Chapter 4
Construction and Demolition (C&D) Wastes

4.1 General

Although C&D wastes are a problem of increasing magnitude, there is little consensus about its volume. This subject is dependent on the absence of reliable statistics because in most countries these kinds of wastes are illegally dumped. Solis-Guzman et al. (2009) reported that worldwide, C&D wastes represent approximately 35% of the total waste and for Europe the same authors mention that C&D wastes represent 450 million ton/year. However, this figure cannot be taken for granted because it is unlikely that in Europe C&D wastes represent 22% of the total. For instance, the production of MSW ash exceeds C&D wastes more than 20 times (Tiruta-Barna et al. 2007). In the EU 15 the C&D wastes generated per capita are as much as 480 kg, meaning a total of 180 million ton/year. Kofoworola and Gheewala (2009) mentioned C&D wastes generated per capita for different European countries: Austria (300 kg), Denmark (500 kg), Germany (2,600 kg), The Netherlands (900 kg). The Eurostat (2010) mention a total of 970 million ton/year of C&D wastes and 2.0 ton/per capita. In terms of C&D wastes recycling rates, the values also differ from country to country. While the European average is only 25% (Solis-Guzman et al. 2009), some countries may reach 80%, as it happens in Denmark or in The Netherlands (Chini 2005). However, a recent report shows that these rates are very outdated (Table 4.1).

The landfill of C&D wastes generated in EU15 that are not recycled represent a volume with a 10 m height and 13 km^2 surface each year. The benefits of proper waste management are not solely environmental as we already saw in Chap. 1 but also economic. The preservation of biodiversity has a very relevant economic value associated with it. According to Weisleder and Nasseri 2006 the German market for recycled materials generated about 4,940 million euros in 2004, and the employment in this segment increased from 13,357 to 17,000 jobs between 2000 and 2004. A good example of the economic benefits associated with the recycling of C&D wastes is illustrated by the Environment Agency of the U.S. (EPA 2002), which states that the incineration of 10,000 tonnes of wastes can mean the creation

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Table 4.1 Recycling rates of C&D wastes in Europe (Sonigo et al. 2010)

Countries	Recycling rates (%)
Belgium (Flanders)	Over 90
Denmark, Estonia, Germany, Ireland and The Netherlands	Over 70
Austria, Belgium, France, Lithuania, UK	60–70
Luxemburgo, Letónia, Eslovenia	40–60
Average recycling rate for EU-27	47
Cyprus, Czech Republic, Finland, Greece, Hungary, Poland, Portugal and Spain	Below 40
Bulgaria, Italy, Malta, Romania, Slovakia and Sweden	No data available

of one job, the landfill can create six jobs, but if the same amount of waste is recycled it can create 36 jobs.

4.2 Regulations

According to the Waste Management Acts 1996 and 2001, wastes can be defined as "any substance or object belonging to a category of waste which the holder discards or intends or is required to discard, and anything which is discarded or otherwise dealt with as if it were waste shall be presumed to be waste until the contrary is proved". The European waste catalogue-EWC encompasses 20 chapters related to different waste categories:

1. Wastes resulting from exploration, mining, quarrying, physical and chemical treatment of minerals;
2. Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing;
3. Wastes from wood processing and the production of panels and furniture, pulp, paper and cardboard;
4. Wastes from the leather, fur and textile industries;
5. Wastes from petroleum refining, natural gas purification and pyrolytic treatment of coal;
6. Wastes from inorganic chemical processes;
7. Wastes from organic chemical processes;
8. Wastes from the manufacture, formulation, supply and use (MFSU) of coatings (paints, varnishes and vitreous enamels), sealants and printing inks;
9. Wastes from photographic industry;
10. Wastes from thermal processes;
11. Wastes from chemical surface treatment and coating of metals and other materials; non-ferrous hydro-metallurgy;
12. Wastes from shaping and physical and mechanical surface treatment of metals and plastics;
13. Oil wastes and wastes of liquid fuels (except edible oils, 05 and 12);

14. Waste organic solvents, refrigerants and propellants (except 07 and 08);
15. Waste packaging; absorbents, wiping cloths, filter materials and protective clothing not otherwise specified;
16. Wastes not otherwise specified in the list;
17. Construction and demolition wastes (including excavated soil from contaminated sites);
18. Wastes from human or animal health care and/or related research (except kitchen and restaurant wastes not arising from immediate health care);
19. Wastes from waste management facilities, off-site waste water treatment plants and the preparation of water intended for human consumption and water for industrial use;
20. Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions.

Table 4.2 presents Chap. 17 of the EWC related to the construction and demolition wastes.

Figure 4.1 presents a sequence to evaluate whether a waste can be classified as a hazardous one. According to Annex III of the European Council Directive 91/689/EC on hazardous waste, the properties of the wastes which render them hazardous are as follows:

H1: Explosive;
H2: Oxidizing;
H3: A—Highly flammable;
H3: B—Flammable;
H4: Irritant;
H5: Harmful;
H6: Toxic;
H7: Carcinogenic;
H8: Corrosive;
H9: Infectious;
H10: Teratogenic;
H11: Mutagenic;
H12: Substances and preparations which release toxic or very toxic gases in contact with water, air or an acid;
H13: Substances and preparations capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above;
H14: Ecotoxic.

In 1991 the Japanese Government approved the "Recycling Law" under which they set minimum recycling targets for several by-products (Kawano 2003). As a consequence, the recycling percentages increase significantly (Fig. 4.2).

