# Chapter 2
# Recycled Aggregates for Concrete Production: State-of-the-Art

## 2.1 Construction and Demolition Waste

All the waste materials coming from construction and demolition operations are known as C&DWs. These materials represent one of the most voluminous stream of waste generated in the world, accounting for about 25–30 % of the whole waste produced in the EU. As an indicative data, approximately 3 billion tons of waste are generated in EU 27 each year. Of this, around one third (1 billion tons) comes from construction and demolition activities [1]. C&DW typically comprises large quantities of inert mineral materials, with smaller amounts of a range of other components, depending on the source and separation techniques. The Waste Framework Directive 2008/98/EC [2] excludes from its definition the uncontaminated soil and other naturally occurring material, which are excavated during construction activities, when the material is used, and remains on site. However C&DW definition and composition may vary from state to state (e.g. with respect to the inclusion of excavated soil), and hence some caution is needed when reviewing statistics about its production in Europe and, more generally speaking, around the world. In the US total C&DW was estimated to be 170 million tons in 2003 [3]: a large fraction of this amount ends up in C&D landfills, and barriers to materials recovery still exist. Several reasons can explain the still low valorization of C&DW, including that buildings are not designed to be nor reused nor recycled, there is a lack of recovery facilities in some areas, and for some materials, the demand is too low due to the unwillingness to use recycled materials in place of virgin ones principally for some regulatory preventions. The competitiveness of C&DW recycling could be improved with several operations, i.e. raising the price of raw materials, through taxation, and setting End-of-Waste criteria for certain C&DW fractions [4].

Concerning C&DW composition, generally it is divided into five main fractions: metal, concrete and mineral, wood, miscellaneous and unsorted mixed fraction. More precisely, it may contain:



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- concrete;
- bricks, tiles and ceramics;
- wood;
- glass;
- plastic;
- bituminous mixtures and tars;
- metals (ferrous and non-ferrous);
- soils and stones;
- insulation materials (including asbestos);
- gypsum-based materials (including plasterboards);
- chemicals;
- waste electronic and electrical equipment (WEEE);
- packaging materials;
- hazardous substances.

In this list several hazardous substances appear, which are generally present in building materials because they are used, together with concrete, for completing the structure and for realizing the finishes. These substances are asbestos (found in insulation, roofs and tiles and fire-resistant sealing), lead based paints (found on roofs, tiles and electrical cables), phenols (in resin-based coatings, adhesives and other materials), polychlorinated biphenyls (PCBs) (which can be found in joint sealing and flame-retardant paints/coats, as well as electrical items) and polycyclic aromatic hydrocarbons (PAHs) (frequently present in roofing felt and floorings). The composition of C&DW generally varies highly in relation to the site, because of the local typology and construction technique, climate conditions, economic activities and technologic development of an area, and hence it is difficult to define univocally a composition representative for a large region. The composition of C&DW is also changing during time, due to ageing of the existing buildings and to the low-quality structures, especially build between 1960s and 70s, which are coming to the end of their lifetimes and needing demolishing [5]. Selective demolition of existing structures can determine clear benefits in this context: it would not only reduce the amount of waste destined to landfill, but also increases the quality of the recycled aggregates, minimizing the quantity of impurities and contaminant in the C&DW [6]. However this approach is still under debate, mainly because of the slight practical value and economic benefit, even though some Countries are encouraging this practice [7]. Additionally, in the next future, waste management will be more controlled by the waste treatment BAT reference document (WT BREF) currently under preparation, including when dealing with C&DW management [8].

Concerning C&DW composition, as an indicative data, also inside a single State, it can be very different: for instance in Northern Italy, soils and stone represent the 17 % of the whole waste, but in Central Italy this datum decreases until the 4 % [9]. In average, Italian composition of C&DW is constituted by about 32 % of mixed construction and demolition waste, 27 % of a mixture of concrete, bricks, tiles and ceramics, 14 % of iron and steel, and 11 % of bituminous mixtures. In the typical Finnish C&DW, wood and mineral materials constitute the predominant fraction (respectively about 36 and 35 %), followed by metal (nearly to 14 %) and the rest is other materials e.g. glass, plastic, gypsum and mixed waste [10]. In Germany 72.4 million tons of building waste were produced in 2007, corresponding to a recycling rate of about 68%: around 70 % is constituted by mineral debris from buildings, concrete and asphalt together represent about 25 %, and construction site waste is about 3 %, including gypsum-based waste [9]. In Greece, C&DW exceeded 3.9 million tons in 2000, representing about 656 kg per capita [11]. In Great Britain the production of recycled aggregate follows a WRAP Quality Protocol, and about 60 % of the recycled C&DW is used as aggregate, general fill or land reclamation. Around 17 % of UK aggregate needs are already met from recycled material [12]. Japan is one of the country where recycling of C&DW is more advanced: by 2000, demolished concrete was recycled up to 96 %, exceeding the target (90 %) proposed by the Japanese Ministry of Construction in the "recycled 21" program in 1992. RCA is applied almost at all as sub-base material for road carriageways [13]. Norwegian C&DW comes both from residential and non residential sources: in 2003 it was estimated that 1.256 million tons were generated, being principally constituted by concrete and bricks (about 67 %) [14]. In the US, 170 million tons of C&DW were produced in 2003: 39 % came from residential and 61 % from nonresidential sources. Cochran et al. [15] estimated that about 3.75 million tons of C&D waste were generated in 2000 in Florida, constituted mainly by concrete, representing the 56 % of all the waste. In Asia various studies have been done separately in some cities: in Shangai C&D waste generation estimate was 13.71 million tons in 2012, and waste concrete, bricks and blocks represented more than 80 % of the whole [16].

The official data regarding the non-hazardous inert wastes' recycling in Italy indicate that there are about 52 million tons of C&DWs produced per year [9], even though this number is poorly reliable. Between these, a relevant number of this waste is constituted by contaminated soils, which are generally also sent to inert waste treatment plants. Technology for separating and recovering C&DWs is well established, readily accessible and in general inexpensive. During the process of recycled aggregate production, the undesirable fractions are eliminated, and through grading and sorting, recycled aggregates are obtained. Also at the European level, the statistical significance of figures about C&DWs production is quite poor, and the different available sources are reporting fragmented data and several discrepancies. Currently the level of recycling and material recovery of C&DW varies greatly (between less than 10 % and over 90 %) across the Union, even though this number should increase and be homogenized in the next future, according to Article 11.2 of Waste Framework Directive [2], which states that "*Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70 % (by weight) of non-hazardous construction and demolition waste excluding naturally occurring material defined in category 17 05 04 in the List of Wastes shall be prepared for re-use, recycled or undergo other material recovery*" (including

**Table 2.1** CDWs European production [17]

| State | (×1000 ton) | State | (×1000 ton) |
|---|---|---|---|
| Belgium | 22,239 | Lithuania | 357 |
| Bulgaria | 2235 | Luxembourg | 8867 |
| Czech Republic | 9354 | Hungary | 3072 |
| Denmark | 3176 | Malta | 988 |
| Germany | 190,990 | Netherlands | 78,064 |
| Estonia | 436 | Austria | 9010 |
| Ireland | 1610 | Poland | 20,818 |
| Greece | 2086 | Portugal | 11,071 |
| Spain | 37,497 | Romania | 238 |
| France | 260,226 | Slovenia | 1509 |
| Croatia | 8 | Slovakia | 1786 |
| Italy | 59,340 | Finland | 24,645 |
| Cyprus | 1068 | Sweden | 9381 |
| Latvia | 22 | United Kingdom | 105,560 |
| Liechtenstein | 0 | Norway | 1543 |

backfilling operations using waste to substitute other materials). According to the Eurostat [17], the C&DWs production of the European countries in 2010 is reported in Table 2.1, overall representing about 867 million tons.

