# Chapter 1
# Introduction

## 1.1 Introduction

Solid waste has become one of the major environmental concerns of the today's world. The rapid increase in the construction activities and large amount of construction and demolition waste result a huge contribution to the total solid waste. The composition of typical construction and demolition waste is presented in Fig. 1.1 (Oikanomou 2005). The construction industry contributes substantially to the generation of solid waste in almost all the countries. In North America, the construction and demolition waste contributes around 25–40% of the total waste generated depending upon the region (Tabsh and Abdelfatah 2009). The Construction Materials Recycling Association (CMRA) has conducted a study on construction and demolition waste, related to the buildings and it was estimated to be around 136 million tonnes of waste material. Also, it was reported that apart from the building waste, a millions of tonnes of waste is coming from roads, bridges and airports construction and renovation. In developed countries, the annual per capita building and construction waste generation was 500–1000 kg and in European countries, the building and construction waste was estimated to be around 175 million tonnes per year (Nitivattananon and Borongan 2007). As per the European Commission (DG ENV 2011), the European Union construction industry generates 531 million tonnes of construction and demolition waste annually which is approximately 25% of the total waste materials exists in the world and the construction waste and recycling rate in each of the European countries is presented in Table 1.1 (Ozalp et al. 2016). Approximately 46% of construction and demolition waste was recycled in the 27 member countries of the European Union (Ozalp et al. 2016). The construction and demolition waste generation scenario in Asian countries is also in the same trend. It was reported that Asia alone generates about 760 million tonnes of construction and demolition waste every year (World Bank 1999). In China, around 15.5 million tonnes of construction waste generated annually. Recent natural disasters such as Wenchuan earthquake in 2008, Yushu



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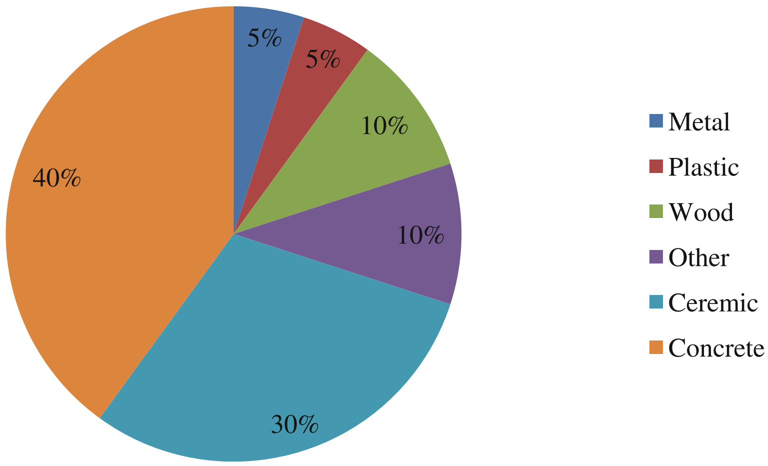


**Fig. 1.1** Composition of construction and demolition waste (Oikonomou 2005)

**Table 1.1** As per European Commission (DG ENV 2011), EU construction and demolition waste (C&DW) quantity and recycling rates

| Country | C&DW (Million tonnes) | Recycling (%) | Country | C&DW (Million tonnes) | Recycling (%) |
|---|---|---|---|---|---|
| Denmark | 5.27 | 94 | Malta | 0.8 | 0 |
| Estonia | 1.51 | 92 | Holland | 23.9 | 98 |
| Finland | 5.21 | 26 | Poland | 38.19 | 28 |
| France | 85.65 | 45 | Portuguese | 11.42 | 5 |
| Germany | 72.4 | 86 | Romania | 21.71 | 0 |
| Greece | 11.04 | 5 | Slovakia | 5.38 | 0 |
| Hungary | 10.12 | 16 | Slovenia | 2 | 53 |
| Ireland | 2.54 | 80 | Spain | 31.34 | 14 |
| Italy | 46.31 | 0 | Sweden | 10.23 | 0 |
| Latvia | 2.32 | 46 | England | 99.1 | 75 |
| Lithuania | 3.45 | 60 | EU-27 | 531.38 | 46 |
| Luxemburg | 0.67 | 46 | – | – | – |

earthquake in 2010, Yunnan earthquake in 2011 in China have resulted a large quantity of waste concrete (Xiao and Li 2013). According to the annual report of Dubai Municipality's Waste Management Department, there was about 27.7 million tonnes of construction waste generated from various construction sites in the city in 2007 (Shrivastava and Chini 2009). This was recording growth in construction waste generation of 163% in comparison to the waste generated in 2006.

Like other developing countries, India too is generating a huge quantity of construction and demolition waste due to rapid growth in construction industry. According to eleventh five-year plan, the construction industry was second to agriculture in terms of magnitude (Government of India 2007). It is one of the largest employers in the country. The employment figures have shown steady increase from 14.6 million in 1995 to 31.46 million in 2005. The construction industry in India significantly affects the economic growth of the country. During 2004–2005, over US$ 100 billion has been invested in this sector. Due to the Government of India's (GOI) recent initiative to allow 100% foreign direct investment in real estate development projects, the construction sector likely to continue to record higher growth in the coming years (Market Research 2006). The contribution of the construction industry in total gross domestic product (GDP) has risen from 6.4% in 2000–2001 to 7.2% in 2004–2005 (TIFAC Ed 2005). Technology Information, Forecasting and Assessment Council (TIFAC) indicates that the total construction work was equivalent to $847 billion during the period 2006–2011 (TIFAC Ed 2005). According to the tenth five-year plan, the materials' cost was around 40–60% of the total project cost. The construction and demolition waste in India was estimated to be approximately 14.5 million tonnes per year (Pappu et al. 2007). The Central Pollution Control Board (CPCB) had estimated the total solid waste generation as 48 million tonnes per year for the year 2001 and out of which 12–14.7 million tonnes from the construction industry alone and by 2010, this was expected to be around 24 million tonnes (TIFAC Ed 2005). In addition, the new zoning bye-laws, legitimization of squatter settlements and increase in the urban population due to industrial development have led to the demolition of structures in the larger cities. Insufficient capacity of old road bridges for present and future growing traffic and modernization of highway bridges needs the demolition of old bridges too. Also, structures are destroyed due to either natural disasters like earthquakes, cyclones, etc. or man-made disasters. Hence, the entire world is facing the problem of handling the waste material generated from the demolition. On the other side, there is a huge requirement of raw materials in the construction sector in India. Projections for building material requirement of the housing sector indicate a shortage of aggregates to the extent of about 55,000 million cubic meters. For achieving the target for road development up to 2010, an estimated 750 million cubic meters of coarse aggregate as subbase material shall be required (TIFAC Ed 2005). Recycling of aggregate material from the construction and demolition waste may reduce the demand–supply gap in both these sectors.

The use of old construction materials in new constructions is not a new technique. Many civilizations have used and reused the construction materials of earlier civilizations or their own destroyed architectures either due to war or due to natural disaster to construct new structures. The best example is that the construction of Vatican Basilica with the stones of ruined Romanesque. The waste management hierarchy which consists of four strategies is shown in Fig. 1.2 including reducing, reusing, recycling and disposing waste (Peng et al. 1997).The main principle of this hierarchy is to minimize the usage of resources and elimination of environmental pollution, which happens to be the two main aspects of sustainable construction

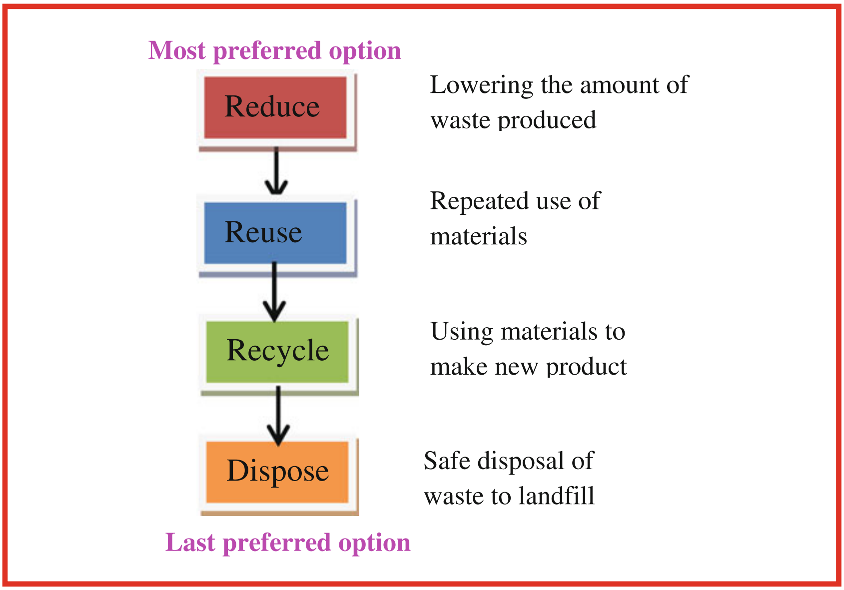


**Fig. 1.2** Waste management hierarchy (Ghafourian et al. 2016)

sector (Peng et al. 1997; Zare et al. 2016). The first three strategies of waste management hierarchy are often called 3R's in the management of C&DW (Ghafourian et al. 2016). Though the "3R" formula, i.e., reduce, reuse, recycle is one of the best policies to achieve the sustainable construction, due to partial implementation of this technique in most of the countries still lots of quantities of construction and demolition waste is lying in the site and deposited on landfills. The European Demolition Association estimates that about 200 million tonnes of waste generated annually, out of which 30% of this quantity being recycled. However, there was large difference in the quantities of recycling in the region wise. For example, Netherlands and Belgium achieve recycling rates of about 90%, whereas, other European countries like Italy and Spain, the recycling rate was below 10% (Collepardi 2002). The Japan and Germany have also reached the recycling rates of around 96% and 86%, respectively. The Construction Materials Recycling Association (CMRA) estimate that 25% of the construction and demolition waste was recycled and most of these recycled materials were used as base materials for road construction. In India, the recycling of the construction and demolition waste is being started recently.

