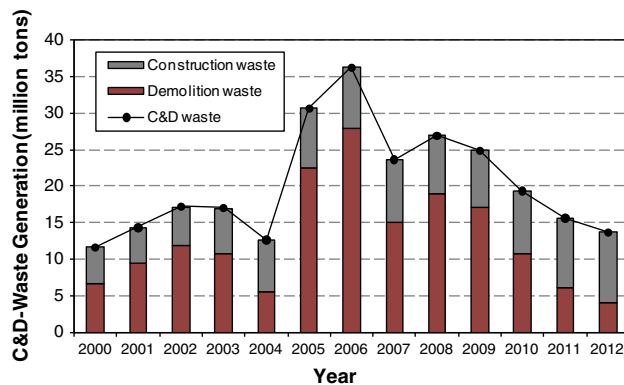
Average ratio of material loss in building construction on-site.

	Concrete (%)	Brick or block (%)	Steel (%)	Wood (%)	Gypsum (%)
Building Construction Handbook (2012)	1.5	5	3	5	2.5
Lu et al. (2011)	1.33	7	2.88	5	–
Li et al. (2013)	1	5	3	–	–

**Table 6**

Data for variable used in Eq. (3) for construction waste estimation in Shanghai.

		Brick–wood	Brick–concrete	Concrete	Steel-frame
$CW_r$	$F_{sr}$	0%	7%	93%	0%
$CW_{nr}$	$F_{snr}$	0%	0%	80%	20%

**Fig. 3.** C&D waste generated in Shanghai from 2000 to 2012.

generation amount trend of C&D waste was in substantial agreement with the production of demolition waste. This trend suggests that in a region with rapid development and urban planning, the total accumulation of C&D waste was much determined by the amount of the demolition waste. It was also demonstrated in Fig. 3 that the total C&D waste generated in Shanghai was 13.71 million tons in 2012, a minimum value in the last 5 years. However, compared with the C&D waste generation amount in Florida, US (Cochran et al., 2007), Seoul in South Korea (Seo and Hwang, 1999), Athens in Greece (Fatta et al., 2003), and Hong Kong (Poon et al., 2001), seen in Table 1, the amount of C&D waste produced in Shanghai per year was still relatively high.

### 3.3. Composition analysis

Since it may not be enough to know the quantification of C&D waste in global terms, another target of this study is to estimate the composition of C&D waste in Shanghai, which is useful for

the governments in formulating C&D waste recycling policies and predicting waste management cost.

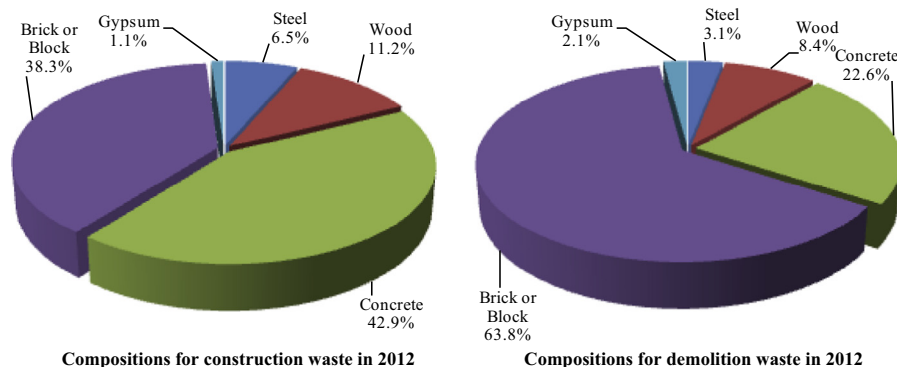
For simplicity's sake, without considering some miscellaneous waste, Fig. 4 presents the material compositions for construction waste and demolition waste in percentage of weight for Shanghai in 2012, determined by the methodology mentioned above. Percentages for the waste materials in other years are very close to the values in Fig. 4. The C&D waste compositions both largely contained concrete, bricks and blocks. The percentage of waste bricks and blocks in demolition waste was comparatively higher, and occupied a percentage of 63.8%. Waste concrete, as the second major C&D waste, shared 42.9% of the demolition waste and 22.6% of the construction waste. It is consistent with what was expected, as a large fraction of buildings in Shanghai constructed in 1980s or before was the brick–wood or brick–concrete structure type. Concrete structures have been the common structural type these days in Shanghai, so the construction waste is expected to contain a lower percentage of bricks and blocks in comparison to the demolition waste. However, it still must be admitted that no matter the construction waste or the demolition waste, concrete, bricks and blocks represented more than 80% of whole C&D waste.