C&DWs are characterized by high potential for recycling and re-use, since some of their components have high resource value, particularly with respect to a re-use market for recycled aggregates. Depending on their quality, recycled aggregates coming from C&DWs can be employed in roads, drainage and other construction projects, including structural concrete production. However this recycling potential is still under-exploited, especially in those States where the recycling rate is still low.

### *2.1.1 Processing Procedures for Recycled Aggregates Production*

Two categories of plants are available for treating C&DWs and processing them into recycled aggregates: stationary and mobile ones. Stationary facilities are recycling plants located in an enclosed site authorized to recycle C&DW, through the use of fixed equipment and conducting no off-site operations. Mobile recycling machinery and equipment are instead sent to worksites to recycle waste at the source. The same equipment (screens, crushers, magnetic separators, etc.) is furnished by modules that allow recycling operations directly on the site.

Fixed plants may have the disadvantage of being far from the site where demolition takes place, but generally the system is more productive than the mobile one (and therefore the burden associated to the increased transport is compensated by the better quality of the product and the higher capacity of the plant). Stationary plants generally process also natural aggregates and have higher capacity than mobile ones, allowing to limit the processing cost of the recycled aggregate (economies of scale). In Spain for instance there is a predominance of stationary facilities (48 stationary, vs. 1 mobile), even though in the last years some of them (4.1 %) temporarily engaged in mobile equipment rentals for off-site operations [18]. On the contrary, in Piemonte region (Italy) mobile plants account for 83% of the total and stationary facilities for only 4.4 % [19].

Plants can accept different types of C&DW, depending essentially on the basis of how clean it is and the materials it contains. The standard classification of the input material is clean, mixed and dirty. Preliminary cleaning can be performed through separation (typically in dry conditions), to eliminate impurity e.g. wood, plastic and paper. Magnetic separation is also useful to remove steel and iron from the input material.

The same processes take place in both the plants, aiming to separate the contaminants from the bulk stony material, and to obtain a useful grading:

- separation;
- crushing;
- separation of ferrous elements;
- screening;
- decontamination and removal of impurity (i.e. wood, paper, plastics,…).

The first operation to be done aims to reduce the debris dimensions, which have to be used to feed easily the crusher. Then, several operations, mainly mechanical actions, are conducted to reduce again the size of the material, being grinding, squeezing and impacting. Primary and secondary crushing could be performed, with milling operations, to achieve the required grading. At the end of the productive chain, washing could also be done, even though this procedure is not very common due to the difficulties in the produced mud disposal (both in terms of costs and administrative procedures).

A simplified scheme of a C&DWs treatment plant is represented in Fig. 2.1.

### *2.1.2 International Codes, Guidelines and Regulations*

Recycled aggregates (RA) coming from C&DWs are valuable materials, for which a re-use market already exists, and it consists mainly in earthworks, road base, pavements and other construction applications. From an economical point of view, they are particularly attractive in densely populated areas, i.e. where demand and supply are close together. In those cases, low transportation costs and limited availability of natural aggregates are key factors that make recycled aggregate

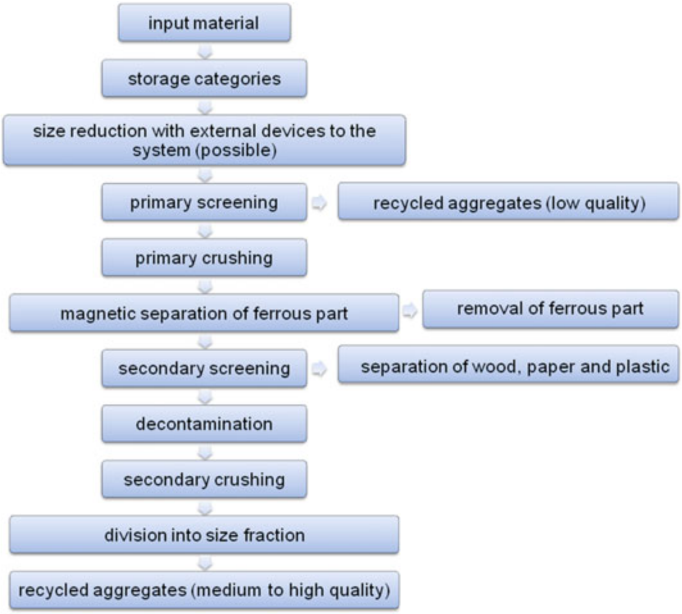


**Fig. 2.1** Scheme of a C&DWs treatment plant

competitive with their natural counterparts, without any necessity of specific policy instruments (e.g. taxation of raw natural materials).

Their use in structural concrete production has been widely explored in literature, principally at the lab-scale level, often reporting good results when the replacement ratio of natural aggregates is limited, and high quality RA are used. However, the international codes, guidelines and recommendations vary greatly from country to country, with respect to the maximum allowable quantity and quality allowed in structural concrete mixtures. In this section a brief outline of the current situation about the existing codes and normative regulating the use of recycled aggregates is given, paying a particular attention on their application for concrete production.

**Belgium** In Belgium, the set of standards which regulates the use of recycled aggregates is made up by the existing European ones:

- EN 13242:2008—Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction [20];
- EN 13043:2002—Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas [21];
- EN 13285:2010—Unbound mixtures—Specifications [22];
- EN 14227 serie—Hydraulically bound mixtures [23].

Recycled aggregates characterization is performed using the existing standards for natural aggregates, and additionally, with:

- EN 933-11:2009—Tests for geometrical properties of aggregates—Part 11: Classification test for the constituents of coarse recycled aggregate [24];
- EN 1744-6:2006—Tests for chemical properties of aggregates—Part 6: Determination of the influence of recycled aggregate extract on the initial setting time of cement [25].

A national standard, PTV 406 Technical Prescription "Recycled aggregates from construction and demolition waste" [26] also exists, and it regulates the composition of the recycled aggregate that could be used in concrete production. Three RA classes are defined: recycled concrete aggregate (RCA), recycled masonry aggregate (RMA), and mixed aggregate, being a mixture of both concrete and masonry aggregates.

The use of recycled aggregates for concrete production is regulated through the European existing standards, and it is limited to the coarse recycled concrete aggregate fraction (CRCA). It can be used in the exposure class X0 and XC1, and Belgian environmental classes E0 and E1. Concretes produced with these aggregates should have a maximum strength class limited to C25/30; when higher strength classes and different exposure conditions are used, the technical validity should be experimentally demonstrated. The maximum allowed substitution ratio is 20 % in volume of the total coarse aggregates in the mixture.