Although there is a considerable potential for using the construction and demolition waste as aggregates in concrete, considerable amount is either remain in site or landfilled, the "last resort" in the waste management hierarchy (Rao 2005). Most of the developed/developing countries, the construction waste treated as inert waste, harmless, and bulky, which does not give rise to problems. However, this waste consists of mixture of various materials of different characteristics that are often deposited (dumped on land) without any considerations, causing many problems and encouraging the illegal dumping of other kinds of waste. This puts an additional burden to the solid waste management. Also, there is a shortage of dumping sites in the developed countries. Further, there is increase in the cost of transport to dispose waste to the dumping sites. Additionally, there is a need to preserve the depletion of natural resources from the environmental pollution point of view and also, it is essential for the sustainable development. Therefore, there is no wonder that the recycling is one of the best solutions sought. The recycling technology not only solves the problem of waste disposal, but reduces the cost and preserves environment also. In addition, the recycling and proper management of construction and demolition waste gives better opportunities to handle the other kinds of waste, as less land is used for dumping of construction and demolition waste.

Recycling of different materials has been tried in the past in different forms. Recycling of coarse aggregates, generated from the demolished or disaster driven waste concrete, has attracted the researchers in the recent past. Coarse aggregates, one of the important ingredients of concrete, are becoming dearer in terms of the increasing cost of the materials and its availability. Hence, recycling of coarse aggregates is of utmost importance to overcome these difficulties. Thus, this book mainly focuses on using the construction and demolition waste as recycled coarse aggregate (RCA) in the production of concrete. The Building Contractors Society of Japan (BCSJ 1978) had proposed the following terminology on recycled aggregate and recycled aggregate concrete (RAC).

*Waste concrete*: It is the concrete debris from demolished structures as well as the fresh and hardened concrete refused by ready-mix plants or site mix concrete producers or concrete product manufacturers.

*Original concrete*: It is the concrete from plain and reinforced concrete structures or precast concrete elements which can be used as raw material for the production of recycled aggregates.

*Recycled concrete aggregates*: These are the aggregates produced by the crushing of original concrete. These aggregates may be either fine or coarse recycled aggregates.

*Recycled aggregate concrete (RAC)*: It is the concrete produced by using the recycled aggregates or the combination of recycled and natural aggregates.

## 1.2 Applications of Recycled Aggregates

Application of recycled aggregates are very important to attain the sustainability in the construction sector as it reduces the construction and demolition waste and preserves the natural resources thereby reduces the environmental pollution. In general, the applications without any processing include (Yong and Teo 2009):

a. many types of general bulk fills;
b. bank protection;
c. base or fill for drainage structures;
d. road construction;
e. noise barriers and embankments.

After removal of contaminants through selective demolition, screening, air separation and size reduction in a crusher to aggregate sizes, crushed concrete can be used as (Yong and Teo 2009):

a. new concrete for pavements, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations;
b. structural grade concrete;
c. soil-cement pavement bases;
d. lean-concrete bases;
e. bituminous concrete.

Growth in the use of recycled concrete for retaining wall backfill, Portland cement concrete mix, landscaping rock, drainage aggregates and erosion control is also happening (Nuruzzaman and Salauddin 2016). The some of the applications of RAC are shown in Figs. 1.3, 1.4, 1.5, 1.6, 1.7, and 1.8.

**Fig. 1.3** RAC pavement in Shanghai, China (Li 2009). This pavement was designed for a width of 7 m and 240 mm height. 50% RCA was used. The RCA was derived from the highway of an airport

**Fig. 1.4** Shanghai ecological building, China (Li 2008). This was a demonstrative ecological green building constructed in Xinzhuang, Shanghai, in 2004 with a total area of 1900 $m^2$. Large amount of RAC (388 $m^3$) was used mainly in foundations and walls. The RCA was produced by crushing old concrete pavements and structural elements

**Fig. 1.5** The BRE office building in Watford, UK, 1995/96 (BRE 1998). For the foundations, a C25 mix (75 mm slump) was used with a minimum OPC-based cement content of 350 kg/$m^3$ and a maximum free water–cement ratio of 0.50 was required. For floor slabs, a C35 mix, also with 75 mm slump was specified. Over 1500 $m^3$ of RAC supplied for foundations, floor slabs, structural columns, and waffle floors

**Fig. 1.6** Waldspirale residential building in Darmstadt, Germany, 1998 (Marinkovc and Ignjatovic 2010) Total 12 000 m$^3$ of RAC was built in (Source: http://www.b-i-m.de/projekte/projframe.htm)

| Component | Type | Quantity (kg/m$^3$) | |
|---|---|---|---|
| | | C30/37 | C25/30 |
| Recycled aggregate | 0/2 mm | 616 | 615 |
| | 2/8 mm | 530 | 290 |
| | 8/16 mm | 569 | 334 |
| | 16/32 mm | | 554 |
| Portland cement | CEM I 42,5 R | 300 | |
| Portland cement | CEM I 32,5 R | | 290 |
| Additives | Pulverised fuelash | 50 | 40 |
| Superplasticiser | | 1.5 kg/m$^3$ | |
| Workability | | Normal (According to DIN 1045) | |
| Compressive strength (Avg. 28 days) | | 42.9 MPa | 36.4 MPa |

## 1.3 Benefits of Recycled Aggregates

The benefits of recycled aggregate concrete are advantageous to the environment. The major benefits are (i) economic aspects, (ii) reducing environmental aspects and (iii) saving natural resources.

**Fig. 1.7** Vilbeler Weg office building, Darmstadt, Germany, 1997/98 (Marinkovc and Ignjatovic Marinkovic and Ignjatovic 2010) Total 480 $m^3$ of RAC was built in (Source: http://www.b-i-m.de/projekte/projframe.htm)

| Component | Type | Quantity (kg/$m^3$) |
|---|---|---|
| | | C30/37 |
| Recycled aggregate | 0/2 mm<br>2/8 mm<br>8/16 mm | 585<br>545<br>568 |
| Portland cement | CEM I 42,5 R | 300 |
| Free water | | 170 |
| Additives | Pulverised fuelash | 40 |
| Superplasticiser | | 5-18 ml/kg of cement |
| Workability (flow table value) | | 550 mm |
| Avg. Compressive strength (28 days) | | 45 MPa |

## *1.3.1 Economic Aspects*

Using construction and demolished concrete as aggregate is an effective and economically viable option to recycle waste materials. This option reduces solid waste, thus saving landfill spaces and minimizing consumption of natural sources (TDS 1998).

**Fig. 1.8** New high school building in Norway (Mehus and Hauck 2002), in which 35% recycled coarse aggregates were used in foundations, basement walls, and columns

### *1.3.2 Reducing Environmental Impacts*

Recycling of waste can greatly reduce the environmental damages caused by incorrect disposal, extend the useful life of landfills and preserve finite natural resources (Carneiro 2000). The main advantage of recycling of construction and demolition waste concrete is that substances are reused which would otherwise be classified as waste. Recycled aggregate can have lower embodied energy in addition to abridged transport emissions especially where recycled materials were reused in close juxtaposition to the site of processing.

### *1.3.3 Saving Resources*

Recycling of concrete demolition wastes can provide opportunities for saving resources, energy, time and money. Furthermore, recycling and controlled management of concrete demolition wastes will save use of land and create better opportunities for handling other kinds of wastes.

## 1.4 Constraints of Recycled Aggregate Concrete

Even though there are benefits to the industry and environment by the use of recycled aggregate concrete, there are some constraints during implementation in the aspects of both technology and management.

### *1.4.1 Management Problems (Tam and Gao 2003)*

#### 1.4.1.1 Lack of Suitable Regulations

Suitable regulations are insufficient to managing the use of recycled materials (Kawano 2000). As a result, the industry is loath to adopt recycled products which need investment in research, production and use to the non-mandatory nature in adoption.

