Chapter 2
Reclaim of Waste Concrete

Abstract In this chapter, the sources, quantity and classification of waste concrete are described and analyzed. The methods for reducing waste concrete are introduced. Furthermore, the reclaim of waste concrete, including reusing recycling philosophy and technology is described and discussed.

2.1 Introduction

As is described in Chap. 1, in recent years, due to the rapid urbanization and the urgent requirement of sustainable development, an increasing number of buildings and infrastructures have been demolished and produced a lot of construction and demolish (C and D) wastes. Besides, many earthquakes in China, such as Wenchuan earthquake (2008), Yushu earthquake (2010) and Ya'an earthquake (2013) have produced huge quantities of C and D wastes. Among these C and D wastes, about 30% is waste concrete. It is necessary to discuss the sources and quantity of waste concrete before researching on the reclamation of the waste concrete.

2.2 Source of Waste Concrete

2.2.1 General Sources—Pavement, Buildings, Bridges and Other Types of Constructions

Through the studies carried out in Shanghai and some other parts of China, it was discovered that waste concrete mainly comes from the following sources:

(1) Buildings which have achieved their service lives and been demolished were found to be the main source of concrete waste. In China, the design life of concrete structures generally ranges from 50 to 100 years. Therefore, the

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concrete buildings which were built before 1949 or during the 1950s have achieved or close reached their service life by now. It means that they are likely to be demolished in recent years. Meanwhile, new buildings will be built on the site of the demolished buildings. So in the next several decades, C and D wastes in China, especially waste concrete, will reach the peak. Table 2.1 shows the investigation results [1] of the current state of demolition waste concrete produced in China. It can be found that although the sources of building wastes are complex and the basic components are the same, mainly including soil, mortar, shattered and broken bricks, waste concrete, steel, other metals, asphalt, bamboo material, different types of packaging material waste and other types of waste, see Table 2.1 for clarity.

(2) Waste concrete produced as results of demolition due to eminent domain or municipal planning adjustment. With the rapid economic improvement as well as urbanization, this type of waste concrete is increasing.

(3) The site waste produced during the process of a new construction. Referreing to the definition of site waste by Ekanayake et al. [2], the site waste concrete can be defined as "the concrete which needed to be transported elsewhere from the construction site or used on the site itself other than the intended specific purpose of project due to damage, excess or non-use or which cannot be used due to non-compliance with the specifications, or which is a by-product of construction process." During construction, there is an amount of concrete that turns to waste such as remains of broken bricks, mortar or even fall outs during pouring concrete columns, beams and slabs, which cannot be avoided. Table 2.2 lists the construction sites of different structures and the waste [2] they produce. It can be seen that waste produced during construction is also large.

(4) The concrete components in commercial concrete plant and prefabrication plants which are not compliant with design standards or which do not meet their desired expectations are therefore culminate dumped. This amount of waste concrete accounts for 1–3% of annual waste concrete.

(5) The concrete used as specimens in scientific research by research organizations, inspection company, and universities. This amount of waste concrete is relatively small.

Table 2.1 Building waste produced from demolition of old buildings (Unit: m^3/m^2)

Structure	Steel	Concrete	Bricks	Non-metal materials	Glass	Wood	Total
Concrete structure	0.0132	0.6100	0.0723	0.0011	0.0008	0.03	0.7274
Steel structure	0.0210	0.2107	0.0585	0.0036	0.0009	0.03	0.3247
Masonry structure	0.0000	0.0000	0.4800	0.0002	0.0008	0.20	0.6810
Concrete masonry structure	0.0027	0.3200	0.4000	0.0002	0.0008	0.32	1.0437
Timber structure	0.0000	0.0000	0.0500	0.0002	0.0008	0.80	0.8510
Other structures	0.0074	0.2281	0.2122	0.0011	0.0008	0.276	0.7256

Table 2.2 Amount of building waste produced during construction

Types of waste	Building waste composition (%)			Percentage of materials (%)
	Brick concrete structure	Frame structure	Frame-load bearing structure	
Broken bricks	30–50	15–30	10–20	3–12
Mortar	8–15	10–20	10–20	5–10
Concrete	8–15	15–30	15–35	1–4
Pile-head	–	8–15	8–20	5–15
Steel	1–5	2–8	2–8	2–8
Wood	1–5	1–5	1–5	5–10
Other	10–20	10–20	10–20	–
Total	100	100	100	–
Production unit area (kg/m^2)	50–200	45–150	40–150	–

2.2.2 *Disasters*

Both natural and man-made disasters, such as earthquakes, avalanche, flood and war, can generate a huge amount of waste concrete. Take earthquakes for an example, reports from newspapers and internets reported that a great amount of building waste is often generated when a strong earthquake happens. The building waste occupied much space and proper treatment of the large quantities of the waste become an enormous task for government in the earthquake-hit area.