Since 1995 a C&D waste plan was implemented in Belgium. In 1996 the German industry accepted to cut by half the C&D wastes that were landfilled. In 1997 the Government of Finland decided that by the year 2000 50% of this waste

Table 4.2 Chapter 17 of the European waste catalogue-EWC

Code	Description
17	Construction and demolition wastes (including excavated soil from contaminated sites)
1701	Concrete, bricks, tiles and ceramics
170101	Concrete
17 01 02	Bricks
17 01 03	Tiles and ceramics
17 01 06	(*) Mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07	Mixture of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06
17 02	Wood, glass and plastic
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 02 04	(*) Glass, plastic and wood containing or contaminated with dangerous substances
17 03	Bituminous mixtures, coal tar and tarred products
17 03 01	Bituminous mixtures containing coal tar
17 03 02	Bituminous mixtures containing other than those mentioned in 17 03 01
17 03 03	(*) Coal tar and tarred products
17 04	Metals (including their alloys)
17 04 01	Copper, bronze, brass
17 04 02	Aluminium
17 04 03	Lead
17 04 04	Zinc
17 04 05	Iron and steel
17 04 06	Tin
17 04 07	Mixed metals
17 04 09	(*) Metal waste contaminated with dangerous substances
17 04 10	(*) Cables containing oil, coal tar and other dangerous substances
17 04 11	Cables other than those mentioned in 17 04 10
17 05	Soil (including excavated soil from contaminated sites), stones and dredging spoil
17 05 03	(*) Soil and stones containing dangerous substances
17 05 04	Soil and stones other than those mentioned in 17 05 03
17 05 05	(*) Dredging spoil containing dangerous substances
17 05 06	Dredging spoil other than those mentioned 17 05 05
17 05 07	(*) Track ballast containing dangerous substances
17 05 08	Track ballast other than those mentioned in 17 05 07
17 06	Insulation materials and asbestos-containing construction materials
17 06 01	(*) Insulation materials containing asbestos
17 06 03	(*) Other insulation materials consisting of or containing dangerous substances
17 06 04	Insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05	(*) Construction materials containing asbestos

(continued)

Table 4.2 (continued)

Code	Description
17 08	Gypsum-based construction material
17 08 01	(*) Gypsum-based construction materials contaminated with dangerous substances
17 08 02	Gypsum-based construction materials other than those mentioned in 17 08 01
17 09	Other construction and demolition waste
17 09 01	(*) Construction and demolition wastes containing mercury
17 09 02	(*) Construction and demolition wastes containing PCB (for example PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03	(*) Other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

The wastes with (*) are considered hazardous wastes

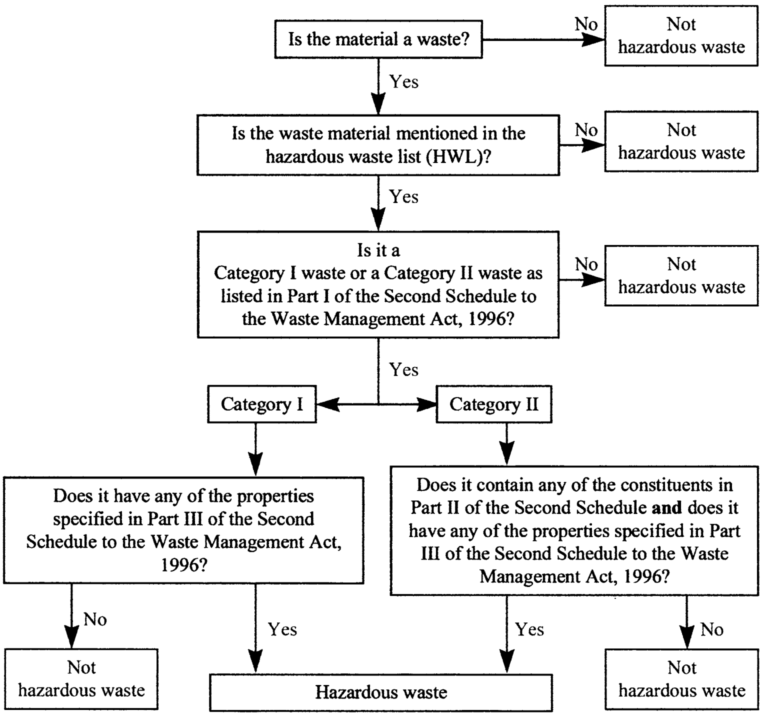

Fig. 4.1 Hazardous waste flowchart

should be recycled. In Spain, the first national plan on C&D waste occured in 2001. On November 19 of 2008 the EU approved the Revised Waste framework Directive No. 2008/98/EC. According to this Directive the minimum recycling percentage for

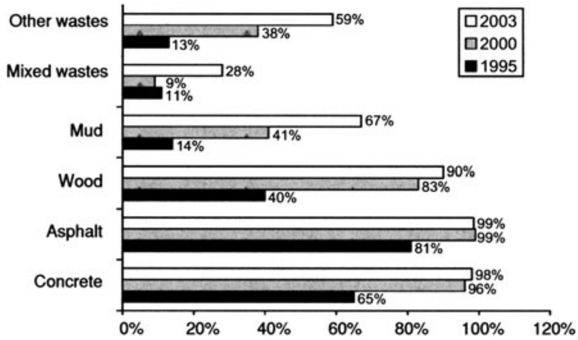

Fig. 4.2 Recycling percentage between 1995 and 2003 (Kawano 2003)

C&D wastes by the year 2020 should be at least 70% by weight. This regulation appears quite promising in order to achieve a more sustainable construction; however, it is unclear why it sets a delay of more than 10 years.

4.3 C&D Waste Management Plan

In order to reduce the C&D wastes several regulations impose the execution of a waste management plan. This plan should contain information about:

- Characterization of the construction works;
- Main waste streams;
- Waste management framework;
- Estimation of the quantities of each material;
- Proposal for minimization, reuse and recycling;
- Transport of the C&D wastes.

According to (DEHLG 2006) a C&D waste management plan should be prepared in case of development projects that exceed any of the following thresholds:

- New residential development of ten houses or more;
- New developments other than the above, including institutional, educational, health and other public facilities, with an aggregate floor area in excess of 1,250 m^2;
- Demolition/renovation/refurbishment projects generating in excess of 100 m^3 in volume, of C&D waste;
- Civil Engineering projects producing an excess of 500 m^3 of waste, excluding waste materials used for development works on the site.