**Germany** In Germany, the set of standards which regulates the use of recycled aggregates for concrete production is given by the European existing ones, and additionally by the standard DIN 4226-100 [27]. In the latter, some specifications about the aggregates requirements in relation to the field of application are defined. Four types of RA are allowed (Type 1–4), depending on the content of 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. For each class of RA, two acceptance criteria are defined: oven-dry density and absorption ratio of aggregate. The limits are reported in Table 2.2.

**Table 2.2** Acceptance criteria for RA according to German standards

| | Oven-dry density criterion (kg/m$^3$) | Absorption ratio of aggregate criterion (%) |
|---|---|---|
| Type 1: concrete chippings/concrete crusher sand | $\geq 2000$ | $\leq 10$ |
| Type 2: construction chippings/construction crusher sand | $\geq 2000$ | $\leq 15$ |
| Type 3: masonry chippings/masonry crusher sand | $\geq 1800$ | $\leq 20$ |
| Type 4: mixed chippings/mixed crusher sand | $\geq 1500$ | No requirement |

Only the chipping of concrete according to type 1 and type 2 (as defined in the above standard) can be used for concrete production. Type 1 RA can be associated to a RCA: it contains at least 90 % of concrete and natural aggregates, not more than 10 % of clinker, non-pored bricks, sand-lime bricks, less than 2 % of other mineral materials and less than 1 % of asphalt. Foreign substances such as glass, metal slag, etc. should be less than 0.2 %. Type 2 RA contains instead at least 70 % of concrete and natural aggregates, not more than 30 % of clinker, non-pored bricks, sand-lime bricks, less than 3 % of other mineral materials and less than 1 % of asphalt. Other substances can be present in a quantity not greater than 0.5 %.

The other type of aggregates, i.e. masonry chippings and mixed chippings are excluded from the reuse as aggregate in structural concrete. Additionally also crusher sand is excluded from the reuse as recycled aggregate: the minimum RCA diameter allowed is 2 mm. Further limits are reported in the German Committee for Reinforced Concrete (DAFSTB) Code [28]: Concrete with Recycled Aggregate, where a limitation on the strength class (C30/37) and on the substitution ratios are given in relation with the exposure class and application (Table 2.3).

**Great Britain** In Great Britain the normative distinguishes two types of recycled aggregates, RCA and RA, the former coming just from concrete-based material, characterized by a limitation of about 5 % in masonry content (in weight), and the second from a mixed waste. The complementary UK Standard to EN 206-1, BS 8500-2 2015 [31], limited the use of RA to the production of road surfaces or underpinning works [9]. The use of recycled aggregates is limited until C16/20 strength class, and only in the mildest structure exposure conditions. This choice is governed by the absence of a specific regulation about recycled aggregates use, which is reflected in a great variability of their properties, composition and origin. Concerning the RCA, they are admitted to partially substitute natural aggregates, until 20 % in weight, up to concrete strength class C40/50, and within prescribed exposure classes: X0, XC1, XC2, XC3, XC4, XF1, DC-1. Exposure to salt (XS, XD) and severe freeze-thaw (XF2–XF4) are excluded. Higher replacement ratio are allowed only with documented experimental results, hence if the prescriber takes his own responsibility for the results.

**Italy** In Italy, the existing set of European standards are applied to characterize recycled aggregates. The approach is very similar to the other European countries. The Italian Code for constructions regulates the maximum allowable quantities of RA in concrete, with respect to concrete strength class and exposure conditions [32], as reported in Table 2.4.

**Table 2.3** Substitution ratio (in % by volume) according to EN 206-1 [29] and DIN 1045-2 [30]

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

**Table 2.4** Maximum allowable quantity of RA in concrete according to Italian normative

| Origin of recycled aggregate | Concrete class | Rate of use |
|---|---|---|
| Demolition of building (debris) | =C8/10 | Up to 100 % |
| Demolition of concrete or reinforced concrete | ≤C30/37 | Up to 30 % |
| | ≤C20/25 | Up to 60 % |
| Reuse in certified precast concrete industries—any class of concrete | ≤C45/55 | Up to 15 % |
| Reuse in certified precast concrete industry—class of concrete > C45/55 | Same class of original concrete | Up to 5 % |

The Code however does not provide any information about the values of mechanical or physical properties that the recycled aggregates should comply with; these limits are present in the EN standards, specifically in the EN 12620 "Aggregates for Concrete" [33]. This standard defines the properties needed by the aggregates to comply with the requirements stated in the EN 206-1 [29]. The Italian standards UNI 8520-1 [34] and UNI 8520-2 [35] provide some complementary instructions necessary to apply the above standard. Lastly, UNI EN 13242 "Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction" [20] provides the possible applications of recycled aggregates in specific fields, i.e. civil engineering work and road construction.

**Japan** In Japan, three types of recycled aggregates are currently considered, depending on their quality in terms of composition and physical properties: high-quality recycled aggregates (type H), medium-quality (type M) and low-quality (type L). One of the first regulation in the field of recycled aggregate use was JIS A 5021 [36], which established standards for high-quality recycled aggregate use in concrete since 2005. This standard has been recently substituted with the novel JIS A 5021:2011 [37]. Recycled aggregates type H is produced through advanced processing, including crushing, grinding and classifying, of concrete masses generated in the demolition of structures. Class H recycled aggregates should comply with stricter limits about composition, contaminants content and physical properties with respect to medium-quality M [38] and low-quality recycled aggregates L [39].

Type H aggregates, characterized by not more than 3 % of other non concrete and non virgin aggregates material, can be used, without restrictions, in structures with nominal strength lower than 45 MPa. Type M aggregates can be used in members that are not subjected to frost action, such as piles, underground beams, and concrete filled in steel tubes. Lastly, type L could be used in backfilling, filling and leveling concrete applications. The latter type of aggregates can be used only with type B blended cements, as a measure against alkali-aggregates reactivity. The acceptance criteria for RA (type H, M and L), in terms of minimum OD (oven-dry) density and maximum absorption ratio, are specified in Table 2.5.

**Table 2.5** Acceptance criteria for RA according to Japanese standards

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

**Netherlands** In the Netherlands, the set of standards which regulates the use of recycled aggregates for concrete production is given by the European existing ones, and additionally by the standard NEN 5905 [40], where the requirements that RA should satisfy are reported. Two types of recycled aggregates are defined, depending on their composition. The current normative allows the use of RCA, characterized by at least 95 % of concrete-originated material, for concrete manufacturing for pre-stressed and reinforced structures, but it is limited to the coarse fraction (CRCA). RCA should not contain more than 5 % of masonry, 0.1 % of organic materials, and 1 % of impurities (asphalt is not included in this definition). It should satisfy three minimum requirements in terms of minimum OD density, maximum chloride and sulfate content, being respectively 2000 kg/m$^3$, 0.05 and 1 %. CRCA can be applied in structures with a maximum strength class equal to C40/50, and in non-aggressive environments. For non-structural concrete (i.e. strength class lower than C16/20), also mixed RA can be used: this type of aggregate should satisfy the same physical and chemical requirements of RCA, but its composition can be made by until 65 % of masonry and 1 % of organic material.