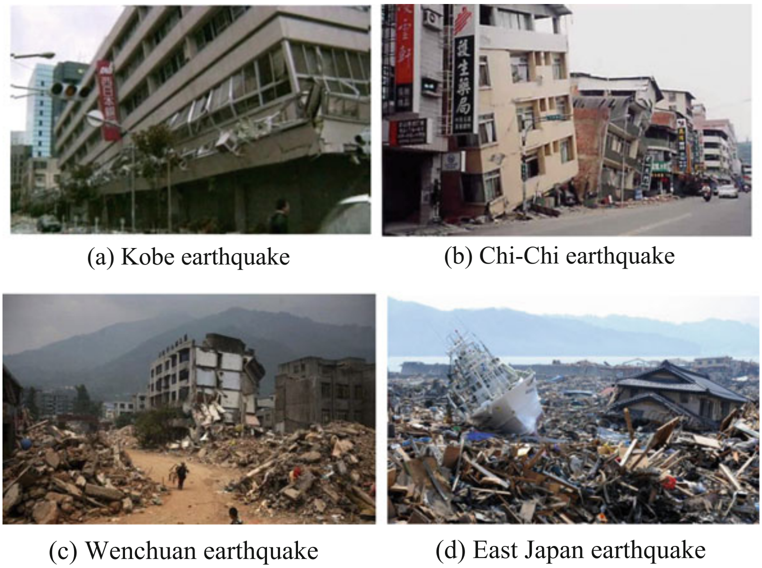
(1) On January 17, 1995, the Hyogoken-Nambu earthquake (Fig. 2.1a) resulted in devastating damages to the highly developed urbanized region of Kansai, Japan, and created a total of 2000 million tonnes of debris [3]. Debris clearance in the next two years became an urgent and difficult emergency management issue for the disaster management entities in Kobe city and Hyogo Prefecture/County. The debris clearance included the demolition and operation phase, transportation, crushing and separation at a temporary storage location and then disposal at final landfill site phases. In practice, most of the debris was either disposed off at landfill sites or reused as materials for reconstruction.

(2) On September 21, 1999, more than 20 million cubic meters of demolition waste were created as a result of the devastating Chi-Chi earthquake (Fig. 2.1b) in Taiwan, China [4]. It was found out from investigations that about 70–90% of the demolition waste was concrete, brick and fines, all of which could be reclaimed and recycled. Due to their typical characteristics of building materials, they were suitable for use as substitute materials for construction aggregates, and the possible applications included land backfill, roadway subgrade materials, pavement structures, embankments, revetments, and concrete bricks or blocks.

(3) On May 12, 2008, the Wenchuan earthquake or the Great Sichuan Earthquake (Fig. 2.1c) hit Sichuan province of China at CST time 14:28, which was a disastrous earthquake measuring 8.0 on the surface wave magnitude scale

and 7.9 on the moment magnitude scale [5]. It was proved by the latest official statistics [6] that the direct economic loss caused by the Wenchuan earthquake had reached as much as 845.1 billion ¥. Of this total, the loss of buildings were the largest and nearly accounted for half the losses. In detail, the loss of residential buildings and non-residential buildings (schools, hospitals and others) was 27.4% and 20.4% of the total loss, respectively. Besides, according to the disaster area statistics [7], 6,945,000 rooms collapsed and 5,932,500 rooms were serious destroyed after the Wenchuan earthquake. Thus a huge amount of building waste had certainly been generated by these collapsed houses and dilapidated buildings. For the post-earthquake reconstruction, the building waste not just burdens but also reduces resources which ought to be considered to be reclaimed. Therefore, special attentions should be paid to the problem of how to assess the total amount of building waste scientifically and accurately, and how to collect statistics of building waste amount to lead a better reclaiming of building waste. A detailed analysis on building waste is helpful for the strategic treatment and resource recovery of building waste in the post-earthquake reconstruction activities. (* ¥ = Chinese Yuan)

(4) On March 11, 2011, the Great East Japan Earthquake (Fig. 2.1d) hit the northeast part of Japan with a magnitude of 9.0 on the Richter scale, which was one of the largest ocean-trench earthquakes ever recorded in Japan. The earthquake caused huge damage, including 15,492 dead and 628,377 destroyed houses [8]. Furthermore, about 22.5 million tonnes debris, such as pieces of



(a) Kobe earthquake (b) Chi-Chi earthquake

(c) Wenchuan earthquake (d) East Japan earthquake

Fig. 2.1 Building waste caused by earthquakes lumber, steel and concrete, needed to be incinerated, reclaimed and recycled, which have to overwhelm the capacity of existing facilities and have a negative influence on other emergency response and recovery activities [9].

2.3 Quantity of Waste Concrete

2.3.1 Quantity in China

2.3.1.1 Damage of Buildings for Different Types of Structures in Disaster Area

The amount of building waste caused by an earthquake is quite difficult to predict precisely since the damage extent and characteristics are indefinable in the whole disaster area due to the diverse structural types, design method, construction management and local site characteristics. Thanks to statistics, damage of buildings can be estimated considering different structural forms, the difference between urban and rural buildings and different economic levels if the earthquake hits the area. Tsinghua University et al. [10] have done some investigations on the damaged buildings in the disaster area in Wenchuan earthquake and have got the relevant statistics (see Table 2.3). The statistics are targeted at the damage extent of 380 buildings (with different structural types) in the main disaster areas. As shown in Table 2.3, the damage of steel structures and concrete structures are relatively slight compared with masonry structure and masonry-frame structure. Therefore, it is inferred that the masonry structures, concrete frame structure and their hybrid structure were the main sources of building waste in the Wenchuan earthquake-hit disaster area.