Table 4.3 shows an example of a C&D waste management plan.

Tam (2008) ranked some measures to help the implementation of the C&D waste management plans:

1. Use of prefabricated building components
2. Purchase management

Table 4.3 C&D waste management plan (DEHLG 2006)

Project Name:

[Insert/Add/Delete to Detail as appropriate]

Description of Project:

The Project consists of the _______________(development/redevelopment etc.) of a ________________ (housing/commercial/institutional/roads/water/wastewater etc.) scheme on a ______________ (greenfield/infill/redevelopment/brownfield etc.) site. The project is situated at ________, ____________, Co. _______, in the administrative area of ____________________ Council. The site of the works is located approximately ________ (metres/kilometres) from ________ (town/village/main road etc.) and access will be via the___________ (local/regional/national) road. The work will generally consist of the demolition of ___ (m3) of __________ and the construction of _______ (No./m2) of _________ (houses/offices/institutional/roads etc.).

In the course of the Project, it is estimated that the following quantities of C&D wastes/material surpluses will arise:

C&D Waste Material	Quantity (tonnes)
Clay and Stones	
Concrete	
Masonry	
Wood	
Packaging	
Hazardous Materials	
Other Waste Materials	
Total Arisings	

Table SF1: Estimated C&D Waste Arisings on Site

Proposals for Minimisation, Reuse and Recycling of C&D Waste

C&D waste will arise on the Project mainly from _________ (excavation/demolition) and __________ (unavoidable construction waste/material surpluses/damaged materials). The __________________ (Purchasing Manager etc.) shall ensure that materials are ordered so that the quantity delivered, the timing of the delivery and the storage is not conducive to the creation of unnecessary waste.

Excavated clay will be _________(carefully stored in segregated piles on the site for subsequent reuse/removed from site for direct beneficial use elsewhere). Concrete waste will be ____________ (source segregated/collected in receptacles with mixed C&D waste materials, for subsequent separation and recovery at a remote facility). Masonry and wood will be ____________ (source segregated/collected in receptacles with mixed C&D waste materials, for subsequent separation and recovery at a remote facility). Packaging will be _______________ (source segregated for recycling or return to suppliers). Hazardous wastes will be __________ (identified, removed and kept separate from other C&D waste materials in order to avoid further contamination). Other C&D waste materials will be _______________ (collected in receptacles with mixed C&D waste materials, for subsequent separation and disposal at a remote facility).

Excavation clay and C&D waste-derived aggregates are considered suitable for certain on-site construction applications. It is proposed that the following quantities, corresponding to all C&D Waste arisings from the project, will be used within the works:

(continued)

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C&D Waste Type	Clay and Stones	Concrete	Masonry	TOTALS
Proposed Use	(t)	(t)	(t)	
Earthworks				
General Fill/Hardcore				
Pipe Bedding				
Selected Trench Backfill				
Fill to Structures				
Beneath Paths Structure				
Beneath Road Structure				
Other Site Use A				
Other Site Use B				
Off-Site Use				
TOTAL				

Table SF2: Proposals for Beneficial Use/Management of C&D Material Surpluses/Deficits and Waste Arisings on and off the Project

It is anticipated that waste materials ________(will/will not) have to be moved off site. It __(is/is not) the intention to engage specialist waste service contractors, who will possess the requisite authorisations, for the collection and movement of waste off-site, and to bring the material to a facility which currently (holds/does not hold) a ___________(Waste Licence/Waste Permit/Certificate of Registration). Accordingly, it will be necessary to arrange the following waste authorisations specifically for the Project:

Authorisation Type	Specific Need for Project (Yes/No?)	
Waste Licence	Yes	No
Waste Permit	Yes	No
Waste Collection Permit	Yes	No
Transfrontier Shipment Notification	Yes	No
Movement of Hazardous Waste Form	Yes	No

Table SF3: Specific Waste Authorisations Necessary for the Scheme

Demolition Procedures

The demolition works shall be undertaken in a manner which maximises the potential for recycling, including source segregating waste where appropriate. Activities shall be carried out in the following sequence:

Demolition Activity Sequence	General Description
Disconnection of Services/Vermin Control	Shutoff of E.S.B. , Gas etc.
Inventory of Hazardous Wastes	e.g. Asbestos etc.
Removal of Abandoned Furniture/Equipment	e.g. Furniture/White Goods
Removal of Asbestos/Hazardous Materials	e.g. Application of H&S Procedures
Removal of Fixtures	e.g. Fitted Presses etc.
Removal of Timber	e.g. Removal of Floors, Trusses, Rafters
Demolition of Structure Shell	Manual or Mechanical Demolition
Source Segregation of Material Fractions	Separation into Designated Material Fractions
Transport of Material from Site to Treatment Facilities	e.g. C&D Waste Recycling Facility
Transport of Material from Site to Controlled Disposal Sites	e.g. Inertised Hazardous Landfill Site
Site Preparation/Restoration	e.g. Hardstanding, Landscaping

(continued)

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Assignment of Responsibilities

A _______________ (Site Engineer/Manager/Assistant Manager etc.) shall be designated as the C&D Waste Manager and have overall responsibility for the implementation of the Project C&D Waste Management Plan. The C&D Waste Manager will be assigned the authority to instruct all site personnel to comply with the specific provisions of the Plan. At the operational level, a __________ (Ganger etc.) from the main contractor and ________ (appropriate personnel) from each sub-contractor on the site shall be assigned the direct responsibility to ensure that the discrete operations stated in the Project C&D Waste Management Plan are performed on an on-going basis.

Training

Copies of the Project C&D Waste Management Plan will be made available to all relevant personnel on site. All site personnel and sub-contractors will be instructed about the objectives of the Project C&D Waste Management Plan and informed of the responsibilities which fall upon them as a consequence of its provisions. Where source segregation, selective demolition and material reuse techniques apply, each member of staff will be given instructions on how to comply with the Project C&D Waste Management Plan. Posters will be designed to reinforce the key messages within the Project C&D Waste Management Plan and will be displayed prominently for the benefit of site staff.