**Portugal** In Portugal the use of recycled aggregates for structural purposes is regulated by the LNEC E 471 standard [41]: this specification classifies coarse recycled aggregates and defines minimum requirements for their use in concrete. Various other standards exist about the use of RA for several applications: LNEC E 472 [42] focuses on hot mix asphalt applications, LNEC E 473 [43] is about unbound pavement layers, and LNEC E 474 [44] is about embankment and capping layer of transport infrastructures.

Three types of recycled aggregates are defined with respect to their composition, e.g. concrete, masonry, asphalt, floating matter and other materials content, according to the classification reported in Table 2.6. Only classes ARB1 and

**Table 2.6** Classification of recycled aggregate according to Portuguese normative

| Classes | Concrete (%) | Masonry (%) | Bituminous (%) | Contaminant (%) | Floating (%) |
|---|---|---|---|---|---|
| ARB1 | $\geq 90$ | $\leq 10$ | $\leq 5$ | $\leq 0.5$ | $\leq 0.2$ |
| ARB2 | $\geq 70$ | $\leq 30$ | $\leq 5$ | $\leq 1$ | $\leq 0.5$ |
| ARC | $\geq 90$ | – | $\leq 10$ | $\leq 2$ | $\leq 1$ |

ARB2, which are made principally by concrete-origin aggregates, are allowed to be applied into structural concrete. Class ARC is excluded from structural applications: coarse ARC aggregate can be only used for non-structural applications, i.e. leveling and filling concrete, in non-aggressive exposure classes. It is worth noting that, for these applications, no limits about the maximum replacement level exist for ARB1 and ARB2 types.

The replacement ratio for structural application is defined in accordance with the exposure and strength class of the structures were they will be placed: ARB1 aggregates can be used in structures with a maximum strength class of C40/50, up to 25 % replacement of natural aggregates. ARB2 aggregates can instead be used in structures with maximum strength class of C35/45, up to 20 % replacement of natural aggregates. In both the cases, the exposure classes of the structure where they will be placed is limited in certain ranges, and it should fall within the followings: X0, XC1, XC2, XC3, XC4, XS1 and XA1. The use of fine recycled aggregates for concrete production is not allowed. In addition, concrete produced with recycled aggregate could not be used in structures in contact with water for human consumption.

**Spain** In Spain the use of recycled aggregates for structural concrete application is regulated by the Structural Concrete Instruction EHE-08 [45]. RA should comply with some compositional requirements, i.e. ceramic materials must not exceed 5 % of the total weight sample, light particles, asphalt and other impurities such as glass, plastic, etc, should not exceed 1 %. The Code fixes the limit of maximum substitution ratio for structural concrete applications equal to 20 % in volume of the whole coarse aggregates. The maximum characteristic compressive strength of the structures where RA could be placed should be 30 MPa. For non-structural concrete applications, in the Annex 18 of the previous Code, the maximum allowable content of RA could arise up to 100 % of the whole coarse aggregates.

**US** In the United States there is no regulatory barrier to the use of recycled concrete aggregate in structural concrete: since 1982, ASTM C33 [46] has included crushed hydraulic cement concrete in its definition of coarse aggregate, while ASTM 125 [47] allowed crushed hydraulic-cement concrete as manufactured sand. However the use of recycled concrete aggregate still remains limited for structural purposes.

### *2.1.3 RAC Concrete—Mixture Proportioning*

For satisfactorily high quality concrete, recycled aggregate must comply with some minimum requirements, mainly concerning chemical stability and physical–mechanical characteristics. International codes and standards establish different requirements, in relation to the specific necessity of each Country, the composition of the input C&DW, the available construction techniques and climate conditions. In general terms, high quality RA are mainly constituted by low quantity of masonry aggregates (less than 5 % in weight of the sample), low content of impurities, OD density should be comparable to the natural aggregates one, and water absorption should be limited.

Mix proportions also greatly influence the final performance of concrete. In particular, the design of recycled aggregate concrete (RAC) is usually carried out by simply replacing the Natural Aggregate (NA) of a Natural Aggregate Concrete (NAC) with recycled material. Differences in physical properties among aggregates, such as surface texture and water absorption, are just taken into account as a parameter which the aggregates should comply with. When replacement ratio is limited (not greater than 20 %), ordinary performances concrete made with RCA (mostly composed by concrete-material) are not affected by the substitution. However, when the substitution ratio increases, or when specific performances are required, e.g. durability in severe exposure conditions, high strength, etc., the use of RCA may determine a loss of performances, both in mechanical and durability terms.

Typically, when designing RAC, RA is taken as NA, through two possible methods: Direct Volume Replacement (DVR), and Direct Weight Replacement (DWR), substituting NA with an equivalent amount of RCA in volume or weight percentage respectively. This is the main cause of the poor mechanical performance often reported in the literature when different kinds of RAC mixes were tested [48–50], principally in the test conditions above reported (high replacement ratio, high strength target, severe exposure conditions). A novel method, recently introduced by Fathifazl et al. [51], called Equivalent Mortar Volume (EMV), has been used to prevent the strength losses often reported in literature. The method basically considers RCA as a two-phase material, composed of NA and the mortar attached to it (here denoted as RM, residual mortar), which must be quantified and counted in the proportion of the mix (Fig. 2.2). Since the physical properties of RCA are affected by the RM quantity and characteristics, this method can directly account for any deficiencies in low-quality aggregate, balancing the mix without affecting the mechanical and durability-related performance of the final concrete. This allows the RAC mix to be prepared with a similar internal structure to that of NAC [52, 53].

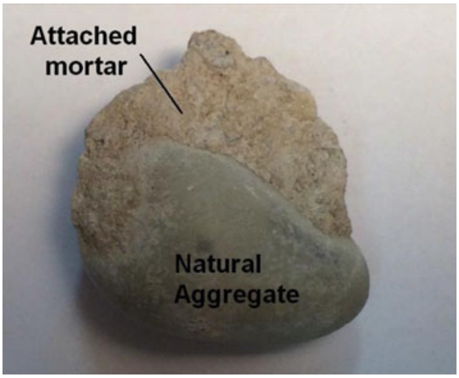


**Fig. 2.2** Recycled concrete aggregate

As regards possible workability problems, replacement of NA by RA generally confers greater stiffness to concrete, as confirmed by the lower slump values often reported in the literature when testing the fresh properties of recycled concretes. Several authors have confirmed this problem [54, 55], arguing that the reasons for this behavior are closely related to the physical properties of the RA: higher water absorption, higher angularity and rough surface texture. The lower quality of the recycled aggregates, the higher slump losses have been indeed experimentally observed. This problem can be overcome following two approaches: the first is through the use of water-reducing admixtures (WRA) in the mix, acting directly on concrete mix design. Alternatively, certain mixing procedures for RACs can be also applied. The commonly named Mixing Water Compensation Method [56] for elaborating concrete, based on added water which recycled aggregate absorbs to the total needed by the mix, allows acceptable workability to be achieved. In the case of EMV methodology, the parameters controlling workability should be carefully taken into account, due to the reduced amount of fresh mortar in the mix in favor of increased coarse aggregate volume.