Referring to the "Evaluation standard for seismic damage of buildings" [11] formulated by the Ministry of Construction of China, the damage extent of buildings is classified into 5 classes, i.e., nearly undamaged, slightly damaged, moderately destroyed, seriously destroyed, and collapsed. In practice, nearly

Table 2.3 Statistics on damage of buildings (CSGTU et al. 2008) [10]

Structure type	Usable	Usable after retrofit	Disused	Immediately demolish	Total
Masonry structure	42	74	33	52	211
Masonry-frame structure	20	9	4	9	42
Concrete frame structure	66	40	8	9	106
Concrete frame-shear wall structure	5	2	0	0	7
Steel structure	4	3	0	0	7

Table 2.4 Statistics on building damage of different structures

Structure (*i*)	The number of seriously destroyed buildings			
	Sample survey		Estimated total number	
	Disused	Immediately demolish	Disused	Immediately demolish
Masonry structure	33 (28.7%)	52 (45.2%)	1,702,628	2,681,490
Masonry-frame structure	4 (3.5%)	9 (7.8%)	207,637	462,735
Concrete frame structure	8 (7%)	9 (7.8%)	415,275	462,735
Total	45 (39.2%)	70 (60.8%)	2,325,540	3,606,960

undamaged or slightly damaged buildings are treated as the buildings which can still be inhabited [12], while moderately destroyed buildings are considered as the buildings which can be used after retrofit, and seriously destroyed or collapsed buildings are forbidden for further use or human inhabitation. Correspondingly, to satisfy the relevant requirements, the buildings in disaster areas are classified into 4 grades according to the damage severities of the structures through post-earthquake safety inspections, as shown in Table 2.4. These 4 grades are "usable," "usable after retrofit," "disused (demolished during the reconstruction)," and "immediately demolish." The buildings that are named as "disused" or "immediately demolish" should be classified as seriously destroyed buildings. According to this classification, the slightly damaged buildings can still be inhabited, and the moderately destroyed buildings can also be inhabited after repairing or strengthening; thus, it is generally assumed that both of them have generated little building waste.

It is mentioned above that there were 5,932,500 rooms seriously destroyed after the Wenchuan earthquake in the disaster area. The total number of seriously destroyed buildings with different types of structures may be estimated with the proportion in sample survey, as listed in Table 2.4. In addition, as mentioned before, the seriously destroyed buildings generated a large amount of building waste.

2.3.1.2 Characteristics of Building Waste for Different Types of Structures

Building waste generation in the disaster area is closely related to the seismic-resistance performance of structures; thus, the relationship between the structural type and the building waste generation should be established before the statistical analysis of the building waste.

Building collapse during the Wenchuan earthquake mainly occurred in the rural area. According to incomplete statistics data [13] (Shi et al. 2008) more than 100 million square meters of dwelling houses collapsed in the rural areas. According to the statistics by National Bureau of Statistics of the People's Republic of China, masonry and wood structures accounted for 53.8% of houses in rural areas in 2010. In consideration of the relative lagging economic development level of rural areas, with the advantage of low cost and convenience to construct, the weak seismic-resistance performance is usually ignored. It was surveyed [14] (Chen et al. 2008) that only 15% of rural dwelling houses in the Wenchan earthquake-hit disaster area were set up with ring beams and tie columns, while more than 90% of floors/roofs in masonry structures were made with precast slabs. As a result, the masonry houses with weak seismic-resistance performance were seriously damaged by strong earthquake, and then generated a mass of building waste.

In general, the concrete frame structure has a good seismic-resistance performance. However, in meizoseismal areas, there were still many concrete frame structures were seriously destroyed or even collapsed. On the one hand, it was owing to that the actual seismic intensity of Wenchuan earthquake was much higher than the local fortification intensity; on the other hand, it was found by investigation that the many structural elements of collapsed buildings could hardly meet the requirements of Chinese seismic design codes and specifications, and there were also defects concerning site construction details. Besides, to the concrete frame structures, though the major structures were just slightly damaged, the accessory structures, such as filled walls, of some buildings were seriously destroyed. Hence, although the moderately destroyed concrete frame structures could be inhabited after repairing or strengthening, it should not be neglected that still much building waste was produced by the seriously destroyed accessory structures.

There were many masonry-reinforced concrete hybrid structures, usually concrete frame for lower story and masonry structure for higher story, or concrete frame on the inner side and masonry stucture on the outside in both urban and rural areas. Because of the different composites, this kind of structures has quite different seismic behavior during earthquakes. It is necessary to conduct further research on building waste generated by this type of structures.

Both concrete frame-shear wall structures and steel structures showed better seismic-resistance performance during the Wenchuan earthquake [6]. Referring to Table 2.3, it is safe to draw a conclusion that the building waste produced by concrete frame-shear wall structures and steel structures need not be taken into account. So, during the following statistical calculations on building waste, much attentions have been paid to the masonry structures, concrete frame structures, hybrid structures and then the total amount of building waste in the disaster area can, therefore be estimated.