Waste Auditing

The C&D Waste Manager shall arrange for full details of all arisings, movements and treatment of construction and demolition waste discards to be recorded during the construction stage of the Project. Each consignment of C&D waste taken from the site will be subject to documentation, which will conform with Table SF4 and ensure full traceability of the material to its final destination.

Detail	Particulars
Name of Project of Origin	e.g. New Harbour, Motorway
Material being Transported	e.g. Soil, Demolition Concrete, Crushed Asphalt etc.
Quantity of Material	e.g. 20.50 tonnes
Date of Material Movement	e.g. 01/01/2007
Name of Carrier	e.g. Authorised Carriers Ltd.
Destination of Material	e.g. Newtown Residential and Office Development
Proposed Use	e.g. Use as Hardcore in Dwelling Floors

Table SF4: Details to be Included within Transportation Dockets

Details of the inputs of materials to the construction site and the outputs of wastage arising from the Project will be investigated and recorded in a Waste Audit, which will identify the amount, nature and composition of the waste generated on the site. The Waste Audit will examine the manner in which the waste is produced and will provide a commentary highlighting how management policies and practices may inherently contribute to the production of construction and demolition waste. The measured waste quantities will be used to quantify the costs of management and disposal in a Waste Audit Report, which will also record lessons learned from these experiences which can be applied to future projects. The total cost of C&D waste management will be measured and will take account of the purchase cost of materials (including imported soil), handling costs, storage costs, transportation costs, revenue from sales, disposal costs etc. Costs will be calculated for the management of a range of C&D waste materials, using the format shown in Table SF5 below:

Material	Estimated Quantities & Costs (tonnes & Euro)
SOIL	
Quantity of Waste Soil (tonnes)	
Purchase Cost i.e. Import Costs (€)	
Materials Handling Costs (€)	
Material Storage Costs (€)	
Material Transportation Costs (€)	
Revenue from Material Sales (€)	
Material Disposal Costs (€)	
Material Treatment Costs (€)	
Total Waste Soil Management Costs (€)	
Unit Waste Soil Management Costs (€)	

Table SF5: Standard Record Form for Costs of C&D Waste Management (Sample relates to Soil – separate record forms should be compiled in respect of each waste material)

Table 4.4 Example of a calculation chart for Wambucalc (Lipsmeier and Gunther 2002)

Cat	Nr	Construction component	Construction design		SUM (kg)	Rate (%)
			Unit	Amount		
Shell						
S	1	Foundation	m^2	81.97	2,156.6	17.1

3. Education and training
4. Proper site layout planning
5. On-site waste recycling operation
6. Implementation of environmental management systems
7. High-level management commitment
8. Install underground mechanical wheel washing machines
9. Identification of available recycling facilitate
10. On-site sorting of construction and demolition materials

This author mentioned that the ''Low financial incentive'' and the ''Increase in overhead cost'' are considered the major difficulties in the implementation of the waste management plan. Other authors (Katz and Baum 2010) mentioned that on-site sorting of construction and demolition materials and waste management can slow down the construction rate.

Estimating C&D wastes. The estimation of the quantities of the different C&D wastes depends on the building system, the characteristics of the demolition and sorting process. It also depends on the amount of buildings under construction, rehabilitation or demolition at any given time, which will influence the quantities of C&D wastes for a certain area or country. Between 1998 and 2002 the University of Minho in Portugal participated in the European waste manual for building construction-WAMBUCO which was coordinated by the University of Dresden (Lipsmeier and Gunther 2002). In this project several card files were developed for specific waste building elements (walls, ceilings, floors and renders). Specific files were also developed for the amount of wastes associated with building construction. The specific card files allow for an estimation of the amount of wastes generated during the construction of a new building using the MS-Excel based Wambucalc software tool (Table 4.4).

The column "Sum" shows the total amount of waste generated during the specified construction component. The column "Rate" it shows the percentage contribution of the construction component on the overall waste generation. If the characteristics of building components are unknown it is still possible to estimate the quantity of waste produced on-site using the building card files. For this purpose it is necessary to know the construction area, the type of building (dwelling house, hotel or office building), and the comfort level (low, medium or high). Figure 4.3 shows the relationship between the floor area and the waste mass for dwelling houses.

Pascual and Cladera (2004) base their estimation of C&D wastes on the existence of a linear correlation between the amount of waste generation and the

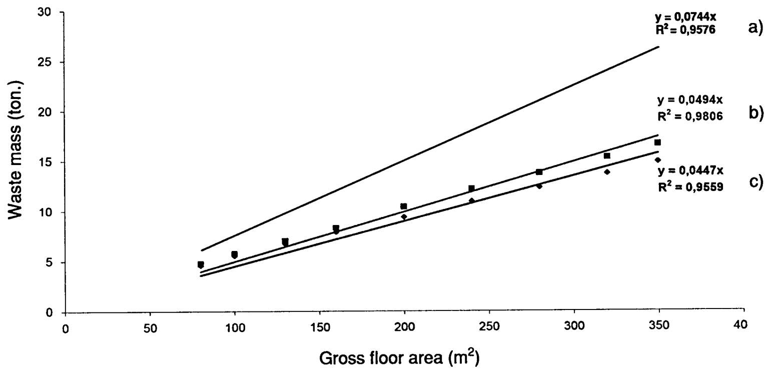

Fig. 4.3 Waste generation for dwelling houses according to the comfort level: **a** high; **b** medium; **c** low (Lipsmeier and Gunther 2002)

Table 4.5 Comparing the amount of C&D wastes generated during the construction phase (Mariano 2008)