#### 1.4.1.2 Lack of Codes, Specifications, Standards and Guidelines

There are sufficient codes, standards, specifications and guidelines for normal concrete. In the recent times, few countries have published the specifications and norms for the use of recycled aggregate in structural and non-structural concrete applications. But, these are very limited and many countries are yet to move in this direction.

#### 1.4.1.3 Lack of Experience

Experience needs to be accumulated to ensure safety in the use of any new materials; the lack of which forms a barrier in the use of recycled aggregate concrete (Chan et al. 2000)

### *1.4.2 Technology Problems*

Even though a few researchers suggested new techniques for quality improvement of recycled aggregate and recycled aggregate concrete, still there are some technical problems assorted to RAC mainly comes from the poor performance of recycled aggregates (Tam and Gao 2003). These includes

#### 1.4.2.1 Cement Mortar Attached to Aggregate

Recycled aggregates are mainly consists of considerable amount of light porous old cement paste, thus effecting the physical and mechanical properties and performance of recycled aggregate. Further, it affects the properties of concrete particularly the long-term and durability performance of recycled aggregate concrete.

#### 1.4.2.2 Poor Grading

During the crushing process, large amount of finer particles produced due to the adhered old cement mortar on the surface of the recycled aggregate. Poor grading, such as too harsh or too many fines, is one of the problems in the use of recycled aggregate concrete. Fine particles of recycled aggregate will severely affect the water demand and water-to-cement ratio in RAC.

#### 1.4.2.3 High Porosity of Recycled Aggregates

As the recycled aggregates are obtained by crushing the old concrete, light porous nature of old cement mortar attached to recycled aggregates. Therefore, the recycled aggregates are more porous and thus less resistance against mechanical actions compared to natural aggregates.

#### 1.4.2.4 Weak Interfacial Transition Zone

In general, the interfacial transition zone (ITZ) between cement mortar and aggregate plays a major role in determining the mechanical properties of concrete. In recycled aggregate concrete, there are more ITZs: ITZ between RA and new cement paste and ITZ between old cement paste and new cement paste. Therefore, these weak transition zones thus exist between old and new mortars and aggregates exhibit a different microstructure in recycled aggregate concrete and this will directly influence the performance of concrete.

#### 1.4.2.5 Transverse Cracks Generated

Recycled aggregate seems to have direct relationship with transverse cracks within the concrete (Buch et al. 2000). In general, the poor performance of RAC is related with the cracks and fissures, which were formed in the recycled aggregate during crushing process, thereby rendering the aggregate susceptible to permeation, diffusion and absorption of fluids (Olorunsogo and Padayachee 2002). Larbi et al. (2000) reported the classification of the extent on microcracking is presented in Table 1.2.

**Table 1.2** Criteria used for classifying the extent of micro-cracking of the treated concrete aggregate (Larbi et al. 2000)

| Classification of the extent of microcracking | Description of classification |
|---|---|
| Very low | $\leq$ 20% of the aggregates in a specimen contains more than 5 microcracks |
| Low | 20–40% or less of the aggregates in a specimen contains extra than 5 microcracks |
| Moderate | 40–60% or less of the aggregates in a specimen contains more than 5 microcracks |
| High | 60–80% or less of the aggregates in a specimen contains extra than 5 microcracks |
| Very high | $\geq$ 80% of the aggregates in a specimen contains more than 5 microcracks |

#### 1.4.2.6 Variations in Quality

The quality of demolished concrete depends on type of structures and the quality of parent concrete that was used and these are vary from site to site and structure to structure. Therefore, this brings a wide variation in the quality of recycled aggregate (Kawano 2000).

#### 1.4.2.7 High Impurity

Even though the standards limits the levels of chloride and sulfate compositions for the use of aggregate in concrete, other impurities in recycled aggregate (RA) required to be monitored and controlled to confirm the finished concrete has consistent strength and durability (Coventry 1999).

#### 1.4.2.8 Low Quality

The main problem in usage of recycled aggregate concrete is that the quality of recycled aggregate is poorer than the natural aggregate due to the light and porous nature of old cement mortar attached with the surface of RA (Tomosawa and Noguchi 2000). That is why most of the users are not having assurance in adopting recycled aggregate.

## 1.5 Classification of Recycled Aggregates

In general, the C&DW contains the concrete rubble/ceramic, brick, glass, wood, etc. Based on the composition of C&DW, the recycled aggregates were classified in different National Standards and are presented in Table 1.3 (Martin-Morales 2013).

## 1.6 Current Global Scenario

This section describes the recycling status of the construction and demolition waste, the specifications and guidelines existing on the use of recycled aggregates in the production of concrete in countries like Japan, Germany, UK, Hong Kong, Australia, China.

### *1.6.1 Japan*

The Japanese government has launched the Recycling Law in the year 1991. The Ministry of Construction (MOC) has established the “Recycle 21” in 1992, which specifies the targets for recycling of different kinds of construction by-products. By the year 2000, 96% of the demolished concrete was recycled against the target of 90%. But, all most all the recycled aggregates were used as sub-base materials for road pavements. The current Japanese Industrial Standards (JIS) JIS A 5308 for ready mixed concrete does not allow using the recycled aggregate in the concrete. To encourage the recycled materials in the construction industry, the JIS Civil Engineering Committee has made a recommendation in 1998. In response to this, the Japanese Concrete Institute established a committee to draft a new JIS for recycled materials in construction. One of the drafts released by JIS in 2000 was Technical Report TR A 0006 “Recycled Concrete using Recycled Aggregates.” It allows recycled concrete to be used independently from JIS A 5308. According to this, the quality of recycled aggregates should satisfy the requirements presented in Table 1.4 (Hirotaka and Kawano 2002). In addition, it was specified that the grading limits for recycled coarse aggregates are same as natural aggregate. However, the grading specifications for fine recycled aggregate were changed from that of natural aggregate: The limit of upper percentage of fine particles under 0.15 mm is raised from 10% to 15% and the ranges of 1.2–2.5 mm and 2.5–5.0 mm were widened considering the state of actual products.

The recycled concrete was classified into three categories, and their requirements are presented in Table 1.5.

Normal recycled concrete denotes filling and leveling concrete that is for non-structural purpose where high strength and high durability are not prime concern. Chloride controlled concrete is same as normal concrete, but for members

**Table 1.3** Recycled aggregate classifications on the basis of composition (%) (Martin-Morales et al. 2013)

| Scope | Standard/ guidelines | Standard class | Unified class | Concrete | Masonry | Natural aggregate | Organic material | Contaminants/ impurities | Lightweight materials | Fines |
|---|---|---|---|---|---|---|---|---|---|---|
| Australia | CSIRO | Class 1A | RCA | <100 | | | n.a. | 1 | n.a. | n.a. |
| | | Class 1B | MRA | <70 | <30 | | n.a. | 2 | n.a. | n.a. |
| Belgium | PTV 406 | Crushed concrete debris | RCA | >90 | <10 | | 0.5 | 0.5(a) | n.a. | n.a. |
| | | Crushed mixed debris | MRA | >40 | >10 | | 0.5 | 1(a) | n.a. | n.a. |
| | | Crushed brickwork debris | RMA | <40 | >60 | | 0.5 | 1(a) | n.a. | n.a. |
| Brazil | NBR 15116 | ARC | RCA | >90 | | (b) | n.a. | 3 | n.a. | 7 |
| | | ARM | MRA | <90 | | (b) | n.a. | 3 | n.a. | 10 |
| China (c) | DG/TJ07/ 008 | Type I | RCA | >95 | <5 | | 0.5 | 1 | n.a. | n.a. |
| | | Type II | MRA | <90 | >10 | | n.a. | n.a | n.a. | n.a. |
| Denmark | DS 2426 | GP1 | RCA | >95 | | | n.a. | n.a | n.a. | n.a. |
| | | GP2 | MRA | >95 | | | n.a. | n.a | n.a. | n.a. |
| Germany | DIN 4226-100 | Type 1 | RCA | >90 | <10 | | n.a. | 1(e) | n.a. | 1 |
| | | Type 2 | RCA | >70 | <30 | | n.a. | 1(e) | n.a. | 1.5 |
| | | Type 3 | RMA | <20 | >80 | <20 | n.a. | 1(e) | n.a. | 3 |
| | | Type 4 | MRA | | >80(d) | | n.a. | 1(e) | n.a. | 4 |
| Hong Kong | WBTC 12 | Type II | RCA | <100 | | | n.a. | 1 | 0.5 | 4 |
| Japan (c) | JIS A 5021 | ARH | RCA | | | | n.a. | 3 | 0.5 | 4 |
| Netherlands | CUR | ARH | RCA | >95 | <5 | | n.a. | 0.1 | n.a. | |
| | NEN 5905 | ARH | RCA | <80 | | <20 | n.a. | n.a | 0.1 | 3 |
| Norway | NB 26 | Type 1 | RCA | >94 | <5 | (b) | n.a. | 1(e) | 0.1 | n.a. |
| | | Type 2 | MRA | >90 | | (b) | n.a. | 1(e) | 0.1 | n.a. |