2.3.1.3 Statistics of Building Waste Generated by Different Types of Structures

The amount (by volume) of building waste per square meter from demolished buildings with different types of structures is available and listed in Table 2.5 [1]. As mentioned above, most of the building waste in the earthquake-hit disaster area was generated by seriously destroyed buildings, which including disused case, immediately demolish and collapsed buildings, therefore the amount of building wastes which has been generated and will be generated from seriously destroyed or collapsed buildings in the earthquake-hit disaster area can be estimated according to the statistics in Table 2.5.

According to Table 2.5, the amount (by volume) of demolition waste per unit area generated by different materials and from different types of structures could be estimated. Thus the total amount (by mass) of building waste per unit area from different types of structures is obtained and is listed in Table 2.6.

Table 2.7 is extracted from Table 2.4, containing the information of damage status of buildings in the earthquake-hit disaster area.

Table 2.5 The experienced amount of demolition waste in old buildings (Unit: m^3/m^2)

Structures (*i*)	Materials (*x*)						
	Steel	Concrete	Brick	Non-metallic material	Glass	Wood	Total
Masonry structure	0.0027	0.3200	0.4000	0.0002	0.0008	0.10	1.0117
Masonry-frame structure	0.0054	0.39	0.328	0.0004	0.0008	0.10	1.064
Concrete frame structure	0.0132	0.6100	0.0723	0.0011	0.0008	0.03	0.7274
Apparent density ρ_x (1000 kg/m^3)	7.8	2.2	1.7	1.5	2.7	0.54	–

Table 2.6 The mass of building waste per m^2 generated by demolished buildings (Unit: 1000 kg/m^2)

Structures (*i*)	Materials (*x*)					
	Concrete	Brick	Steel	Wood	The rest	Total
Masonry structure	0.704	0.680	0.021	0.054	0.002	1.461
Masonry-frame structure	0.858	0.558	0.042	0.054	0.003	1.515
Concrete frame structure	1.342	0.123	0.088	0.016	0.004	1.573

Table 2.7 Statistics on buildings under different damage status (Unit: 1000 kg)

Structures (*i*)	Collapsed	Immediately demolished	Disused
Masonry structure	5167.080	268.1490	1702.628
Masonry-frame structure	888.960	462.735	207.637
Concrete frame structure	888.960	462.735	415.275
Total	6945.000	3606.960	2325.540

2.3.2 Future Tendency Forecast

2.3.2.1 Estimation Formula

The amount of building waste can be calculated according to the following equations:

$$W_{ix} = S_i \times \rho_x \times d_{ix} = S_i \times m_{ix} \quad (2.1)$$

$$W_x = \sum_{i=1}^{n} W_{ix}, \quad W_i = \sum_{x=1}^{k} W_{ix} \quad (2.2)$$

$$W = \sum_{x=1}^{k} W_x, \quad W = \sum_{i=1}^{n} W_i \quad (2.3)$$

In Eqs. (2.1)–(2.3), n indicates the number of the structure types, and k indicates the number of building material types. W_{ix} is the total amount of x-type building waste generated in the i-type structures in the earthquake-hit disaster area. S_i is the total building area of i-type structures where the building area of each room in the investigated area was supposed to be 20 m^2. ρ_x is the apparent density of x-type building waste, whereas d_{ix} means the volume of the x-type building waste per m^2 generated by i-type structure. W_x is the total volume of x-type building waste produced; $W_{i.}$ is the total amount of building waste from the i-type structures; and W is the whole volume of building waste generated in the earthquake-hit disaster area.

Based on Tables 2.6, 2.7 and Eqs. (2.1)–(2.3), the mass of building waste in the Wenchuan earthquake-hit disaster area is calculated and listed in Table 2.8. According to the calculations, the total amount of building waste generated in the disaster area is approximately 380 million tonnes.

2.3.2.2 Relationship Between Building Waste and Seismic Intensity

As it can be discovered from the Wenchuan earthquake, building waste in geographical regions is closely related to the local seismic intensity. Figure 2.2 shows that, with higher seismic intensity, buildings would be damaged more seriously and generate more building waste. The study of the relationship among building waste, damage status and seismic intensity will contribute a lot for quick responses when any earthquake occurs and give an important guidance for both emergency rescue and reconstruction activities.