Material	Amount of waste (kg/m^2)			
	Mariano (2008)	Monteiro et al. (2001)	Bohne et al. (2005)	Tozzi (2006)
Concrete	9.08	87	19.11	3.0
Ceramics	2.55		–	17.65
Mortar	2.93	189.0	–	18.33
Wood	16.82	3.0	2.75	0.87
Paper	0.16	21	0.46	0.58
Plastic	0.04			2.43
Fiber cement	0.63		0	
Others	1.94		6.19	
Hazardous	–	–	0.07	–
Gypsum	–	–	1.38	–
Glass	–	–	0.12	–
EPS	–	–	0.21	–
Metals	–	–	0.48	–
Total	34.15	300.0	30.77	42.89

consumption of Portland cement.Mariano (2008) analyzed the C&D wastes generated during the construction of a school with a floor area of 4,465 m^2, comparing it with that reported by other authors (Table 4.5)

This author mentioned that the large difference between the total value of 34.15 kg/m^2 and the value of 300 kg/m^2 reported by Monteiro et al. (2001), is due to the fact that in the first case some of the wastes have been reused and also because Monteiro also considered the demolition wastes. The differences between the results of Bohne et al. (2005) and Tozzi (2006) are minor and can be explained

Table 4.6 Efficiency of the waste management plan (Mariano 2008)

Material	Purchased materials (ton.)	Waste materials Q (ton.)	Efficiency (%)
Concrete	2,175.4	40.5	98.1
Ceramics	508.7	11.4	97.8
Mortar	629.8	13.0	97.9
Fibercement	27.6	2.8	89.8
Wood	88.3	75.1	14.9
Total	3,429.8	142.9	95.8

by the differences in the materials used in both cases. Mariano (2008) defines the efficiency of the waste management plan, as the relationship between the amount of materials purchased and the amount of waste generated at the end of the site work, which could not be reused (Table 4.6).

Although the value of the total efficiency is rather high, this form of accounting does not illustrate how much waste is recycled during the construction phase, which is a true measure of efficiency. In addition, this ratio does not allow for comparisons with smaller construction works in which the possibility of C&D wastes reuse is much lower. Solis-Guzman et al. (2009) mentioned that in February of 2008 a Government decree was enforced in Spain related to the C&D wastes management. This regulation requires the execution of a study about C&D wastes during the design phase. It also states that the contractor is responsible for the execution of a C&D wastes management plan. These two parts are required to obtain a building permit and must contain an estimation of the quantities of each waste stream and also an estimate of their treatment cost. The authors describe a new method for the estimation of C&D wastes whose indices were obtained from the study of a sample of 100 buildings. Lage et al. (2010) predict that in 2011 the Spanish region of Galicia will generate 2.2 million tonnes of C&D wastes per year, which corresponds to a ratio of 800 kg/person. In their study they assumed an estimate of 80 kg/m^2 of construction wastes from new constructions (0.11 m^3/m^2), an estimate of 80 kg/m^2 for renovation/rehabilitation works (without demolition) and an estimate of 1,350 kg/m^2 related to demolition wastes. Also, of the total C&D wastes produced, 40% relates to new construction, 20% to rehabilitation works and 40% to demolition works. Kofoworola and Gheewala (2009) used a value of 21.38 kg/m^2 as an estimate for the construction wastes generated in Thailand; this figure is quite low when compared with other countries. These authors mentioned that the reason is related to the fact that construction and maintenance of infrastructure (such as bridges and highways) were not considered. Demolition in any form was also not considered for the same reason. Last but not the least, most of the waste is dumped illegally and not accounted for. According to Katz and Baum (2010) the total amount of waste expected to accumulate exponentially in a residential construction site is estimated at 0.2 m^3/m^2 (Fig. 4.4).

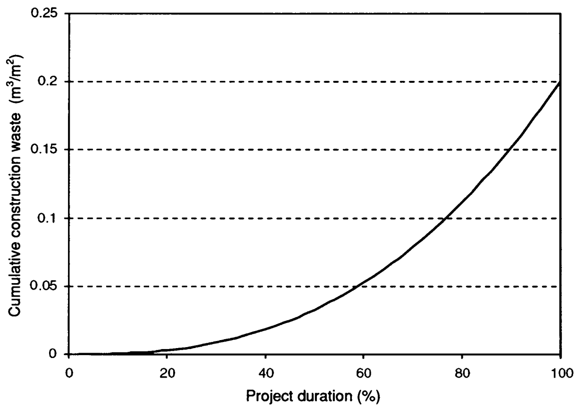

Fig. 4.4 Accumulation of construction waste throughout the project duration (Katz 2010)

4.4 Selective Demolition and Disassembly

Until very recently demolition processes were subordinate to a single principle, the minimization of the time spent in this operation, as a consequence the different waste streams would end all mixed up. However, the need to maximize the reuse and recycling of C&D wastes has forced the appearance of a new principle named "selective demolition" (Lipsmeier and Gunther 2002). The selective demolition involves the removal of components of the building in the inverse direction of its construction (Fig. 4.5).

Given that the selective demolition takes longer and is therefore more expensive than traditional demolition, this means that this technique could only be viable if financial compensation for this option is provided or if the regulations favour selective demolition. Regulations that set very low recycling rates, inhibit the implementation of selective demolition. Harnessing the full potential of selective demolition implies that in the design phase some principles to enhance the disassembly of the building are met (Kibert 2005):

1. Use of recycled and recyclable materials;
2. Minimize the number of types of materials;
3. Avoid toxic and hazardous materials;
4. Avoid composite materials and make inseparable products from the same material;
5. Avoid secondary finishes to materials;
6. Provide standard and permanent identification of material types;
7. Minimize the number of different types of components;
8. Use mechanical rather than chemical connections;
9. Use an open building system with interchangeable parts;
10. Use modular design;
11. Use assembly technologies compatible with the standard building practices;
12. Separate the structure from the cladding;
13. Provide access to all building components;