(continued)

**Table 1.3** (continued)

| Scope | Standard/ guidelines | Standard class | Unified class | Concrete | Masonry | Natural aggregate | Organic material | Contaminants/ impurities | Lightweight materials | Fines |
|---|---|---|---|---|---|---|---|---|---|---|
| Portugal | LNECE 471 | ARB 1 | RCA | >90 | <10 | (b) | n.a. | 0.2(f) | 1 | n.a. |
| | | ARB 2 | RCA | >70 | <30 | (b) | n.a. | 0.5 (f) | 1 | n.a. |
| | | ARC | MRA | >90 | | >10 | n.a. | 1 (f) | 1 | n.a. |
| Spain | EHE-08 | RCA | RCA | | <5 | | 0.5 | (g) | 1 | 2 |
| Switzerland | SIA 2030 | BC | RCA | | <3 | | n.a. | 1 | n.a. | n.a. |
| | | BNC | MRA | | | | n.a. | 2 | n.a. | n.a. |
| UK | BS 8500-2 | RCA | RCA | >95 | <5 | | n.a. | 1 (h) | 0.5 | 5 |
| | | RA | MRA | | <100 | | n.a. | 1 (h) | 1 | 3 |
| | BRE Digest 433 | RCA I | RMA | | <20 | >80 | n.a. | 5 | 1 | n.a. |
| | | RCA II | RCA | <20 | | >80 | n.a. | 1 | 0.5 | n.a. |
| | | RCA III | MRA | <10 | <10 | >80 | n.a. | 5 | 2.5 | n.a. |
| | RILEM | Type I | RMA | | <100 | | 1 | 5 | 1 | 3 |
| | | Type II | RCA | <100 | | | 0.5 | 1 | 0.5 | 2 |
| | | Type III | RCA | <20 | <10 | >80 | 0.5 | 1 | 0.5 | 2 |

*n.a* no limit available in the standard or guideline
(a) Less than 5% of bituminous material in all types
(b) Included in the percentage of recycled concrete aggregate
(c) This standard classifies recycled aggregate according to its properties
(d) 20% bituminous materials and others
(e) For bituminous materials 1% in all types.
(f) Contaminants of bituminous materials ARB 1 < 5%; ARB 2 < 5%; ARC < 10%
(g) Bituminous materials < 1%; glass, metals, plastics, etc. < 1%
(h) Bituminous materials, RCA < 5%; RA < 10%

**Table 1.4** Quality of recycled aggregates in Japan (Hirotaka and Kawano 2002)

| | Water absorption (%) | Fine particle content (%) |
|---|---|---|
| Coarse aggregate | <7 | <2 |
| Fine aggregate | <10 | <10 |

**Table 1.5** Requirements for recycled concrete for different usage (Hirotaka and Kawano 2002)

| Description | Class | | |
|---|---|---|---|
| | Normal | Chloride controlled | Flexible use |
| Nominal strength (MPa) | 12 | 12 | 18 |
| Max. grain size (mm) | 20 or 25 | 20 or 25 | As required |
| Slump (mm) | 150 | 15 | As required |
| Chloride content (kg/m$^3$) | – | 0.6 | As required |

with steel reinforcement, whereas flexible use recycled concrete is basically for wide range of members, may be sometimes for structural use, but under the guidance of engineer who has expert knowledge on recycled concrete. It is important to mention that the recycled aggregates should be presoaked for controlling the workability and also, the blast furnace slag cement (Class B) or fly-ash cement (Class B) should be used to reduce the alkali–aggregate reaction (AAR).

**Quality** The quality of different classes, i.e., normal and chloride controlled recycled concrete are established by experiments. The individual experiment results of any strength must be greater than 10 N/mm$^2$ and the mean of three such test results must be greater than 12 N/mm$^2$ for strength. Similarly, the results of chloride content and slump tests must lower than 0.3 kg/m$^3$ and 15 cm, respectively. Further, the test result of air content must lies between 3.0% and 7.0%. According to JIS A 5308, any strength of individual test result should be larger than the nominal strength and the mean of three such test results should be larger than 85% of the nominal strength.

**Mix Proportion** the Technical Report (TR) outline specifies that by using one of the following methods the mix proportion shall be fixed: test mixing (but w/c < 65%); standard mixing w/c < 60%, cement > 280 kg/m$^3$. Based on the composition and physical properties, presently three types of recycled aggregates such as high-quality RA (type H), medium-quality RA (type M) and low-quality RA (type L) are considered in Japan. The JIS A 5021 was established in 2005 for the use of high-quality recycled aggregate in concrete (Pellegrino and Faleschini 2016). Recently, this has been replaced by JIS A 5021-2011. Type H recycled aggregates are produced from the demolition of concrete structures by advanced processing (crushing, grinding). With respect to the type M and type L recycled aggregates, the RA of type H should strictly follow the limits of contaminants, composition and physical properties. Type H recycled aggregates can be used in structures with nominal strength lower than 45 MPa provided if they have less than 3% of other

**Table 1.6** Acceptance criteria of recycled aggregate type according to Japanese Standards (Pellegrino and Faleschini 2016)

| | Absorption ratio of aggregate (%) | Oven-dry density (kg/m$^3$) |
|---|---|---|
| Type H coarse RA | $\leq 3.0$ | $\geq 2500$ |
| Type H fine RA | $\leq 3.5$ | $\geq 2500$ |
| Type M coarse RA | $\leq 5.0$ | $\geq 2300$ |
| Type M fine RA | $\leq 7.0$ | $\geq 2200$ |
| Type L coarse RA | $\leq 7.0$ | No requirement |
| Type L fine RA | $\leq 13.0$ | No requirement |

non-concrete and non-virgin aggregate materials. The recycled aggregate of Type M can be used where the members not imperiled to frost action (concrete filled in steel tubes, piles, and underground beams), and the RA of type L can be used in the applications of filling and leveling and backfilling. As an assessment of the degree of extent of alkali–aggregate reactivity, the recycled aggregates of type L can be used only with type B blended cements. The criteria for acceptance of type H, type M and type L recycled aggregates in terms of absorption ratio and oven-dry density are listed in Table 1.6 (Pellegrino and Faleschini 2016).

### *1.6.2 Germany*

According to Federal Statistical Office (Destatis 2005a, b, 2006), Germany, the construction and demolition waste generated in 2002 and 2003 was 241 and 233 million tonnes, respectively. Out of which, 85.6% and 86.2% were recycled in 2002 and 2003, respectively, and the rest of the construction and demolition waste was disposed on land. High material, energy, labor and waste disposal costs of Germany favors the economics of recovering, reusing, and recycling as much construction and demolition waste as possible. Additionally, strong waste management systems have long been required bylaws and regulations at all levels of government in order to minimize the impact of construction and demolition waste in the waste stream.

"Guideline for Recycled Concrete Aggregate" of the German Standardization Association for Reinforced Concrete has introduced the possibility to recycle the construction and demolition waste as aggregate for structural concrete since 1998. According to this guideline, up to 30% recycled aggregate may be used as concrete material. However, there is a limitation on grade of concrete and exposure conditions. Attempts were also made to develop the guidelines for masonry rubble in higher concentrations for concrete aggregate in low-grade concrete or for non-structural applications provided a sufficient durability can be assured. The guidelines for the quality requirements for aggregates from mixed waste are given in newly published Standard DIN 4226-100 (2002). According to this standard, the recycled aggregates are classified into four types (Type 1–4) based on the content of

**Table 1.7** Composition and use of recycled aggregates according to DIN 4226-100 (2002) (Tam and Gao 2003)

| Constituents | Maximum or minimum content as percentage by mass | | | |
|---|---|---|---|---|
| | Type 1: Concrete Aggregate | Type 2: Building Aggregate | Type 3: Masonry Aggregate | Type 4: Mixed Aggregate |
| Concrete and natural aggregate as in DIN 4226-1 | $\geq 90$ | $\geq 70$ | $\geq 20$ | $\geq 80$ |
| Clinker, solid bricks | $\leq 10$ | $\leq 30$ | $\geq 80$ | |
| Calcareous sandstone | | | $\leq 5$ | |
| Other mineral constituents such as porous bricks, aerated concrete, lightweight concrete, plaster, mortar, porous slag, pumice | $\leq 2$ | $\leq 3$ | $\leq 5$ | $\leq 20$ |
| Asphalt | $\leq 1$ | $\leq 1$ | $\leq 1$ | |
| Foreign matter such as glass, non-ferrous metal slag, lump, gypsum, rubber, plastic, wood, plant residue, paper and other similar materials | $\leq 0.2$ | $\leq 0.5$ | $\leq 0.5$ | $\leq 1$ |
| Oven-dry density (kg/m$^3$) | $\geq 2000$ | $\geq 2000$ | $\geq 1800$ | $\geq 1500$ |
| Water absorption after 10 min | $\leq 10$ | $\leq 15$ | $\leq 20$ | Not specified |