In order to investigate the relationship, some data were collected and sorted out, as shown in Fig. 2.3. All the investigated regions considered the same fortification intensity of 7.0 against the earthquake happened in Wenchuan. The buildings for

Table 2.8 Statistical overview of building waste in the disaster area (Unit: 10^4 tonnes)

Structures (i)	Damage status	Materials (x)					
		Concrete	Brick	Steel	Wood	The rest	Total
Masonry structure	Collapsed	7275.2	7027.2	217	558	20.7	15098.1
	Immediately demolished	3775.5	3646.8	112.6	289.6	10.7	7835.2
	Disused	2397.3	2315.6	71.5	183.9	6.8	4975.1
	Total W_{1x}	13,448	12989.6	401.1	1031.5	38.2	27908.4
Masonry-frame structure	Collapsed	1525.5	992.1	74.7	96	5.3	2693.6
	Immediately demolished	794.1	516.4	38.9	50	2.8	1402.2
	Disused	356.3	231.7	17.4	22.4	1.2	629
	Total W_{2x}	2675.9	1740.2	131	168.4	9.3	4724.8
Concrete frame structure	Collapsed	2386	218.7	156.5	28.4	7.1	2796.7
	Immediately demolished	1161.5	106.5	76.2	13.8	3.5	1361.5
	Disused	1141.6	102.2	73.1	13.3	3.3	1333.5
	Total W_{3x}	4689.1	427.4	305.8	55.5	13.9	5491.7
Total	Collapsed	11186.7	8238	448.2	682.4	33.1	20588.4
	Immediately demolished	5731.1	4269.7	227.7	353.4	17	10598.9
	Disused	3895.2	2649.5	162	219.6	11.3	6937.6
	Total W_x	20,813	15157.2	837.9	1255.4	61.4	38124.9

(a) The collapsed buildings (b) Waste concrete and bricks

Fig. 2.2 A view of building waste in Hanwang town

the statistics, basically meet the requirements of the fortification standards, so that the relationship between the seismic intensity and the percentage of building waste can be studied directly. The damage due to aftershocks was not considered in this investigation.

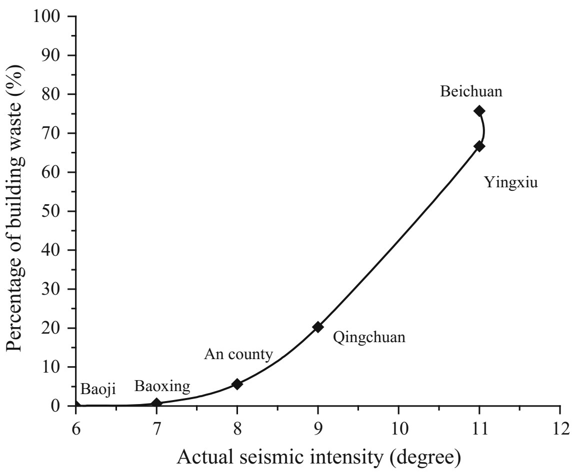


Fig. 2.3 Percentage of building waste versus the actual seismic intensity

Figure 2.3 reveals that, from moderate seismic areas to strong seismic behavior areas, the percentage of the building waste increases with the increase of the seismic intensity, and the curve of increase trend is nonlinear. Specifically, for Baoji and Baoxing where the actual seismic intensity was 6.0 and 7.0, respectively, the earthquake was of a medium intensity, and just few buildings collapsed in both the areas. However, for areas with an intensity over 8.0, as the actual seismic intensity increases, the percentage of building waste increases very quickly. In addition, most serious damages happened in Yingxiu town and Beichuan County in strong seismic behavior areas, yet still some buildings did not collapse and were only slightly damaged. This was due to relatively good construction sites on one hand and strong seismic/anti-earthquake capability of the structures adopted for some new buildings with high quality construction on the other hand.

Beichuan County had the earthquake with same seismic intensity as Yingxiu town. But in fact, the damage of buildings was more severe. This was mainly because Beichuan County is situated on soft subgrade foundation soils with bad construction sites and poor geological conditions, where foundation failure aggravated the damage of buildings. Geological hazards after the earthquake including landslides, rockslides and mudflows doubtless worsen the grave/terrible situation.

2.4 Classification of Waste Concrete

2.4.1 Standard

As mentioned above, with so much building waste being generated annually, its environmental and economic impacts cannot be ignored. Waste concrete accounts for a large mass of building waste. Therefore, the need of recycling waste concrete is urgent.

The waste concrete can be classified into two categories, considering the economic efficiency, and the mechanical properties of recycled aggregates (RA). One category is the recyclable waste concrete, and the other is non-recyclable waste concrete. Part of waste concrete, whose properties are poor or which are contaminated and can influence the properties of new in-production recycled aggregate concrete (RAC), should not be reclaimed or should be used in other ways. Whether waste concrete can be recycled or not, it basically depends on its source, environmental conditions during service life of structure, exposed conditions and carbonation levels. It is advised not to recycle waste concrete under the following conditions.

(1) Waste concrete from lightweight concrete or aerated concrete.
(2) Waste concrete from erosion environment condition or contaminated environment condition such as chemical engineering plants, nuclear power plants, hospital X-ray room etc.
(3) Waste concrete which showed durability failure.
(4) Waste concrete which has been polluted by heavy metals or organic content.
(5) Waste concrete with alkali-aggregate reaction.
(6) Waste concrete which contains fraction of wood, sludge, asphalt etc. that are difficult to separate.

Since the mechanical properties of recycled coarse aggregate (RCA) are significantly influenced by the factors such as designed strength grade and environmental conditions of parent concrete so, waste concrete should be stacked apart.

2.4.2 Classification

2.4.2.1 Building Waste Classification by Chronological Order/Damage Status of Buildings

To make a better program of the treatment of building waste in the earthquake-hit disaster area, and to provide a reference for formulating the corresponding policies, in this book, the building waste is divided according to the order in which it was generated. Then from the viewpoint of different damage status of buildings, the relevant statistics data on building waste are conducted, as shown in Fig. 2.4.