Other techniques to improve RCA quality, and therefore limiting possible deficiencies in RAC properties, are currently available, such as the Autogenous Cleaning. This method, at least when implemented at the laboratory scale, led to positive results in terms of enhancement of properties of crushed concrete particles, especially in terms of reduction of RM content and, consequently, on their water absorption [57].

### *2.1.4 RAC Concrete—Mechanical Properties*

Concrete strength is the key mechanical property of structural concrete. Particularly uniaxial strength in compression is accepted as the representative index of compressive strength, which is also related to strength under other stress states, i.e. tensile and flexural strength, elastic modulus, etc. Several factors affect concrete strength, starting from the water/cement ratio, which is particularly important because it directly affects concrete porosity and the quality of the interfacial transition zone (ITZ). In addition, aggregate size, mineralogy and type (natural–limestone or siliceous aggregates, recycled, artificial, etc) are also particularly relevant in influencing concrete strength. Recycled aggregate quality can highly affect RAC concrete properties too, and its composition is one of the most important acceptance criteria which should be verified. Referring to RCA, the quantity of the adhered mortar attached to the virgin aggregates, is also a very important parameter to be analyzed when designing RAC.

Concerning the quality of the microstructure of ITZ in RAC, as reported in [58], SEM observations revealed that the aggregate-cement matrix interfacial zone is very porous with respect to the same ITZ in a conventional concrete, which is denser. Increasing substitution ratio generally decreases mechanical strength, as obtained in numerous research works [48–50]. A linear relation between RAC density (depending directly on RCA substitution ratio, which has typically lower density than NA) and compressive strength was also obtained in [59]. The quality of recycled aggregate, in terms of RM mechanical properties, affects the strength of recycled aggregate concrete when the water-binder ratio is low; on the contrary, this not happens when the water-binder ratio is high, being the strength principally affected by the water content in the mix. Admixture types and content, and the rate of loading also influences RAC quality and strength.

Typically, the full replacement of NA with RCA through both DVR and DWR concrete design methods leads to a reduction of 20–25 % in 28-days compressive strength, with respect to conventional mixtures. An increase of cement content may be useful to achieve the same strength of the control concretes, but it is considered nor cost- nor environmental-effective. Additionally, the reduction in the elastic modulus can reach 45 % when the RCA replacement is 100 % [60].

A full replacement of NA with RCA has been used successfully in concretes with low-medium compressive strength, i.e. until 20–40 MPa [61]. Some studies have been carried out also to assess the feasibility of using RCA in HPC [62], obtaining in most cases that high replacement ratios (more than 30 %) significantly affect concrete strength and density. With the increase of the RCA content, water absorption, shrinkage and creep strains increase ceteris paribus. However, it should be recalled that the source of RCA is very important with respect to RAC properties [63], and the more restrictive the acceptance criteria, the lower differences would be expected between recycled and conventional concretes.

### *2.1.5 RAC Concrete—Durability*

Durability of RAC can be evaluated through several experimental methods, depending on the deterioration process which should be represented at laboratory scale. Generally the lower properties of recycled aggregates, i.e. the lower density and mechanical strength, within the higher absorption and porosity, determine RAC to be less durable in terms of carbonation, chloride penetration, permeation, and freezing/thawing resistance [64]. Another internal source of deterioration arises from the possible contamination of recycled aggregates by gypsum or admixtures and binders, which lead to an increased content of sulfates inside the mix [65]. The same may occur if recycled aggregate is contaminated by chlorides, which can lead to an internal source of chlorides inside the mix. In both the cases the addition of mineral admixtures, such as fly ash, can reduce the chloride penetration depth, in particular at low water/cement ratio (a factor which also, per se, improves RAC durability).

It has to be recalled that also the mixture proportioning method may affect concrete durability: recent research works demonstrated that, for instance, when the EMV proportioning method is used, durability-related properties in chlorides-exposed environment are improved with respect to RAC proportioned with DWR method [53].

### 2.1.6 RAC Concrete—Structural Concrete

A number of experiments on structural elements have been performed in literature, with the aim of analyzing structural properties of real-scale elements. One of the most important property that was analyzed is related to the flexural behavior of reinforced recycled concrete beams: a typical load scheme which can be found in many papers involves simply supported beams subjected to four point bending tests. In this test, the specimens are loaded at two points, symmetrically with respect to the mid-span of the element. Generally, flexural behavior is discussed with reference to control virgin concrete beams, in which the reinforcement ratio, curing conditions, and concrete mix design (except for the aggregates substitution effect) are maintained constant. The parameters which are often analyzed are load, deflection at the mid-span, and when it is possible, the stresses in the reinforcement.

Flexibility of RAC beams is generally greater than in NA concrete, under the conditions of same bending moment, w/c ratio, steel reinforcement ratio. In addition, RAC beams experienced often wider cracks and smaller crack spacing, with a lower flexural strength compared to the companion control members. Those results may discourage the use of RAC in structural concrete elements, because it creates further uncertainty with respect to the serviceability and long-term performances of RCA concrete structure [66, 67]. However when high quality RAC are used, or when EMV proportioning method is applied, also structural properties highly improve, reducing significantly the dispersion of the results: at both the service and ultimate states, the flexural performance of reinforced RCA-concrete can be comparable or even superior to that of concrete made entirely with natural aggregates. The flexural theory based on equilibrium equations and the current code provisions for flexural design of conventional RC beams seem to be satisfying also for RAC beams design [68].

Unlike in RC beams subjected to flexure, where longitudinal reinforcement has a prior role in the structural response of the element, concrete plays a more significant role in beams subjected to shear loading. In fact, shear behavior is governed by the shear capacity of the reinforcement, as well as the concrete shear capacity. Also in this case a number of works have tried to assess the influence of RAC in the response of RC beams subjected to shear, both when transversal reinforcement (i.e. stirrups) was present and when no.

In general terms, shear strength of RAC beams is lower than in NAC beams with the same reinforcement ratio and shear span-to-depth ratio [69, 70]. The current codes and existing model underestimate shear capacity of RC members, both made with NAC and RAC, hence, the use of RCA does not determine uncertainty which could not be accounted by the models. The same consideration given for the flexural behavior can be given if high-quality RA are used.

Lastly, Corinaldesi et al. [71] investigated also the behavior of reinforced beam-column joints under cyclic loading, to assess the seismic performance of RC frame joints. The parameters observed were the failure modes, the hysteresis loops, the ductility and the variation of strength and stiffness under the seismic loads.

The joint made of RAC showed adequate structural behavior, however, to achieve safe structural performance, the actual RAC shear strength and stiffness should be considered during the design.

## 2.2 Metallurgical Slag

Several kinds of slag could be used in concrete production, as cement or aggregate replacement. Among the materials that are currently used, or at lab-scale or already covered by specific regulations and standards, Granulated Blast Furnace slag (GBS) and Air-cooled Blast Furnace slag (ABS) are generally used as supplementary cementing material (SCM). In addition, Electric Arc Furnace slag—from carbon (EAFC) or stainless/high alloy steel production (EAFS)—can be potentially used as natural aggregate replacement. Lastly, Basic Oxygen Furnace slag (BOF) has been experimentally used for both the applications.