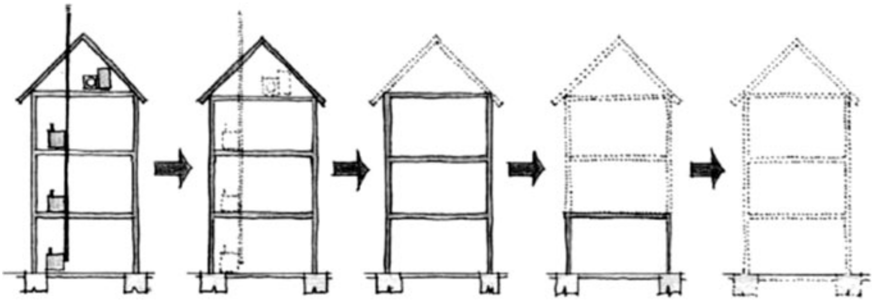

Fig. 4.5 Dismantling of a building in terms of selective demolition

14. Design components sized to suit handling at all stages;
15. Provide for handling components during assembly and disassembly;
16. Provide adequate tolerance to allow for disassembly;
17. Minimize the number of fasteners and connectors;
18. Minimize the types of connectors;
19. Design joints and connectors to withstand repeated assembly and disassembly;
20. Allow for parallel disassembly;
21. Provide permanent identification for each component;
22. Use a standard structural grid;
23. Use prefabricated assemblies;
24. Use lightweight materials and components;
25. Identify the point of disassembly permanently;
26. Provide spare parts and storage for them;
27. Retain information about the building and its assembly process.

According to Thormark (2007) design for disassembly has many environmental, economical as well as social benefits:

Economical motives

- Increased costs for waste handling
- Increased costs for extraction of resource
- Increased score in environmental labelling for demountable buildings
- Increased terminal value for demountable buildings

Social motives

- Demographic changes and changes in household structure
- Buildings are demolished before intended time

Environmental motives

- Increased problems with waste production
- Lack of virgin resources
- Recycling and the quality of the end products

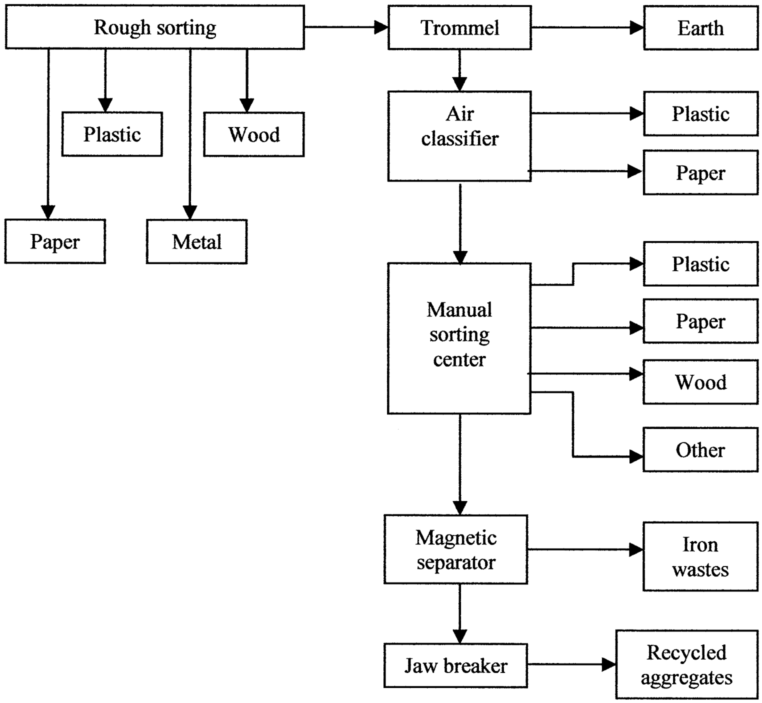

Fig. 4.6 Sorting process for production of recycled aggregates

- Reduced need of energy need for building operation
- Climate changes

4.5 On Site-Sorting and Recycling

On site-sorting allows for the separation of the different stream wastes (paper, wood, metal, plastic, etc.), being a crucial step to increase the recycling rate of C&D wastes. Wang et al. (2011) identified six critical success factors for on-site sorting of construction waste in China.

1. Manpower;
2. Market for recycled materials;
3. Waste sortability;
4. Better management;
5. Site space;
6. Equipment for sorting of construction waste.

The production of recycled aggregates from concrete and masonry wastes represents the most common case of recycling C&D wastes. The reuse of recycled

Table 4.7 Quality criteria for recycled gypsum (Demich 2008)

Parameter	Unit	Quality criteria (% mass)
Humidity	H_2O	<10
Calcium sulfate dihydrate	$C_aSO_4 \cdot 2H_2O$	>95
Chloride	Cl	<0.01
Soluble magnesium salts	MgO	<0.1
Soluble sodium salts	Na_2O	<0.06
Soluble potassium salts	K_2O	–
pH	–	5–9
Toxicity	–	Non toxic

aggregates in concrete is discussed in more detail in Chap. 5, nevertheless, it is important to draw attention to a crucial aspect that can influence the quality of recycled aggregates which has to do with the presence of undesirable materials such as soil, plastics, metals and organic matter. The sorting process can reduce this problem. Figure 4.6 shows the sorting process used for the production of recycled aggregates.

4.5.1 Recycling Gypsum-Based Materials

Gypsum materials can be recycled indefinitely without property loss. The recycling of gypsum materials requires grinding, removal of impurities and a low-temperature calcination. The construction activities directly related to the use of gypsum materials generate large amounts of wastes, either as renders for walls and ceilings or as plasterboards for drywalls. Although no specific values are known for the wastes generated by gypsum renders it is clear that a relevant part of these wastes are due to the fast hardening of the binder. According to Vanderley and Cincotto (2004) gypsum renders are associated with almost 45% of the wastes and plasterboards with about 10% to 12%. The use of recycled aggregates contaminated with gypsum particles for concrete production is a risk factor for concrete durability. The deterioration of concrete is caused by the chemical reaction of sulfate ions with the alumina of the aggregates or with the tricalcium aluminate (C_3A) of the hardened cement paste in the presence of water, both expansion products that can lead to the cracking of concrete. That is why the regulations on C&D wastes limited to less than 1% the presence of SO_3.