**Table 1.8** Maximum amount of coarse recycled aggregate as percentage of total aggregate (Mc Govern 2002)

| Application | Maximum or minimum content as percentage by mass | | | |
|---|---|---|---|---|
| | Type 1: Concrete Aggregate | Type 2: Building Aggregate | Type 3: Masonry Aggregate | Type 4: Mixed Aggregate |
| Reinforced concrete: interior elements | 50 | 40 | 40 | – |
| Exterior elements | 40 | – | – | – |
| Fill or subbase material include fine recycled aggregate | 100 | 100 | 100 | 100 |

concrete, natural aggregates, clinker, non-pored bricks, sand-lime bricks, asphalt, other materials such as pored bricks, lightweight concrete, no-fines concrete, plaster, mortar, porous slag, pumice, stone and foreign substances, e.g., glass, non-ferrous metal slag, gypsum, plastic, wood, paper, etc. The guidelines given in DIN 4226-100 (2002) for the composition and use of recycled aggregate are presented in Tables 1.7 and 1.8 respectively. Further, requirements on properties of recycled aggregates are similar to the requirements on natural aggregates.

**Table 1.9** Substitution ratio (in % by volume) according to EN 206-1 and DIN 1045-2 (Pellegreno and Faleschini 2016)

| Field of application | | Type 1 | Type 2 |
|---|---|---|---|
| Dry | Exposure Class XC 1 | $\leq 45$ | $\leq 35$ |
| Humid | Exposure Class X 0<br>Exposure Class XC 1 to XC 4<br>Exposure Class XF 1 and XF 3<br>Exposure Class XA 1 | $\leq 45$<br>$\leq 45$<br>$\leq 35$<br>$\leq 25$ | $\leq 35$<br>$\leq 35$<br>$\leq 25$<br>$\leq 35$ |

Pellegreno and Faleschini (2016) were reported the other two types, i.e., Type 3 and Type 4 recycled aggregates are barred in making the structural concrete. Further, the usage of crusher sand also barred from the recycled aggregate. The minimum size of recycled aggregate permitted is 2 mm. It was also reported that the limits are specified in code: Concrete with recycled aggregate, in which the substitution ratios and strength class (C30/C37) are specified in relation with the field of application and exposure class (Table 1.9).

### *1.6.3 United Kingdom*

The construction and demolition waste generation has been consistent at 90 million tonnes from the year 2001 to 2005 (Capita Symonds Ltd. 2007). This was an increase of about 21 million tonnes from the year 1999. Recycling of the construction and demolition waste using crushers and screeners has increased from 49% in 2001 to 52% in 2005. However, the proportion of construction and demolition waste sent to landfill has increased from 26 to 31% and the amount of waste going to exempt sites has dropped from around 25 to 17%. To bridge the gap between the current United Kingdom (UK) practice and specifications, The Building Research Establishment (BRE) has published the guidelines on the use of recycled aggregates. According to BRE Digest 433 (1998), the recycled aggregates are classified into three types based on relative composition of concrete to brick masonry and are presented in Table 1.10.

**Table 1.10** Classification of recycled aggregate (BRE Digest 433 1998)

| Class | Origin | Brick content by weight | Strength by ten percent 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 |

**Table 1.11** Maximum recommended limits of impurities (by weight) (BRE Digest 433 1998)

| Type of impurity | Type of Application | | |
|---|---|---|---|
| | Use in concrete as coarse aggregate | Use in road construction | Hardcore, fill or granular material |
| Asphalt and Tar | Included in limit for other foreign material | 10% in RCA (I) and (III)<br>5% in RCA (II) | 10% |
| Glass | | Contents above 5% to be documented | |
| Wood | 1% in RCA (I)<br>0.5% in RCA (II)<br>2.5% in RCA (III) | Subbase: 1%<br>Capping layer: 2% | 2% |
| Sulfates | Concrete and CBM: 1% acid-soluble $SO_3$ | | |
| Other foreign material such as metals, plastics, clay, etc. | 5% in RCA (I) and (III)<br>1% in RCA (II) | | |

The BRE Digest 433 (1998) has also specified the maximum limits on impurities and is presented in Table 1.11. If recycled aggregates of classes RCA (I), RCA (II), or RCA (III) satisfy the quality and grading requirements of BS 882, "Specifications for aggregates from natural sources for concrete" may be used in concrete production.Pellegreno and Faleschini (2016) stated that in the UK, the difference between RCA and RA is clearly distinguished. The former is derived from concrete-based material, in which the maximum content of masonry allowed is 5% (in weight) and the latter is derived from a mixed waste. Vazquez (2013) reported that the use of RA is limited to the applications of underpinning works and road surfaces specified in the complementary UK Standard to EN 206-1; BS 8500-2 2015. The application of recycled aggregate is restricted to mild exposure conditions and strength class of C16/20.

The choice of use of RA, which reveals in a large inconsistency among their origin, composition and properties are ruled by the lack of exact regulation. Whereas, within the recommended exposure classes: X0, XC1, XC2, XC3, XC4, XF1, DC-1 and a concrete strength class of C40/50, up to 20% by weight of natural aggregate is allowed to replace with RCA. The severe freeze–thaw exposure conditions (XF2-XF4) and the salt (XS, XD) are excluded. If the prescriber takes his own responsibility for the experimental results, higher substitution of recycled aggregate-to-natural aggregate is accepted subject to the acceptance of experimental results.

It was reported that BS 8500-2 (BSI 2015) published the coarse recycled aggregate requirements in concrete (Pellegreno and Faleschini 2016). According to this code, the recycled aggregates are classified into recycled concrete aggregate (RCA) and recycled aggregate (RA) based on its composition and other requirements of these classes are presented in Table 1.13. Further, the coarse recycled concrete aggregates are allowed only up to a concrete strength class of C40/50 and within the exposure classes as listed in Table 1.14.

**Table 1.12** Designations for RCA and RA concreting aggregates for general use recommended by BS EN 12620-2002 (Collins et al. 2004)

| Properties | Category to BS EN 12620-2002 or other limit[2] |
|---|---|
| Grading<br>Coarse aggregate | Annex C in BS PD 6682-1: 2003 |
| Flakiness index | $FI_{35}$ (There should be no difficulty in consistently producing RCA or RA to this limit) |
| Fines<br>RCA<br>RA | $f_4$ (BS 8500-2: 2002 will accept up to 5%)<br>$f_3$ |
| Resistance to fragmentation | No requirement. RCA will normally comply with $LA_{40}$ and RA with $LA_{40}$ or $LA_{50}$ |
| Acid-soluble sulfate content | $AS_{1.0}$ |
| Total sulfur | $\leq$ 1% by mass |
| Masonry[a]<br>RCA<br>RA | $\leq$ 5% by mass<br>$\leq$ 100% by mass |
| Lightweight material[b, c]<br>RCA<br>RA | $\leq$ 0.5% by mass<br>$\leq$ 1.0% by mass |
| Asphalt[c]<br>RCA<br>RA | $\leq$ 5% by mass<br>$\leq$ 10% by mass |
| Other foreign material such as glass, plastics, metals[c] | $\leq$ 1.0% by mass |
| Constituents in RCA or RA fine aggregate which alter the rate of setting and hardening of concrete [d]<br>-increase in mortar setting time<br>-decrease in compressive strength of mortar | $\leq$ 120 min<br>$\leq$ 20% at 28 days |

[b]Material with a Density Less Than 1000 $kg/m^3$

[c]Property where currently no BS EN 12620-2002 limit—test and limits taken from BS 8500-2:2002

[d]Comparison should be with mortar made with standard clean sand; heating one sample according to the method in BS EN 1744-1:1998 is not appropriate for RCA/RA. Alternatively, if concrete is made on a regular basis from these materials, consistent strength development in the concrete should be checked for each day's production or batch of materials.