2.4.2.2 Building Waste Classified by Materials

Referring to Table 2.8 and Fig. 2.5 shows the statistics on the amount of building waste classified by building materials. As described in Fig. 2.5, most of the

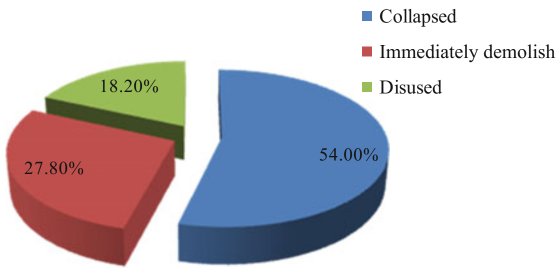


Fig. 2.4 Statistics on the amount of building waste (classified by damage status of buildings)

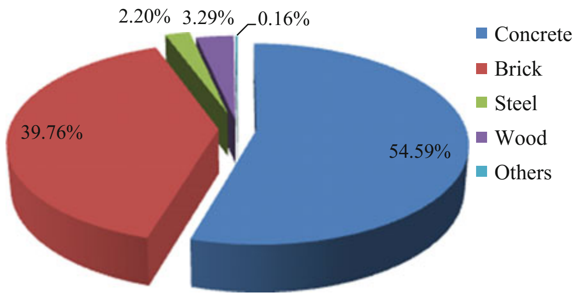


Fig. 2.5 Statistics on the amount of building waste (classified by building materials)

building waste is concrete and bricks, together with a little amount of steel and wood, all of them can be recycled. Considering the fact that the disaster area is faced with many challenges such as shortage of resources after the earthquake, it is quite important to get information on the amount and types of the building waste as well as the corresponding reclaiming methods.

2.4.2.3 Building Waste Classified by Structure Types

To explore the relationship between the building waste and the structure type, the data for the building waste generated from 3 main types of structures were extracted from Table 2.8. Meanwhile, the proportions of building waste generated from different types of structures are also displayed in Fig. 2.6.

It can be seen from Fig. 2.6 that there is a noticeable difference in the amount of building waste from these 3 types of structures. Most of the building waste had been generated from the masonry structures. In contrast, the other two types of structures brought a relatively small amount of building waste. This is due to many reasons, including large quantity masonry structures were constructed in the disaster area (especially in the rural area); the seismic performance of masonry structures was relatively low; and many masonry structures in the disaster area did not meet the fortification requirements against earthquakes. All of these factors led masonry structures to be seriously destroyed or collapsed after this strong disastrous

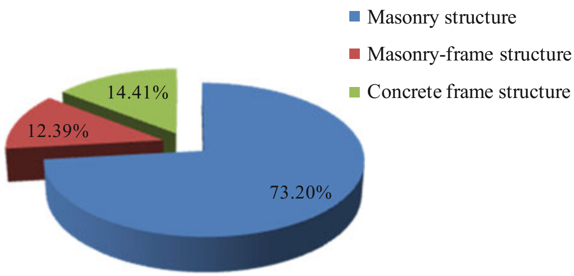


Fig. 2.6 Statistics on the amount of building waste (classified by structure types)

earthquake, which in turn led to the massive production of building waste. Although most of the building waste in the disaster area can be reclaimed, it still would consume tremendous manpower and resources and delay the reconstruction speed. Besides, it would be helpful for reducing casualties and minimizing building waste to lessen the damage of buildings. For this reason, it will be of a far-reaching significance to take correct seismic structural measures and good structure types in the future reconstruction.

2.5 Reduce Principle and Methods

In coming decades, the ratio of urbanization will be constantly increase in China and most developing countries in the world. In order to meet the requirement of dwelling and working of new citizens, meanwhile, to promote the living condition of original citizens, an enormous amount of new buildings will be constructed, accompanying with many buildings will be deconstructed. In this process, as is mentioned above, wealth will be wasted, resources will be consumed, and social problems will emerge.

In the past, structure design is mainly focused on the reliability of buildings, particularly safety, serviceability and durability. In future, sustainability must be considered as a new direction in design process. Thus, the “3R” principle, which means Reduce, Reuse and Recycle, is proposed to guide the sustainable development of building industry.

2.5.1 Reasonable Plan

From the point view of life-cycle analysis, a life of the building is emphasized as one of the most important factors. It is reported that the average life of buildings in China is only 30 years, which is much lower than that of some developed countries, like UK for 132 years, and that of designed life, which is usually 50 or 100 years. And, even more alarmingly, some buildings were demolished even before they were completed. For instance, in 2005, planning department of Hefei decided to demolish a new-built high-rise apartment building when it was constructed to 17th story for pavement reconstruction. Most of demolished buildings were not because these buildings reached their design lives or severely damaged, but because disorganized plan before construction. Thus, it can be found that reasonable design is an effective way to extend the buildings' life span and reduce building wastes disposal.