Between these materials, a particular interest emerges about steel by-products, because of the great amount of slag deriving during its production. In fact, the total amount of steel slag generated in 2006 was about 16.9 million tones. Euroslag, an international organization dealing with iron and steel slag matters, divides this amount in: 57.7 % basic oxygen furnace slag, 25.9 % are electric arc furnace slags from carbon steel production, 5.9 % are electric arc furnace slag from high alloy steel production and 11.1 % come from secondary metallurgical slag (Fig. 2.3).

Steel slag is produced during the separation of molten steel from impurities in steel furnaces. The slag appears as a molten liquid and is a complex solution of silicates and oxides that solidifies upon cooling. As previously stated, there are several types of steel slag produced during the steel-making process: among these, basic oxygen furnace steel slag (BOF slag), electric arc furnace slag (EAF-slag) and

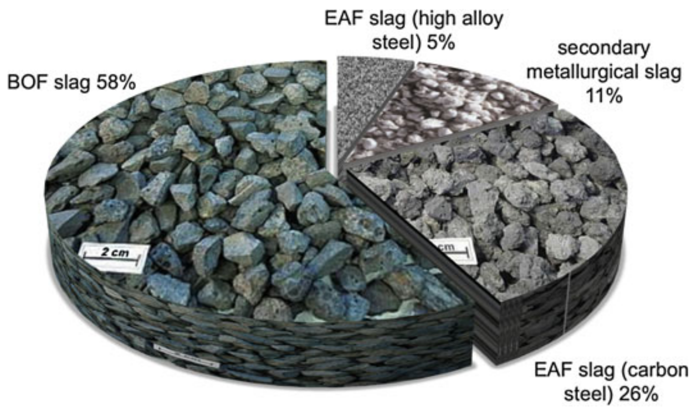


**Fig. 2.3** Steel slag production in Europe [72]

ladle furnace slag (LDF-slag) or refining slag are particularly important, at least in terms of amount produced.

Steel can be produced in electric arc furnaces by melting recycled steel scrap, using heat generated by an arc, created by a large electric current. The slag is formed through the addition of lime, which removes impurities from within the steel. Slag has a lower density than steel and therefore floats on top of the molten bath of steel.

Basic oxygen furnaces are characterized by a different industrial process: hot liquid blast furnace metal, scrap and fluxes, which consist of lime (CaO) and dolomitic lime (CaO-MgO), are initially charged into the furnace. Then, the oxygen, which is injected into the furnace, reacts and removes the impurities in the charge. Those impurities are mainly constituted by carbon as gaseous carbon monoxide, and silicon, manganese, phosphorus and some iron as liquid oxides, which combine with lime and dolomitic lime to form the BOF steel slag.

After being tapped from the furnace, molten steel is transferred in a ladle for further refining to remove additional impurities still contained into the steel. During this operation, known also as ladle refining, additional steel slag are generated by adding again fluxes to the ladle to melt.

Steel mill scale is produced during processing of iron in steel mills. During the processing of steel in steel mill, iron oxides are formed on the surface of the metal during the continuous casting, reheating and hot rolling operations. The iron oxides, also known as steel mill scale, are then removed by water sprays.

According to the physico-chemical properties of each kind of slag, a specific use for each type of material can be found: for example, steel slag are suitable as amour stone and for air quality control; steel slag and ABS are both suitable for gabions manufacture, railway ballast, roofing and for the treatment of waste water; steel slag and GBS are both suitable as sealants; and finally GBS can be applied as sand blasting. In general, both steel slag and blast furnace slag are used for unbound mixtures and hydraulically bound mixtures, for bituminous mixtures, in concrete, in mortar and in embankments. The steel mill scale is similar to steel slag and therefore, like steel slag, it can be used in concrete production.

The use of slag aggregates from iron and steel production in construction has old origins, since when the Romans used crushed slag from the crude iron production for roads building. Nowadays, slag is still used to build roads. Currently it is not only used for road surfaces constructions but also as aggregates for concrete production. Slag must be treated through sieving, crushing and wetting process. The processing techniques are fundamental to obtain high-performances slag. Attention should be paid to allow an adequate particle grading for the intended use, to fit the properties in accordance with product standards or specifications.

A great interest is currently focused in Electric Arc Furnace slag (EAF), because of the great numbers related to its production, which involves approximately 10 million tons every year of material, and it is destined to grow because of the increase in the use of this technology.

EAF slag is the main by-product of steel production in electric arc furnace plant. It could be classified into two types: black basic slag, with a lime content less than 40 %, resulting from the cold loading of scrap; and white basic slag, with a lime content higher than 40 %, generated during grinding, when more lime is added to remove sulfur and phosphorus from the produced steel [73]. An electric arc furnace is a furnace that heats scrap metal or recycled stainless steel by means of an electric arc and it produces steel. The fusion is possible due to an electric arc which is constituted by three cylindrical electrodes made of graphite, which enter inside the crucible of the furnace from the vault. The components of this type of furnace are three: the first is the hearth, the second is the shell and lastly there is a roof. The hearth is a metal structure lined with refractory material and which is able to oscillate so the inclination of the kiln can be changed (this facilitates the operations of slagging and tapping). The shell is a metal cage which allows to contain the material and then pours it into the oven. The roof can be moved to allow the opening during loading of the material, and it is also envisaged of three holes for the passage of the electrodes. Limestone and slag correction agents, e.g. bauxites, can be used as additives, i.e. slag formers. The operations required to produce steel (and EAF slag) are:

- furnace charging;
- melting;
- refining;
- de-slagging;
- tapping;
- furnace turn-around.

During the steel production, slag is also formed: slag has a lower density than steel and therefore floats on top of the molten bath of steel. Then slag is cooled, generally with water, at least for 24 h (see Fig. 2.4), it is aged for about two months

**Fig. 2.4** Slag cooling

or more under atmospheric conditions, and then it is ready to be treated again for its processing as aggregate. Typical treatments to be performed on the EAF slag are:

- Pre-screening;
- Screening;
- Crushing;
- Secondary screening;
- Secondary crushing;
- Magnetic separation;
- Tertiary screening—particle size separation;
- Storage;
- Washing and stabilization.

### 2.2.1 EAF Slag—Characterization

EAF slag is a crushed product, which generally has very good mechanical properties, constituted by particles with a hard, dense and angular shape. It has generally high abrasion resistance, low aggregate crushing value (ACV) and excellent resistance to fragmentation. However, the productive process and the chemical composition of the metal scraps molted in the furnace significantly influence its characteristics.

Several research works were performed in literature aiming to characterize EAF slag, trying to establish a suitable application for this material. One of the first research work was published in 1997 by Al-Negheimish et al. [74], who investigated its potential use in cement-based materials, by means of tests on the main mechanical properties, such as compressive and tensile strength. No studies about the long term concrete properties were done. The slag used was relatively non-porous, with a low absorption rate and with an angular shape that helped in developing very strong interlocking properties. The same characteristics in terms of shape and texture of the slag were derived by the further works of Anastasiou and Papayianni [75, 76], Manso et al. [77], Xue et al. [78], Ahmedzade and Sengoz [79], Pellegrino and Gaddo [80], Pellegrino et al. [81]. EAF slag was appearing as a black color stone, with a rough surface texture, characterized by a higher bulk density than natural aggregates, and in general, a higher porosity. This was also confirmed by SEM images taken in [74]. Some physical properties, experimentally evaluated in some research works reported in literature, were collected and are reported in Table 2.7.