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

**Table 1.13** Requirements of coarse recycled concrete aggregate and recycled aggregate specified by BS 8500-2 (Pellegreno and Faleschini 2016)

| Property | Recycled concrete aggregate | Recycled aggregate |
|---|---|---|
| Maximum masonry content (%) | 5 | 100 |
| Maximum fines (%) | 5 | 3 |
| Max. Lightweight material (density < 1000 kg/m$^3$) (%) | 0.5 | 1.0 |
| Maximum asphalt (%) | 5 | 10 |
| Max. other foreign materials (%) | 1.0 | 1 |
| 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, and 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 1.14** Limitations on the use of coarse recycled concrete aggregate in concrete with different exposure classes in BSI 2002 (Pellegreno and Faleschini 2016)

| 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 the resulting concrete is suitable for the intended applications

### *1.6.4 Hong Kong*

There was about 20 million tonnes of construction and demolition waste generated in 2004, out of which 12% was disposed off at landfills and the rest was at public filling areas (Poon 2007). The amount of construction and demolition waste generated was about four to five times of that of municipal solid waste. The annual generation of construction and demolition waste was more than double from 1999 to 2004. The management of construction and demolition waste has become a major environmental issue in Hong Kong. The General Specifications (GS) for civil engineering works banned the use of recycled inert construction and demolition

**Table 1.15** Specifications for the use of recycled coarse aggregates in concrete (WBTC 12/2002)

| Mandatory requirements | Limits | Testing method |
|---|---|---|
| Minimum dry particle density (kg/m$^3$) | 2000 | BS 812: Part 2 |
| Maximum water absorption (%) | 10 | BS 812: Part 2 |
| Maximum content of wood and other material less dense than water (%) | 0.5 | Manual sorting in accordance with BRE Digest 433 |
| Maximum content of other foreign materials (e.g., metals, plastics, clay lumps, asphalt and tar, glass, etc.) (%) | 1 | |
| Maximum fines (%) | 4 | BS 812: Sect. 103.1 |
| Maximum content of sand (< 4 mm) (% m/m) | 5 | BS 812: Sect. 103.1 |
| Maximum content of sulfate (% m/m) | 1 | BS 812: Part 118 |
| Flakiness index (%) | 40 | BS 812: Sect. 105.1 |
| Ten percent fines value (kN) | 100 | BS 812: Part 111 |
| Grading | Table 3 of BS 882:1992 | |

materials except its use as fill material in reclamation and earth filling projects until 2001. But the revision of GS in 2001 in the form of corrigendum No. 1/2001 allows the use of recycled aggregates for use in earthworks, drainage and marine works. The Work Bureau Technical Circular (WBTC) 12/2002 published the specifications for the use of recycled aggregates in concrete applications in public work projects in Hong Kong and is presented in Table 1.15.

For lower grade applications, 100% recycled coarse aggregates were allowed in the production of concrete. The recycled fine aggregates were not allowed in the production of concrete. The target strength was specified at 20 MPa, and this concrete can be used in stools, benches, concrete mass walls, planter walls and other minor concrete structures where specifically permitted in the contract. For higher grade applications (25–35 MPa concrete), the above specifications allow a maximum of 20% recycled coarse aggregates in the production of concrete and it can be used for general applications except in water retaining structures.

After reviewing the various standards and WBTC 12/2002, the recent standard published by The Government of Hong Kong special administrative region for aggregates for concrete “Construction Standard (CS3: 2013)” has been included the specifications for recycled coarse aggregates in accordance with the WBTC 12/2002. The grading requirements for recycled coarse aggregate as per CS3: 2013 is presented in Table 1.16.

**Table 1.16** Grading of recycled coarse aggregate (CS3: 2013)

| Sieve size (mm) | Nominal size of graded aggregates (mm) | | | Nominal size of single-sized aggregates (mm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | 40 to 5 | 20 to 5 | 14 to 5 | 40 | 20 | 14 | 10 | 5 |
| 50 | 100 | – | – | 100 | – | – | – | – |
| 37.5 | 90–100 | 100 | – | 85–100 | 100 | – | – | – |
| 20 | 35–70 | 90–100 | 100 | 0–25 | 85–100 | 100 | – | – |
| 14 | 25–55 | 40–80 | 90–100 | – | 0–70 | 85–100 | 100 | – |
| 10 | 10–40 | 30–60 | 50–85 | 0–5 | 0–25 | 0–50 | 85–100 | 100 |
| 5 | 0–5 | 0–10 | 0–10 | – | 0–5 | 0–10 | 0–25 | 45–100 |
| 2.36 | – | – | – | – | – | – | 0–5 | 0–30 |

**Note:** For coarse recycled 20 and 10-mm single-sized aggregates, the percentage by mass passing 4-mm test sieve shall not exceed 5%

### *1.6.5 Australia*

About 32.4 million tonnes of solid waste was generated annually of which the waste from construction and demolition sector is of about 13.75 million tonnes (42% of total solid waste). From this, around 57% of the construction and demolition waste was recycled (Tam 2009). Among different types of construction and demolition wastes, concrete waste constitutes about 81.8% of the total waste, from which 54% of the concrete waste was recycled.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) initiated to promote the use of recycled aggregate in the production of concrete. In 1998 and 2002, CSIRO has published two set of guidelines for the use of recycled aggregates in concrete for non-structural applications “Guidance on the preparation of non-structural concrete made from recycled concrete aggregates” and “Guide to the use of recycled concrete and masonry materials,” respectively (CSIRO 1998, H155-2002). Two classes of recycled aggregates, namely Class 1 and Class 2, were recommended for non-structural applications and are presented in Table 1.17.

### *1.6.6 China*

The amount of construction and demolition waste has reached 30–40% of the total solid waste. Among all the construction and demolition wastes, the waste generated from concrete was large. In 2006, the annual waste generated from concrete was about 100 million tonnes and it accounts for about 1/3 of the total construction and demolition wastes. Based on the annual cement production, the concrete waste forecasted for the future and it will be 638 million tonnes in 2020 (Shi and Xu 2006). In recent years, due to the rapid urbanization and the requirement of sustainable

**Table 1.17** Classification of recycled aggregate (CSIRO 1998 and H155-2002)

| Class | Subclass | Definition |
|---|---|---|
| Class 1 | Class 1A | Uniformly graded coarse aggregate (4–32 mm) produced by crushing waste concrete with total contaminant levels lower than 1% of the bulk mass |
| | Class 1B | Class 1A recycled aggregate blended with not more than 30% crushed brick |
| | Grade 1 | Plain unreinforced and reinforced concrete made with a maximum of 30% uniform quality of Class 1A recycled aggregate with characteristic strength up to and including N40 grade, i.e., 40 MPa |
| | Grade 2 | Plain unreinforced and reinforced concrete made with up to 100% uniform quality of Class 1(A or B) recycled aggregate having characteristic strength up to including N25 grade, i.e., 25 MPa, concrete for use in non-structural concrete applications |
| Class 2 | Class 2A1 | Suitable for use in roads with a traffic loading of greater than $1 \times 10^6$ ESA as either base or subbase course |
| | Class 2A2 | Suitable for use in roads with a traffic loading less than or equal to $1 \times 10^6$ ESA as either base or subbase course |
| | Class 2B | For use as a base layer for pavers in pedestrian areas, car parking, and shopping malls |
| | Class 2C | General filling behind curbs and gutters, retaining walls, or beneath grassed areas |
| | Class 2D | Bulk filling for urban and rural development for construction of embankments. |
| | Class 2E | Backfilling for subsoil drains and storm water pipes |

development, more and more research activities have been undertaken. So far, over 30 universities, institutes, and companies in China have been engaged in the research and applications of recycled aggregate concrete (RAC). After experiencing some successful applications of RAC in pavements and buildings, a technical code for Application of Recycled Aggregate Concrete (DG/TJ07-008) was published in 2007 at Shanghai as regional standards (SCSS 2007). The details of the requirements of RAC in DG/TJ07-008 are presented in Table 1.18. In this code, the recycled coarse aggregates were classified in two types, namely Type 1 and Type 2 based on their water absorption, saturated-surface-dry (SSD) density and masonry content. The grading of the recycled coarse aggregates must fall within the limits for natural aggregates specified in current Chinese Codes, i.e., JGJ 52-2006 "Standard for technical requirements and test method of sand and crushed stone or gravel." The recycled fine aggregates were not allowed in RAC in this code.

Further, the following standards have been published related to the recycled coarse and fine aggregates for concrete and mortar and the highlights are presented in Tables 1.19, 1.20, and 1.21 (Bodet 2014).