Fig. 5 provides a breakdown, in percent of the whole, of the residential and nonresidential buildings that generate C&D waste. It is verified from Fig. 5 that before 2010, the C&D waste from residential sources was always larger than that of nonresidential. However, since 2011, the C&D waste produced from residential and nonresidential sources have been roughly identical. For example, in 2007, residential waste made up 75%, a maximum value in the recent decade. Whereas, in 2012, this value changed to 52%, which means the amount of residential and nonresidential waste was almost the same. The analysis results reflect that, since the 2010 Shanghai World Expo, the demolished residential buildings gradually decreased due to the new urban planning.

## 4. Discussion

### 4.1. Waste index comparisons

The C&D waste generation index is helpful to estimate the quantification for one specific region or country, and it could be quite different due to variation of construction materials

**Fig. 4.** Material compositions for C&D waste of Shanghai in 2012.

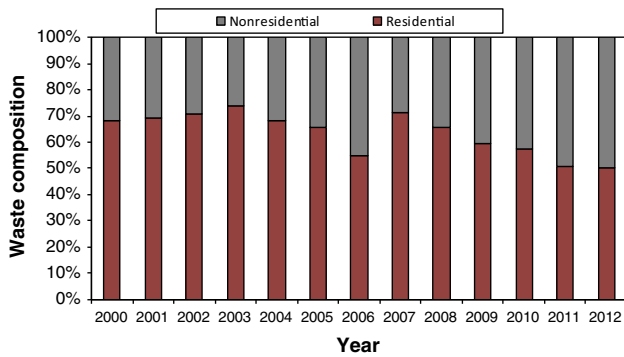


Fig. 5. Residential and nonresidential buildings waste in Shanghai.

production, building industry development level and build environment. According to the analysis presented in this paper, though with a relative high population density, building-related C&D waste generated in 2000 and 2010 was  $724 \text{ kg capita}^{-1} \text{ year}^{-1}$  and  $842 \text{ kg capita}^{-1} \text{ year}^{-1}$  in Shanghai, respectively. It is also noticed that several studies on C&D waste generation index have been proposed related to other countries around the world. The report by Symonds Group Ltd (1999), focusing on European countries, estimated that the average C&D waste generation index in EU was  $481 \text{ kg capita}^{-1} \text{ year}^{-1}$ . Germany was one of the leaders in terms of C&D waste generation, with  $720 \text{ kg capita}^{-1} \text{ year}^{-1}$ , representing 32.8% of the C&D total waste in the EU countries. In the US, the C&D waste generation index was  $530 \text{ kg capita}^{-1} \text{ year}^{-1}$  (USEPA, 2009). Other countries, like Australia and Japan, according to Coelho and de Brito (2011), were 400 and almost  $780 \text{ kg capita}^{-1} \text{ year}^{-1}$ . Fig. 6 presents a comparison on the C&D waste generation index for Shanghai and other countries or regions. Obviously, the data for Shanghai are consistently larger than the cited number for other countries or regions, even 8% higher than the maximum value of Japan in 2010.

One reason for the great per capita generation rate in Shanghai is the ongoing demolition boom, which resulted in the greater contribution to the C&D waste stream. In fact, demolition activities generate significantly larger amounts of waste per area than construction activities. The country like Germany, where as much as 68% of all C&D waste generation came from demolition activities (Bossink and Brouwers, 1996), also owned a large waste generation index. Another factor contributing to the relatively larger per capita construction waste generation for Shanghai compared to other countries or regions is the impact of regular structure type of brick-concrete structures or reinforcement-concrete frame structures. The average waste intensity for brick-concrete or reinforcement-concrete frame structures is much more than some other structure types such as wood-frame, which is rarely applied in this area.