2.5.2 Elaborate Design

Improving the structural performance is one way to expand the lifespan of buildings, and thus, reducing material and energy consumption during construction and demolishment.

As mentioned above, buildings and structures devastated by disasters like earthquake, fire and other are the major sources of building waste, especially earthquake. Thus improving the disaster resistance can be considered as an effective way to reduce the production of waste concrete. As is widely accepted that pre-disaster prevention is not only more humane, but also more economical. For instance, Wenchuan Earthquake killed 69,227 persons, and the direct economic loss reached as much as 845.1 billion ¥ [6]. It has been proved that the damages of buildings designed according to the code of seismic design assuring the earthquake resistance are limited to a small extent [6] and produced less building waste [7].

Structure design has been paid more attention compared to associated system design. However, associated system overhauling, such as waterproofing, appearance of building and pipelines, produced a large amount of building wastes, which is usually been ignored.

Construction materials such as stone and concrete are subjected to the weathering agencies including several physical, chemical and biological factors. Progressive dissolution of the mineral matrix as a consequence of weathering leads to the decrease in mechanical properties. Durability is the performance to resist this decrease in the mechanical property. For reinforcement concrete structures, common durability problems include permeability, freezing and thawing, alkali-aggregate reaction, carbonation, chemical erosion and reinforcement corrosion. Some principles to improve durability include reasonable mix proportion design, declining porosity, assuring the concrete cover thickness, limiting the volume of harmful components and using high-performance concrete (HPC) and mineral admixture.

Sustainability assessment of products or technologies is normally seen as encompassing impacts in three dimensions—the social, the environmental and the economic [15]. Life cycle assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e., from raw material acquisition to product via various phases in production till waste management [16]. The methodological development in LCA has been strong, and LCA is broadly applied in practice. This method is still under development, however. In the future, this method must play a more significant role in the process of optimizing project determination considering environmental impact and waste management.

2.5.3 Ecological Materials

Ecology is nowadays an everyday topic. But what are the characteristics that an ecological building material should have? Bica et al. [17] concluded and described as follows:

- They should be healthy for users; natural materials should be considered.
- They should not consume energy for transportation, thus avoiding collateral pollution; local materials should be considered.
- They should not consume a great quantity of energy for fabrication; again, natural materials should be considered.
- High insulation qualities are necessary, in order to avoid excessive energy consumption; natural materials rarely respond to these requirements without exaggerating their thickness.
- Eventually, the new materials and techniques should have beneficial effects on the environment; vegetation in buildings should be considered.
- They should be recyclable.
- They should be reusable at least once, or even several times.
- They should reuse residues; the reuse of non-ecological materials can be an ecological undertaking.

And Bica et al. [17] also give some examples, including earth, green roofs, living walls and earthbag constructions, as shown in Fig. 2.7.

It is generally agreed that the production of concrete has adverse ecological effects. CO_2, NO_x and SO_x are among the hazardous emissions generated in relatively high volumes by the conventional Portland cement process. However, applying HPC, consuming industrial by-product and recycling aggregates make concrete gradually meet the requirement of ecology. Meanwhile, the appearance of novel cement, such as high belite cement [18, 19], decreases the energy consumption during manufacturing.

2.5.4 Green Construction

Construction is one of the major contributors to environmental problems. Bossink and Brouwers [20] reported that from 1 to 10% of every single purchased construction material leaves the construction site as solid waste. Most of the resources consumed in construction sites are non-renewable, and some may even create

(a) A partial earth shelter
(b) A spectacular green roof
(c) Living wall as an artistic gesture
(d) Bottles for an earthship wall

Fig. 2.7 Structures using ecological materials [17]

adverse environmental effects during their manufacture [20]. Some environmental assessment tools, such as Environmental Assessment (EA) [21], Building Research Establishment Environmental Assessment Method (BREEAM) [22], Leadership in Energy and Environmental Design (LEED) [23] and Green Construction Assessment (GCA) [24], have been created.

2.6 Reuse Materials and Elements

Reuse means that the materials and elements from demolished buildings are directly utilized in new buildings without extra treatment. Carbon emission of a building project consists of operational and embodied carbon. The embodied carbon makes less contribution in office buildings but nonetheless, can make up as much as 45% of the total life cycle carbon [24]. Thus replacement of virgin with recycled materials reduces the carbon footprints of buildings [25]. However, in order to reuse material and elements, a method of design and deconstruction must be promoted to overcome the barriers that fragmented supply chain for reused materials which make it difficult to source sufficient materials for an entire project.

2.6.1 Recycled Blocks

As mentioned above, the building waste is mainly composed of waste concrete and concrete blocks. There exists a large number of undamaged blocks in collapsed or demolished structures, as shown in Fig. 2.8. After being separated from the building waste and their attached cement mortar removed off, these blocks or bricks can be utilized in constructing new buildings, which not only reduce the cost of materials, transportation and treating waste, but also protect the land resources. Moreover, the waste concrete and waste blocks as well as other kinds of inert materials can be reused as backfill materials, such as filling materials of ram-compaction piles with composite bearing bases, after innocuous treatments.