**Table 1.18** Requirements of recycled aggregates in concrete in DG/TJ07-008 (Li 2008)

| Item | Type 1 | Type 2 |
|---|---|---|
| SSD density (kg/m$^3$) | $\geq 2400$ | $\geq 2200$ |
| Absorption (%) | $\leq 7$ | $\leq 10$ |
| Masonry content (%) | $\leq 5$ | $\leq 10$ |
| Crushing value (%) | $\leq 30$ | |
| Soundness (mass loss %) | $\leq 18$ | |
| Flakiness index (%) | $\leq 15$ | |
| Clay content (%) | $\leq 4$ | |
| Sulfate content $SO_3$ (%) | $\leq 1.0$ | |
| Chlorides content (%) | $\leq 0.25$ | |
| Organic material (%) | $\leq 0.5$ | |
| Impurity content (%) (metal, glass, plastics, asphalt, wood) | $\leq 1$ | |

**Table 1.19** Particles made of concrete, mortar, stone, tile and brick from construction waste, with size larger than 4.75 mm as per GB/T 25177-2010 (Bodet 2014)

| Items | Level-1 | Level-2 | Level-3 |
|---|---|---|---|
| Content of fine powder (mass%) | <1.0 | <2.0 | <3.0 |
| Content of silt lump (mass%) | <0.5 | <0.7 | <1.0 |
| Water absorption (mass%) | <3.0 | <5.0 | <8.0 |
| Elongated and flaky particle (mass%) | <10 | <10 | <10 |
| Hazardous content: organic | Conforming | Conforming | Conforming |
| Hazardous content: sulfate mass % | <2.0 | <2.0 | <2.0 |
| Hazardous content: chloride mass % | <0.06 | <0.06 | <0.06 |
| Impurities content mass % | <1.0 | <1.0 | <1.0 |
| Soundness: mass loss % | <5.0 | <10.0 | <15.0 |
| Crushing index % | <12 | <20 | <30 |
| Apparent density (kg/m3) | >2450 | >2350 | >2250 |
| Void % | <47 | <50 | <53 |

Level 1: any concrete
Level 2: concrete below C40 (including C40)
Level 3: concrete below C25 (including C25). Not suitable for anti-freezing concrete
*Note*
i Recycled aggregates cannot be used in precast concrete
ii Recycled aggregates not meeting the above standard can be used in non-structural concrete component

(i) Recycled coarse aggregate for concrete (GB/T 25177-2010);
(ii) Recycled fine aggregate from concrete and mortar (GB/T 25176-2010);
(iii) Technical specification for application of recycled aggregate (JGJ/T 240-2011).

**Table 1.20** Particles made of concrete, mortar, stone, tile, and brick from construction waste, smaller than 4.75 mm size as per GB/T 25176-2010 (Bodet 2014)

| Items | Level-1 | Level-2 | Level-3 |
|---|---|---|---|
| Content of fine powder (mass% @ MB < 1.40) | <5.0 | <7.0 | <10.0 |
| Content of fine powder (mass% @ MB ≥ 1.40) | <1.0 | <3.0 | <5.0 |
| Content of clay lump (mass%) | <1.0 | <2.0 | <3.0 |
| Hazardous content: mica (mass%) | <2.0 | <2.0 | <2.0 |
| Hazardous content: organic | Conforming | Conforming | Conforming |
| Hazardous content: sulfate mass (%) | <2.0 | <2.0 | <2.0 |
| Hazardous content: chloride mass (%) | <0.06 | <0.06 | <0.06 |
| Hazardous content: light materials mass (%) | <1.0 | <1.0 | <1.0 |
| Soundness: mass loss % in saturated $Na_2SO_4$ | <8.0 | <10.0 | <12.0 |
| Single Grade Max. Crushing index (%) | <20 | <25 | <30 |
| Apparent density (kg/m$^3$) | >2450 | >2350 | >2250 |
| Bulk density (kg/m$^3$) | >1350 | >1300 | >1200 |
| Void (%) | <46 | <48 | <52 |

Level 1: Concrete below C40 (including C40)
Level 2: concrete below C25 (including C25)
Level 3: Non-structural component

**Table 1.21** Recycled aggregates for block and brick as per JGJ/T 240-2011 (Bodet 2014)

| Item | Limit |
|---|---|
| (a) *Coarse aggregates* | |
| Content of fine powder (mass%) | <5.0 |
| Water absorption (mass%) | <10.0 |
| Impurities Content (mass%) | <2.0 |
| Silt lump, hazardous, soundness, crushing index, alkali reaction index | Conforming to Table 1.13 |
| (b) *Fine aggregates* | |
| Content of fine powder (mass% @ MB < 1.40) | <12.0 |
| Content of fine powder (mass% @ MB > 1.40) | <6.0 |
| Silt lump, hazardous, soundness, crushing index, alkali reaction index | Conforming to Table 1.14 |

## 1.6.7 Spain

In Spain, the recommendations on the use of concrete made with recycled aggregate obtained from waste concrete crushing was established in structural concrete instruction EHE-08 (Martinez et al. 2010). The recycled aggregate concrete can be

**Table 1.22** Requirement for coarse aggregate for structural concrete in EHE-08 (Martinez et al. 2010)

| Property | Test standard | Mixed aggregate | Natural aggregate | Recycled aggregate |
|---|---|---|---|---|
| Type of recycled aggregate | prEN 933-11 | – | – | Concrete recycled aggregates |
| Ceramic content (%) | prEN 933–11 | | | ≤ 5 |
| Asphalt content (%) | prEN 933–11 | | | ≤ 1 |
| Contents of other materials (%) (glass, plastics, metals, etc.) | prEN 933–11 | | | ≤ 1 |
| Fine content (%) (< 0.063 mm) | UNE–EN 933–1 | ≤ 1.5 | ≤ 1.5 | ≤ 1.5 |
| Flakiness index | UNE–EN 933–3 | <35 | <35 | <40 |
| Absorption (%) | UNE–EN 1097-6 | ≤ 5 | ≤ 4.5 | ≤ 7 |
| Los Angeles coefficient | UNE–EN 1097-2 | ≤ 40 | ≤ 40 | ≤ 40 |
| Cl- water soluble (%) | UNE–EN 1744–1 | ≤ 0.05 | ≤ 0.05 | ≤ 0.05 |
| Acid soluble sulfates $SO_3$ = (%) | UNE–EN 1744–1 | ≤ 0.8 | ≤ 0.8 | ≤ 0.8 |
| Total sulfur compounds $SO_3$ = (%) | | ≤ 1 | ≤ 1 | ≤ 1 |
| Light particles (%) | UNE–EN 1744–1 | ≤ 1 | ≤ 1 | ≤ 1 |
| Clay particles (%) | UNE 7133 | ≤ 0.25 | ≤ 0.15 | ≤ 0.60 |
| Weight loss in magnesium sulfate (%) | UNE–EN 1367-2 | ≤ 18 | ≤ 18 | ≤ 18 |
| Lower declassified (%) | UNE–EN 933–1 | ≤ 10 | ≤ 10 | ≤ 10 |
| Content of particles < 4 mm (%) | UNE–EN 933–1 | | | ≤ 5 |

used in structural concrete and mass concrete up to strength of 40 MPa. The maximum substitution of recycled coarse aggregate was limited to 20% of the total coarse aggregate in structural concrete applications. The requirement of recycled aggregate for structural concrete as per Annex 15 of EHE-08 is presented in Table 1.22.

Annex 18 of EHE-08 included the specifications of RA for non-structural applications which admit 100% recycled coarse aggregate provided that it satisfy the specifications mentioned in Table 1.23. If recycled coarse aggregate does not satisfy the limits specified in Table 1.22, it can be mixed with natural aggregate in order to report these limitations.

### 1.6.8 RILEM Specifications

The International Union of Testing and Research Laboratories for Materials and Structures (RILEM) has been actively involved in preparing the specifications for the use of recycled aggregates and its use in concrete. In 1994, RILEM had published the specifications for the use of recycled aggregates in concrete. In these specifications, the classification of recycled coarse aggregates and applications in the field of concrete containing these recycled aggregate classes in terms of acceptable environmental exposure classes and strength limits are also specified. The recycled aggregates were classified into three types such as Type I, Type II and Type III and are presented in Table 1.24.

The maximum water absorption limits for Type I, Type II and Type III were 20, 10, and 3% respectively. The requirements for the use of recycled aggregates in concrete are given in Table 1.25.

The limits for maximum strength of concrete with different types of recycled aggregates are presented in Table 1.26.

The above-specified recycled aggregates can be used in plain and reinforced concrete provided they satisfy all other durability requirements specified in RILEM and CEN Codes. The recycled fine aggregates are not allowed.

### 1.6.9 India

The Indian construction industry is one of the major sources for employment and the successive five-year plans of India accounts around 50% of the capital outlay from the construction sector. The projected outlay of the construction in the industrial sector continues to show a rising trend. At the same time, it contributes a large quantity of solid waste which include concrete, gravel, sand, bricks, metal, plastic, etc. A key concern for the town planners is to manage the construction and demolition waste, mainly due to swelling in quantity of demolition rubble, persistent dearth of dumping sites, intensification of transportation and disposal cost and above all budding alarm about pollution and environmental deterioration.