A very discussed problem relates to possible expansion phenomena that may occur in steel slag aggregates. This is due to the presence of some expansive compounds, which may hydrate and increase their molecular volume, affecting the dimensional stability of the aggregate. Accordingly, it is very important to define the content of those components, i.e. free lime (CaO) and free periclase (MgO),

**Table 2.7** Physical properties of steel slag

| Property | EAF slag | Reference |
|---|---|---|
| Specific gravity (t/m³) | 3.5 | Manso et al. [77] |
| | 3.51 | Maslehuddin et al. [83] |
| | 3.33 | Papayianni et al. [76] |
| | 3.64–3.97 | Pellegrino and Gaddo [80] |
| Los Angeles (%) | 15–20 | Manso et al. [77] |
| | 11.6 | Maslehuddin et al. [83] |
| | <20 | Pellegrino and Gaddo [80] |
| Compressive strength (MPa) | >130 MPa | Manso et al. [77] |
| Percentage of voids (%) | 55.5 | Papayianni et al. [76] |
| Water absorption (%) | 0.3–0.9 | Manso et al. [77] |
| | 0.85 | Maslehuddin et al. [83] |
| | 2.50 | Papayianni et al. [76] |
| | 0.18–0.45 | Pellegrino and Gaddo [80] |

which presence may hinder the potential use of slag in construction industry. Free lime and periclase are often detected in BOF slag, whereas their presence has been not frequently experimentally observed in EAF slag. Pretreatment operations are recommended to lower the potential expansion of those materials. Ageing and weathering of slag are often applied, as also steam or autoclave curing. Several works in literature have demonstrated the effectiveness of pretreatment operations in reducing the content of potential expansive compounds [77, 80, 82].

Table 2.8 lists the chemical composition of some EAF slag used in literature. Typically the most abundant oxides corresponded to $Fe_2O_3$, CaO, $SiO_2$ and $Al_2O_3$. EAF slag is generally basic, i.e. the sum of the basic oxides over the sum of the acid oxides is greater than 1. Several indexes are available to classify slag basicity, between which the most common is the ratio $B_2$, between CaO and $SiO_2$. However, several works recommend to use the $B_4$ index, reported in Eq. (2.1):

$$B_4 = (CaO + MgO)/(SiO_2 + Al_2O_3) > 1 \tag{2.1}$$

**Table 2.8** Chemical composition of EAF slag

| | Manso et al. [82] | Pellegrino and Gaddo [80] | Tossavainen [84] |
|---|---|---|---|
| | Spain | Italy | Sweden |
| $SiO_2$ (%) | 15.30 | 10.1 | 32.2 |
| $Al_2O_3$ (%) | 7.40 | 5.70 | 3.70 |
| CaO (%) | 23.90 | 24.20 | 45.50 |
| MnO (%) | 4.50 | 5.10 | 2.0 |
| MgO (%) | 5.10 | 1.90 | 5.20 |
| $Fe_xO_y$ (%) | 42.50 | 37.20 | 27.41 |

According to Daugherty et al. [85], as the acidity of the slag increases, glassy phases are more likely to be produced; on the contrary, basic slags are mainly crystalline. Generally EAF slag are less basic than LDF and BOF slag: Engström et al. [86] obtained for BOF slag a $B_4$ index equal to 3.9, whereas for EAF slag this value decreases until 1.4. It should be noted that the reactivity of CaO increases with the slag basicity [87], and hence problems of expansion linked to EAF slag seem to be very limited. This result is also confirmed by the mineralogical composition of the slag often reported in literature, which is mainly constituted by the following mineral forms: wustite, hematite, magnetite, merwinite, etc.

Another environmental obstacle limiting the use of some slags in construction is represented by the potential leaching of hazardous substances. Particularly some EAF-slags from stainless steelmaking can have insufficient properties to be used as construction material, and may sometimes not meet the environmental requirements due to high leaching rates of chrome. The leaching from steel slags is generally characterized as a surface reaction, followed by a solid-solid diffusion process, in order to retain equilibrium in the materials. A minimization of the surface area of the slag is therefore likely to reduce leachability. Pre-treatment operations are often effective not only in reducing potential expansion phenomena, but also to reduce the concentrations of harmful substances or the high leaching levels of these elements.

### 2.2.2 *EAF Slag Concrete*

Since a long time the use of steel slag has been proposed for designing blended cement, in cement clinker, as aggregate or hydraulic binder in road construction. However, not much is reported as aggregate for cement mortar and concrete manufacture. In the few available literature studies, mainly EAF slag has been used. The analyzed concrete properties were limited to some mechanical characterization, or simple fresh concrete workability measurement.

The first complete chemical analysis on EAF slag was conducted in 1999 in Spain [73], even though the first works were approached in Germany in 1994 and subsequently in France in 1998. The studies were carried out using optical microscopy, inductively coupled plasma spectroscopy (ICP) for the chemical part, X-Ray diffraction (XRD) and infrared (IR) absorption spectroscopy for the mineralogical characterization. Also scanning electron microscopy (SEM) was used to obtain images of the material media. Since the first results, EAF slag appeared as a material with high porosity, dense and compact, with a surface characterized by high iron content. Particle density was very high, whereas water absorption was limited, according to the standard DIN 40 301 “Ferrous and non-ferrous blast furnace slags for building uses” which was active at that time. Also dimensional stability was investigated, because of the increasing necessity to establish if slag could meet the standards as a building material.

After a couple of years, several studies arose as an emerging research topic, regarding slag application in asphalt mixtures. In Arabian areas, where the availability of good-quality aggregate is generally scarce, the research on slag-concrete was significant: several studies aimed to compare mechanical properties of EAF concretes with crushed limestone aggregate concrete. Maslehuddin et al. [83] produced concrete mixes where they substituted all the coarse aggregates with EAF slag, maintaining the dune sand content constant in both recycled and traditional specimens. Results highlighted that, as the substitution ratio increased, compressive strength increased ceteris paribus, maintaining the same aggregates grading curve. At the same time, also flexural strength increased, whereas the absorption, volume of permeable voids and pulse velocity decreased, revealing a denser concrete. Furthermore, results of durability tests were positive, because of the high impermeability of slag concrete.

One of the most important works about EAF slag appeared in 2005 in Spain [82], with the aim of analyzing the durability of slag concrete, and in particular it focused about the possible expansion of EAF concrete, due to the presence of some internal compounds, potentially not volumetrically stable when hydrated (periclase and free lime). Accelerated ageing tests were performed to study the effects of this expansion on mechanical strength. In addition, slag pre-treating processes were analyzed: reduction to standard aggregate sizes following an appropriate crushing, and the successive exposure to weathering over several weeks were demonstrated to be two necessary phases to obtain a stabilized product. A correctly performed treatment requires a permanent wetting, homogenization through a periodic turning of the heaps and a minimum weathering period of 90 days, and it provides a significant improvement in stabilizing the slag, both dimensionally and chemically. Another suggestion extracted from this study relates to the use of an air-entrainer agent for slag concrete, because of the high slag porosity, which could lead to severe deterioration of structures exposed to freezing and thawing cycles. A number of specimens were casted, using different substitution ratios for slag and limestone aggregates: in all the cases, the mechanical resistance was comparable to traditional concrete strength. An exception was obtained for the mix made just by slag (100 % EAF aggregates), which collapsed and could not be practicable. Accelerated ageing tests were performed according to American ASTM standards: one was performed in autoclave, one in a moist room, one providing freezing and thawing cycles, one with wetting and drying conditions and the latter was a leaching simulation.