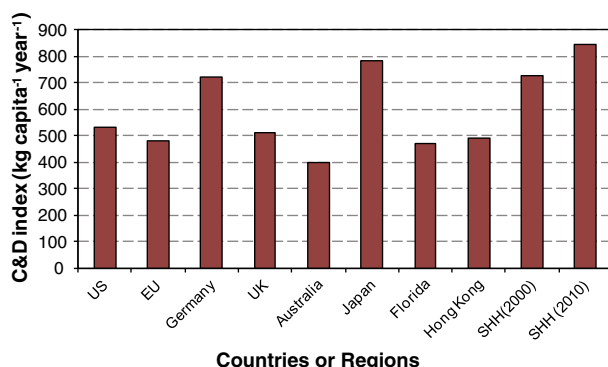


Fig. 6. C&D waste generation index throughout the world.

#### 4.2. Lessons learned for the recycling management

It has been confirmed from this study that a high level of C&D waste exists in Shanghai, PR China, although it is difficult to systematically measure all wastes. 13.71 million tons of C&D waste is a significant waste stream value, which proves that material waste generated in Shanghai is fairly high and much of this waste is predictable and recyclable. However, it is reported that only about 10% waste had been recycled and the remainder was disposed in landfills in this area. These enormous quantities of C&D waste, if recycled, would be economically and environmentally beneficial to this city.

The composition analysis indicates that approximately more than 80% of the building-related C&D waste is concrete, bricks and blocks, which can be reused if applying the current recycled technologies in China. For example, the techniques for recycling aggregates from waste concrete and bricks are well developed and the relevant applications in the mixing new concrete have proved its practicability (Xiao et al., 2012a). Two shake-table tests on recycled aggregate concrete frame and recycled concrete block masonry building in China demonstrated that it is feasible to apply and popularize recycled products in the practical engineering (Xiao et al. 2012b; Wang and Xiao, 2012).

However, the fact that some management measures have not been implemented indicates a lack of knowledge among contractors and construction managers about the performance of recycled products. Therefore, statistics from this study can be utilized to facilitate C&D waste governors and researchers in Shanghai in determining precise managements and specifications. It is also found that demolition waste represented a relatively large component of C&D waste. The total quantification of C&D waste decreased in Shanghai as the demolition activity was reducing in the recent years. Thus, policies and plans aiming at waste recycling from demolition sites could effectively solve large accumulation of C&D waste amount in this region.

Indeed, it must be admitted that dealing with C&D waste to protect the environment in Shanghai is one of the most difficult public problems. Current obstacles for recycling C&D waste include low disposal fees, high transportation costs and lack of confidence on the recycled products to the contractors. Whereas, based on analysis of this study, at least a half of the total accumulation of C&D waste, including the waste concrete, steel, part of the bricks and blocks, could be recycled and reused as new construction materials. Therefore, some relevant measures and regulatory support taken by the government may overcome the current obstacles and establish a recycling society later.

#### 5. Conclusion

With respect to C&D waste estimation becoming an important issue for most countries and regions, this study proposes a modified methodology for quantifying C&D waste generation for building-related C&D waste in Shanghai, PR China. The resulting C&D waste generation estimate was 13.71 million tons in 2012 with a decreasing trend. No matter the construction waste or the demolition waste, waste concrete, bricks and blocks represented more than 80% of the whole. It is found that the generation accumulation tendency of C&D waste was in substantial agreement with the production of demolition waste. Also, the amount of demolition waste was always larger than that of construction waste from 2000 to 2010. However, since the year 2010, this trend changed conversely owing to the increase proportion of construction waste, particularly, representing 70% in 2012.

The estimated C&D waste generation index for Shanghai is  $724 \text{ kg capita}^{-1} \text{ year}^{-1}$  in 2000 and  $842 \text{ kg capita}^{-1} \text{ year}^{-1}$  in

2010, respectively, which are consistently larger than most countries or regions according to the comparisons, even 8% higher than the maximum value of Japan in 2010. It is confirmed that at least a half of the total accumulation of C&D waste, such as the waste concrete, steel, part of the bricks and blocks, could be recycled and reused as new construction materials, which would be economically and environmentally beneficial to Shanghai. Actually, the statistics from this study can be used to facilitate C&D waste governors and researchers in determining precise managements and specifications in Shanghai.

This methodology for estimating building-related C&D waste generation and composition at a regional level considers varieties of structure types and building waste intensities due to the requirement of progressive building design and structure codes. What's more, the approach proposed can also be applied to other fast developing regions to estimate the quantification and composition of C&D waste if appropriately modified, and if the C&D activity data from authorities is not limited.

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