The Central Pollution Control Board (CPCB) has reported that out of 48 million tonnes/annum of solid waste generation, one-fourth of the waste was from construction sector only. This sets a huge burden on solid waste management. The demolition of buildings contributes a major portion to this waste generation. Asnani

**Table 1.23** Specifications for aggregate used for base course, subbase course and subgrade in EHE-08 (Martinez et al. 2010)

| Property | Standard | Carriageway Traffic T2 | Carriageway Traffic T3 | Carriageway Traffic T4 | Shoulders Traffic T2 | Shoulders Traffic T31 | Shoulders Traffic T32 and T4 |
|---|---|---|---|---|---|---|---|
| Type of recycled aggregate | prEN 933-11 | Concrete and mixed | Concrete and mixed | Concrete and mixed | Concrete and mixed | Concrete and mixed | Concrete and mixed |
| Asphalt content | prEN 933-11 | $\leq 5\%$ | $\leq 5\%$ | $\leq 5\%$ | $\leq 5\%$ | $\leq 5\%$ | $\leq 5\%$ |
| Content of light particles and other elements: wood, glass, gypsum, etc. | prEN 933-11 | $\leq 2\%$ | $\leq 2\%$ | $\leq 2\%$ | $\leq 2\%$ | $\leq 2\%$ | $\leq 2\%$ |
| Sand equivalent | UNE-EN 933-8 | >35 | >35 | >35 | >35 | >30 | >30 |
| Plasticity index | UNE 103103 & 103104 | Non-plastic material | Non-plastic material | LL < 25<br>IP < 6 | Non-plastic material | Non-plastic material | LL < 30<br>IP < 10 |
| Los Angeles coefficient | UNE-EN 1097-2 | <35 | <35 | <35 | <35 | <35 | <35 |
| Flakiness index | UNE-EN 933-3 | <35 | <35 | <35 | <35 | <35 | <35 |
| Crushed particles | UNE-EN 933-5 | $\geq 75\%$ | $\geq 50\%$ | $\geq 50\%$ | $\geq 50\%$ | $\geq 50\%$ | $\geq 50\%$ |
| Quotient of material passing through sieve 0.063 mm and material passing sieve 0.25 mm | UNE-EN 933-2 | <2/3 | <2/3 | <2/3 | <2/3 | <2/3 | <2/3 |
| Organic matter content | UNE 103204 | <1% | <1% | <1% | <1% | <1% | <1% |
| Settling in collapse test | NLT 254 | <1% | <1% | <1% | <1% | <1% | <1% |
| Free swelling | UNE 103601 | <3% | <3% | <3% | <3% | <3% | <3% |

**Table 1.24** Classification of recycled aggregates

| Type | Origin |
|---|---|
| Type I | Implicitly understood to originate primarily from masonry rubble |
| Type II | Implicitly understood to originate primarily from concrete rubble |
| Type III | Implicitly understood to consist of a blend of recycled aggregates (maximum 20%) and natural aggregates (mandatory minimum 80%). The maximum content of Type I aggregate is 10% |

**Table 1.25** Mandatory requirements for recycled aggregates

| Requirements | Type I | Type II | Type III | Test method |
|---|---|---|---|---|
| Maximum dry particle density (kg/m$^3$) | 1500 | 2000 | 2400 | Pr EN 1097-6 |
| Maximum weight % with SSD < 2200 kg/m$^3$ | – | 10 | 10 | Pr EN 1744-1 |
| Maximum weight % with SSD < 1800 kg/m$^3$ | 10 | 1 | 1 | |
| Maximum weight % with SSD < 1000 kg/m$^3$ | 1 | 0.5 | 0.5 | |
| Maximum weight % of foreign materials such as metals, glass, soft material, tar, crushed asphalt. | 5 | 1 | 1 | Test by visual separation as in pr EN 933-7 |
| Maximum content of metals (% m/m) | 1 | 1 | 1 | Visual |
| Maximum content of organic material (% m/m) | 1 | 0.5 | 0.5 | NEN 5933 |
| Maximum content of filler less than 0.063 mm (% m/m) | 3 | 2 | 2 | Pr EN 933-1 |
| Maximum content of sand less than 4 mm (% m/m) | 5 | 5 | 5 | Pr EN 933-1 |
| Maximum content of sulfate (% m/m) | 1 | 1 | 1 | BS 812: part 118 |

**Table 1.26** Maximum allowable strength for concrete with recycled aggregates

| | Type I | Type II | Type III |
|---|---|---|---|
| Grade of concrete | C16/20[a] | C 50/60 | No limit |

[a]The strength may be increased to C 30/37 subjected to the condition that the SSD density of the RCA exceeds 2000 kg/m$^3$

(1996) reported that around 300 kg/m$^2$ from semi-pucca buildings and 500 kg/m$^2$ from pucca buildings waste was generated. The total amount of waste from construction sector was estimated to be 12–14.7 million tonnes per annum. The amount of different types of wastes that were arising from the construction industry was estimated and is presented in Table 1.27. Predictions for building material requirement of the housing sector show a dearth of aggregates to the extent of about 55,000 million cubic meters. For achieving the target for road development up to

**Table 1.27** Waste constituents in million tonnes in India (Asnani 1996)

| Constituent | Quantity generated in million tonnes per annum |
|---|---|
| Soil, sand, and gravel | 4.20–5.14 |
| Bricks and Masonry | 3.60–4.40 |
| Concrete | 2.40–3.67 |
| Metals | 0.60–0.73 |
| Bitumen | 0.25–0.30 |
| Wood | 0.25–0.30 |
| Others | 0.10–0.15 |

2010, an estimated 750 million cubic meters of coarse aggregate as sub-base material shall be required. Production of recycled aggregate by recycling the construction and demolition waste may shrink the demand–supply gap in both these sectors. The waste from concrete and masonry is more than 50% of the total construction and demolition waste and is not currently recycled in India.

In view of the importance of recycling in the construction industry, Technology, Information, Forecasting and Assessment Council (TIFAC) appointed a techno-market survey on utilization of waste from construction industry (www.tifac.com). The main objective of this study was to gauge the knowledge of Indian construction industry on the probability of recycling of construction and demolition waste. According to the outcomes of survey, the main reason for not implementing recycling of construction and demolition waste was "the unawareness of the recycling techniques." While 70% of the respondents have cited the lack of awareness as one of the reasons, 30% of the respondents have indicated that they were not even aware of recycling possibilities. The response of industries indicates that presently, the existing specifications do not allow the use of recycled product in the construction activity. Sixty-seven percent of the respondents from user industry have quoted unavailability of recycled product as one of the reasons for not adopting it. It is a very good move in India that recently the Municipal Corporation of Delhi (MCD) has established the construction and demolition waste processing plant at Burari in North Delhi, by way of which the processed waste would be used in roadworks.

**Existing Regulations on the use of Fine Recycled Aggregate (FRA)** Past research shows that the concrete production with fine recycled aggregate (FRA) is very limited. The specifications regulated by different National Standards are presented in Table 1.28. Nevertheless, the recent researchers have reported that it is feasible to use the fine recycled aggregate in structural concrete and preserve its characteristics within the tolerable limits (Evange lista and de Brito 2014).

**Table 1.28** General summary of the use of FRA in concrete in National Specifications (Evangelista and de Brito 2014)

| Country | FRA type | Maximum % of FRA | $f_{c,max}$ (MPa) FRAC | Notes |
|---|---|---|---|---|
| Germany | | 0 | | Only CRA |
| Belgium | FRCA | 100 | 37 | With similar characteristics to FNA |
| Brazil | FRCA/ CDW FRA | 100 | 15 | Non-structural |
| China | | 0 | | Only CRA |
| Denmark | FRCA/ CDW FRA | 20 | 40/20 | Non-aggressive environments |
| Spain | | 0 | | Only CRA |
| USA | FRCA | 100 | No limit | Any type of concrete |
| Holland | FRCA/ CDW FRA | 100 | 50/25 | Only if used with CAN |
| Hong Kong | | 0 | | Only CRA |
| Japan | CDW FRA | 100 | 18 | Less demanding foundations |
| Portugal | | 0 | | Only CRA |
| UK | | 0 | | Only CRA |
| Russia | CDW FRA | 50/100 | 15/20 | Non-prestressed concrete |
| Switzerland | FRCA/ CDW FRA | 20/100 | 37/- | Limited for prestressed concrete/plain concrete |

## 1.7 Summary

The importance of recycling of construction and demolition waste from the viewpoint of solid waste management, preserving the depletion of natural resources from the environmental pollution and also from the sustainable construction is discussed. Terminology on recycled aggregate and recycled aggregate concrete (RAC) proposed by the Building Contractors Society of Japan (BCSJ 1978) is also described. Further, the current scenario of recycling of construction and demolition waste in various countries is discussed. The specifications laid down by different countries and RILEM on recycled aggregates are also highlighted. Based on these discussions, the following observations are highlighted.

- Though the “3R” formula, i.e., reduce, reuse, recycle, is one of the best policies to achieve the sustainable construction, due to partial implementation of this technique in most of the countries still lots of quantities of construction and demolition waste is lying in the site and deposited on landfills.
- The recycled aggregates could be used as structural grade concrete for many concrete applications provided if the demolished waste screened, separated various impurities and graded properly.

- Recycled aggregates have potential benefits such as economic, reduce environmental impacts and saving resources. But at the same time, there are certain constraints during the implementation in terms of both technological and management. Hence, researchers have to pay a serious attention toward the minimizing these problems so that the advantages of recycled aggregate could be availed in the industry.
- Few countries like Japan, Germany, China, Hong Kong, Spain, UK, have been established the specifications, guidelines on the use of RA in various applications, but still most of the countries are yet to make their move in this direction.

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