Another research topic focused on the possibility of using slag as a raw material for Portland cement clinker production, in some percentages. Starting from the knowledge that cement with slag may be weaker than Portland cement, some tests were performed in Greece [88], following the experience of BOF slag—cements. EAF slag has a chemical composition similar to that of cement, like most of metallurgical slags. The main difference is the high iron oxide content, which exists in both di- and trivalent states; another difference was evidenced by previous researches, which stated that pozzolanic activity is low if slag is not pre-treated. So, no mechanical differences would be expected during hydration, and only the possible expansion of slag must be evaluated. Specimens with a substitution ratio of about 10 % on the total were casted, to allow the slag not to affect the hydraulic behavior of the cement produced. XRD analyses were performed, to detect hydration products, and mechanical tests were conducted on small specimens. Results were promising: expansion was under EN 197-3 limit, compressive strength was as good as traditional Portland cement (no significant differences), and the reduction of material costs was remarkable.

Some other works were performed in order to assess the potential use of slag as fine aggregate in concrete [89]. The results have shown a potential use of this material, but an increase of cement content is necessary to do not affect the mechanical strength of EAF concretes.

Also in Italy a research work was conducted to assess the potential use of EAF slag, produced from a local plant, in structural concrete. The research activity, which lasts since more than 6 years, is focused on the application of EAF-C type slag (coming from carbon steel production) for structural concrete production. The first experimental campaign aimed to explore slag use as full replacement of coarse aggregates in concrete, through the analysis of the most common mechanical and durability-related properties, i.e. resistance against wetting/drying and freezing/thawing cycles, and accelerated ageing [81]. Results were excellent in concrete exposed to ordinary environmental conditions. Further experimental campaigns were devoted to assess the potential use of EAF slag fine particles: also in this case promising results were obtained. Contextually to these activities, the first experimental tests on structural reinforced elements casted with EAF slag were done [90]. High performances concrete was also produced including EAF slag as full replacement of coarse natural aggregates [91].

## 2.3 Fly Ash

The use of alternative binders is very common in the concrete industry. Particularly, fly ash (FA) is widely employed as partial replacement of ordinary Portland cement in concrete, and nowadays around 15–25 % of cement is generally replaced by FA in normal structural concrete mixes. Coal fly ash has been successfully used in concrete industry since more than 50 years, primarily as mineral admixture in Portland cement concrete and also as a component of blended cement [92]. Concerning its first use, fly ash can either partially substitute Portland cement or be applied as an addition into ready-mix concrete at the batch plant [93]. It is generally accepted that the use of those Supplementary Cementing Materials (SCMs) promotes sustainability of concrete industry. Usual structural and durability-related properties were widely analyzed in literature [94–96]. In addition, several authors have attempted to relate some properties of SCM-concretes with parameters such as fly ash fineness [97], glass phase content soluble [98] and reactive silica content [99], water to powder ratio [100] and curing conditions [101].

High quantities of FA can be used in concrete, also as partially replacement of fine sand fraction, and as filler. This use is allowed also for low quality fly ash, characterized by low pozzolanic properties.

Fly ash represents the most important coal combustion by-product: approximately 6 million tons are actually used in the EU 15 member states as concrete additions. FA production is about 1Mt/y in Italy and 40 Mt/y in Europe. FA is a product of burning finely ground coal in a boiler to produce electricity: it is removed from the plant of exhaust gases primarily by electrostatic precipitators or baghouses, and secondarily by scrubber systems. Within a power station, coal is fed to a series of mills that pulverize the combustible matter to a very fine powder. This powder is then fed into a boiler which combusts the coal to produce heat, which is used to produce steam required for power generation. During the coal combustion process, minerals present in the coal fuse to form glassy alumino-silicate spheres. These spheres remain in suspension within the flue gas from the boiler and they are collected downstream by either electrostatic or mechanical precipitation.

American Society for Testing and Materials (ASTM) C618-08 [102] classifies fly ash into two big categories, according to their chemical composition and other physical properties. This classification distinguishes FA also from the coal type burned in the coal-fired power plants, being FA quality highly dependent on the burned material. Those classes are Class F (low calcium) and Class C (high calcium) fly ash. Combustion of bituminous or anthracite coal normally produces Class F (low calcium) fly ash and combustion of lignite or sub-bituminous coal normally produces Class C (high calcium) fly ash. High calcium fly ash contains large amounts of free lime and sulfite than that of low calcium fly ash. In Europe, the EN 450-1 standard of 2012 defines the specifics for a correct use of FA in concrete [103].

The mineralogical composition of FA is very complex. FAs are a heterogeneous mixtures of mineral phases and amorphous glassy phases with small amount of unburned carbon. The glassy phase of low calcium fly ash is alumino-silicate type whereas that of high calcium fly ash is a mixture of calcium aluminate and ferrous alumino-silicate. High calcium fly ash contains large amounts of calcium-bearing minerals like lime, anhydrite, gypsum, tricalcium aluminate, alite, gehlenite, akermanite, portlandite and larnite. Some other minerals like quartz, hematite and magnetite are also present in high calcium fly ash. On the other hand, low calcium fly ash mainly contains quartz, mullite, hematite, magnetite and small amounts of calcite [104].

Concerning the physical properties of FAs, also in this case a huge variability was reported in literature. The specific gravity of fly ash may vary from 1.3 to 4.8 t/m$^3$, and the shape is generally roundish (which depends by the spherical glassy phase shape). However, large sized or irregular shaped particles can also be formed from the fusion of smaller fragments and incomplete melting. In addition, there could be also hollow spheres (cenospheres) and microsphere-filled spheres (plerospheres): these lasts are cenosphere, which encapsulate a mass of microspheres with 1 μm or less in diameter. The formation of such spheres is due to many physical and chemical reactions that occur during coal combustion: initially

**Fig. 2.5** Light-brown FA and dark-grey FA

lignite is heated up to about 950–1000 °C and thereafter reactions may occur for some seconds, as the FA is swept towards the stack inlet. The smallest particles are then adhering to the larger ones, thus forming clumps or agglomerate of small particles. Particle size distribution can be very different, and it depends upon the initial grinding of the coal and the efficiency of the thermal power plant and even fluctuations in power generation. Also the color of coal ash can be an index of chemical and mineral constituents. High lime containing FA is normally tan and light in color. Iron containing FA is brownish in color. The dark grey to black color of FA indicates the presence of a high amount of unburned carbon. Figure 2.5 shows two fly ashes: on the left, a light-brown FA from coal-combustion; on the right, a dark-grey FA, rich in unburned carbon content, coming from a co-combustion process where coal is burned together with refuse derived fuel (RDF).

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