The recycling of gypsum plasterboards is already a consolidated reality in several countries. As long as the treatment process can reduce the amount of impurities present in the recovered gypsum this can be an important gypsum source. Table 4.7 defines the acceptance criteria for gypsum obtained from recycled plaster boards according to Eurogypsum.

Figure 4.7 shows the flowchart related to the recycling operations of gypsum plasterboards in Germany.

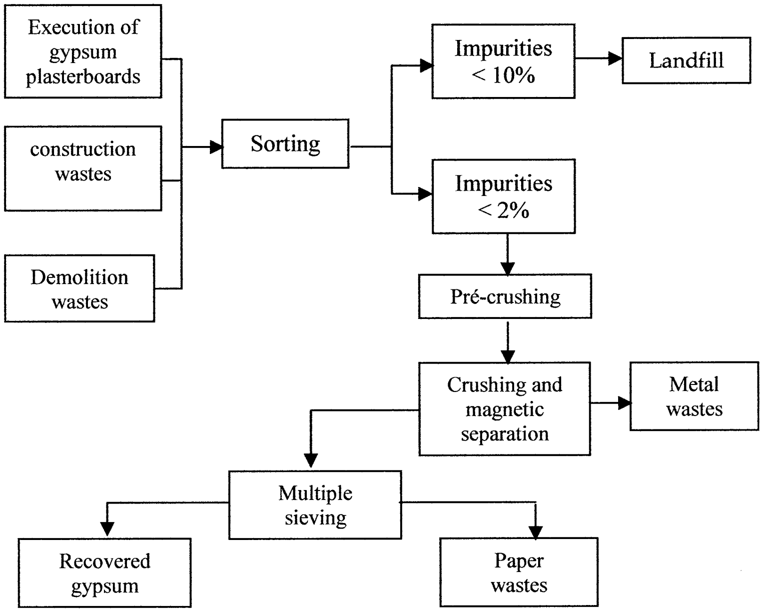

Fig. 4.7 Recycling of gypsum plasterboards. German process (Demich 2008)

4.5.2 Recycling Asbestos-Based Materials

Construction materials with asbestos are considered hazardous wastes under the European waste catalogue (code 170601 and code 170605), nevertheless, the state of the art about asbestos wastes points out to the possibility of their inertization and several industrial processes have already been developed for that purpose: INERTAM (Borderes 2000), ASBESTEX and ARI (Downey and Timmons 2005). The treatment of asbestos-based wastes can be as follows: Thermal treatments; chemical or mechanochemical treatments; microwave treatments (friable asbestos). Gualtieri and Tartaglia (2000) state that the use of a temperature treatment between 1,000 and 1,250°C allows the inertization of friable asbestos and also cement-based asbestos. The temperature is responsible for the transformations of the internal structure of asbestos into new and non-toxic crystalline phases (Fig. 4.8).

Different asbestos fibres present different performances when submitted to calcination operations (Table 4.8). Equations 1 and 2 show the transformations of chrysolite (1) and tremolite (2) asbestos as temperature increases:

$$\underset{\text{Chrysolite}}{Mg_3(OH)_4Si_2O_5} \xrightarrow{500\,^{\circ}C} \underset{\text{Metachrysolite}}{Mg_3Si_2O_7 + 2H_2O} \xrightarrow{500\,^{\circ}C} \underset{\text{Forsterite}}{Mg_2SiO_4} + \underset{\text{Enstatite}}{MgSiO_3} \quad (1)$$

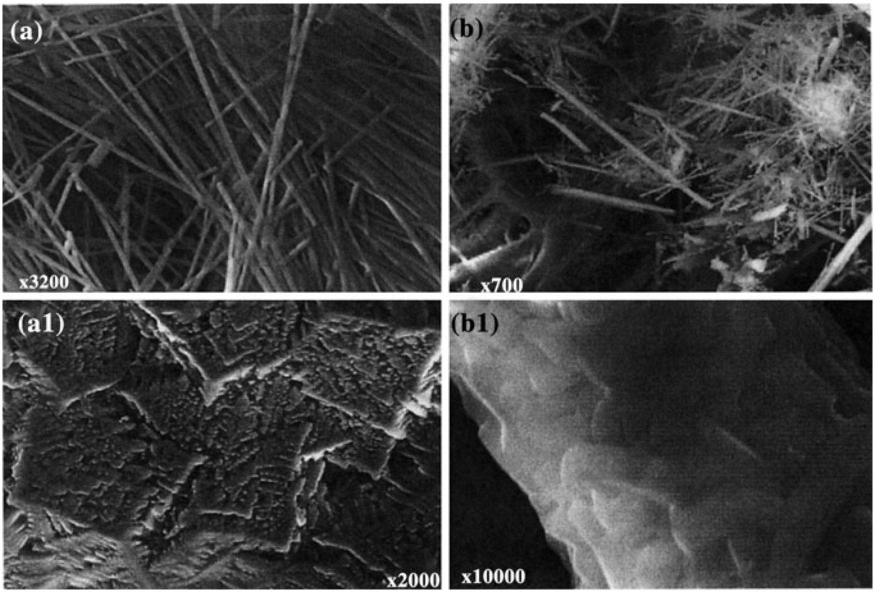

Fig. 4.8 Microstructure of asbestos fibres before and after thermal treatment: **a** and **a1** plain tremolite fibres; **b** and **b1** chrysolite fibres embedded in a cement matrix (Gualtieri and Tartaglia 2000)

$$\underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} \xrightarrow{950\ ^{o}C} \underset{\text{Metatremolite}}{Ca_2Mg_5Si_8O_{23}} + 2H_2O \xrightarrow{1050\ ^{o}C} \underset{\text{Diopside}}{2CaMgSi_2O_6} + \underset{\text{Enstatite}}{3MgSiO_3} + \underset{\text{Chrystobalite}}{SiO_2} \quad (2)$$