2.6.2 Reuse Elements

As mentioned above, embodied carbon accounts for nearly half of carbon emission during life cycle. If the demolished components could be used in new-built structures, the embodied carbon in the demolished components could be transferred into next life cycle, meanwhile reduce some carbon emissions and energy consumptions during manufacturing new components. However, although there have been some attempts to realize this practice [26–28], this method is still in the primary stage and is only applied in several pilot projects. The reason is that although existing buildings can be deconstructed, they are often not suitable for reuse which can result in addition of cost to both the project and damaged salvaged materials [25].

One way in which the supply chain can be increased in the future is by designing all new buildings with deconstruction strategy. If a building has been designed for deconstruction strategy, at the end of life the component parts can be separated with no damage thus enabling maximum reuse.

(a) Waste bricks

(b) The waste bricks applied in a new building structure

Fig. 2.8 The waste bricks and reuse

Design for Deconstruction (DfD) is a novel concept arising in recent decade, which is originated from Design for Disassembly in the industrial field. Many types of structure can meet the requirement of DfD, such as wood structure, steel structure, temporary structure, and some military structure. For concrete structure, it is challenging to achieve the requirement that elements can be deconstructed as a whole, undamaged or slightly damaged. Thus many investigations are focused on connections which elements can be deconstructed easily [29–31].

2.7 Recycling

Recycling means manufacturing accessories or elements using RA or recycled powder crushed from waste concrete to replace virgin aggregate or mineral admixture, as shown in Fig. 2.9. Compared with Reuse, Recycle needs new energy import. However, it is relatively feasible to achieve sustainable development of

(a) The production line of recycled aggregates

(b) Recycled coarse aggregates

(c) Recycled fine aggregates

Fig. 2.9 Recycling of waste concrete building industry at the present stage. It has no special demand that the demolished structure was neither designed for deconstructed, nor needed refined deconstruction techniques. It speeds up the commercialization process of waste concrete, providing sufficient recycled concrete while reduce the investment when plan and conduct a project.

2.7.1 Low-Grade Recycling

Depending on its intended use, recycling of waste concrete divided into low-grade and high-grade recycling. For low-grade recycling, recycled productions are used in nonstructural components, such as man-made landscape, pavement, foundation treatment and recycled concrete blocks [32].

In many countries and regions worldwide, specifications for the application of RA have already been put into practice [33–37]. These specifications extend the application of recycled concrete and blocks in the worldwide.

In China, there are three specifications on recycled concrete at present-"*Technical code for applications of recycled aggregate concrete*" (Shanghai, DG/TJ08-2018-2007), "*Code for design of recycled concrete structures*" (Beijing, DB11/T 803-2011) and "*Technical code for applications of recycled aggregate concrete*" (Shanxi, DBJ61/T 88-2014) [38–40]. According to the Shanghai specification, the properties of RA should meet the relevant standards. Apparent density, water absorption, crush value and soundness are the primary factors which determine the RA quality [41]. Different usage of RA is divided by classification based on these four properties.

A technique has already been promoted for producing concrete bricks and blocks using RA obtained from construction and demolition waste, see Fig. 2.10. Test results showed that the replacement percentage of coarse and fine natural aggregates by RA at the percentages of 25 and 50% had little negative effect on the compressive strength of the brick and block specimens, but higher percentages of replacement reduced the compressive strength. Generally speaking, the properties of the bricks and blocks also satisfied other requirements such as the shrinkage resistance capacity.

Table 2.9 Proposed classification of recycled aggregates

Properties	Apparent density (kg/m^3)	Water absorption (%)	Brick content by mass (%)	Crush value (%)	Soundness (%)
Type I	≥ 2400	≤ 7	≤ 7	≤ 30	≤ 18
Type II	≥ 2200	≤ 10	≤ 10	≤ 30	≤ 18

(a) Recycled bricks (b) Recycled blocks

Fig. 2.10 Recycled bricks and blocks in Dujiangyan, PR China

2.7.2 High-Grade Recycling

Building waste can be used to produce structural RAC, high-performance RAC, and functional RAC.

The RAC has some shortcomings with the same w/c ratio compared to natural aggregate concrete (NAC), such as lower strength, larger dry shrinkage, lower workability, and lower durability. However, by adjusting mix ratio, RAC can reach the same standard of performance as of NAC, which should be illustrated in detail in Chap. 4.

By initial estimation and later optimization of proportion, the optimized proportion for high strength recycled concrete (above C60) can be obtained [42]. From investigations, it can be found that the use of water reducing agent and higher cement content is effective in producing a higher strength RAC, meanwhile improving the workability of RAC [41].

2.8 Concluding Remarks

(1) Waste concrete is produced not only in the process of construction and demolition but also by disasters.
(2) The main building waste is waste concrete and waste bricks, and most of it came from masonry structures and masonry-frame structures. Masonry buildings collapsed or damaged at different extents all produced masses of building waste.
(3) The extent of the damage of buildings correlates closely with both the seismic fortification intensity and actual seismic intensity. Under the conditions of the same fortification intensity, it is observed that the possibilities of collapsed buildings increased sharply with the increase of the actual seismic intensity, and therefore more and more building waste is generated.
(4) "3R" principle is proposed to guide the sustainable development of building industry.

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