Leonelli et al. (2006) studied the inertization of friable asbestos and its incorporation as a magnesium source to produce ceramic-based products. They used a thermal treatment based on microwaves of 2.45 GHz during 13 min. The authors state that the cost of asbestos valorization varies between 0.05 a 0.2 €/kg, which is almost 10 times less than the cost of asbestos landfill disposal. Other investigations by Gualtieri et al. (2008a) confirm these results, referring to the possibility of using 3% to 5% of inertized asbestos in the production of porcelain products. Gualtieri et al. (2008b) patented a tunnel capable of achieving the inertization of asbestos cement wastes by using a temperature of 1,200°C during 16 h. This method has the advantage that it does not need the opening of the asbestos packing and does not require grinding operations. The authors use a low melting glass to reduce the calcination temperature. Dellisanti et al. (2009) refer to a pilot installation using the Joule vitrification method, in which a high intensity electric power (130 A) can melt the asbestos wastes at 1,500°C. Other authors (Plescia et al. 2003) used a mechanochemical treatment to change the morphology of the asbestos fibres into a

Table 4.8 Chemical and physical properties of common asbestos minerals (Leonelli et al. 2006)

Characteristic, chemical analysis (avg)	Serpentine, chrysotile $Mg_3Si_2O_5(OH)_4$	Amphibole				
		Crocidolite $Na_2Fe^{2+}3Fe_2^{3+}(Si_8O_{22})(OH)_2$	Amosite $(MgFe^{2+})7Si_8O_{22}(OH)_2$	Anthophyllite $Mg_7(Si_8O_{22})(OH)_2$	Tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$	Actinolite $Ca_2(MgFe^{2+})5Si_8O_22(OH)_2$
SiO_2	38–42	49–56	49–52	53–60	55–60	51–56
Al_2O_3	0–2	0–1	0–1	0–3	0–3	0–3
Fe_2O_3	0–5	13–18	0–5	0–5	0–5	0–5
FeO	0–3	3–21	35–40	3–20	0–5	5–15
MgO	38–42	0–13	5–7	17–31	20–25	12–20
CaO	0–2	0–2	0–2	0–3	10–15	10–13
Na_2O	0–1	4–8	0–1	0–1	0–2	0–2
Others	11.5–13	1.7–2.8	1.8–2.4	1.5–3	1.5–2.5	1.8–2.3
Decomposition temperature (°C)	450–700	400–600	600–800	600–850	950–1,040	620–960
Fusion temperature of residual material (°C)	1,500	1,200	1,400	1,450	1,315	1,400

non-toxic form. For friable asbestos Takahashi et al. (2009) reported a temperature treatment of 175°C during 24 h and the use of an NaOH (14 M) solution. Anastasiadoua et al. (2010) used a solution of acetic acid, a temperature range between 300 to 700°C and a pressure between 1.75 and 5.8 MPa. Zaremba et al. (2010) reported the detoxification of chrysotile asbestos through a low-temperature heating and grinding treatment with temperatures ranging from 500 to 725°C during 3h. Boccaccini et al. (2007) also used a microwave treatment to achieve the inertization of friable asbestos, turning fibrous structures into magnesium oxide blocks. The thermal treatment of asbestos cement wastes lead to a much lower toxicity level (Giantomassi et al. 2010). More recently Gualtieri et al. (2011) presented results on the reuse of calcined asbestos cement waste into brick, glass, plastics and pigments.

4.5.3 Recycling Concrete with a "Heating and Rubbing Method"

The recycling of concrete structures and masonry walls is carried out through various fragmentation operations (crushing and grinding). In order to reduce the dimensions of the concrete pieces jaw crushers, hammer mills and other mechanical devices are used. Although sorting operations can separate ceramic aggregates from concrete aggregates it is not easy to separate the rock fraction from the cement paste. Coarse aggregates with a cement paste have a higher water absorption reducing the performance of concrete (see Sect. 5.3). Moreover, assuming that the recycling plants will receive and process C&D wastes from numerous sources a dispersion of the properties of the recycled aggregates will increase leading to an increase in the dispersion of the quality of concrete. Shima et al. (2005) studied the possibility of submitting the concrete waste to a heat treatment in order to achieve a complete separation between the aggregates and the cement paste. They mentioned that using a heat treatment between 300 and 500°C allows obtaining aggregates identical to the original ones. The temperature rise causes the evaporation of the hydration water making the cement paste rather fragile, and the use of mechanical energy facilitates the separation between the aggregate and the binder. Mulder et al. (2007) used a similar procedure to separate the aggregates from the binder, however, they reported the need for a temperature near 700°C.

4.6 Conclusions

C&D wastes are a problem of increasing magnitude, however, reliable statistics are lacking because in most countries these kinds of wastes are illegally dumped. For instance there are no data on the recycling percentage of several European countries. Appropriate regulations on the recycling rates constitute a crucial step towards a more sustainable C&D wastes management. Several regulations impose the execution of a waste management plan, representing a crucial step towards C&D wastes reduction. The revised waste framework directive no. 2008/98/EC that sets the minimum recycling percentage for C&D wastes at least 70% by weight until the year 2020 will surely increase the recycling rate in the European area. The success of the C&D wastes recycling is also dependent on the demonstration of the economic advantages associated with it as happened with the techniques that made possible the inertization of asbestos-based materials. Quite appealing is the study of the EPA mentioning that C&D waste recycling allows the creation of a six-fold job increase than their disposal in a landfill. The use of selective demolition will increase the recycling rate of these wastes, and if disassembly principles were used during the design phase this will favour the selective demolition efficiency.

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