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Recycled materials in concrete

2

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s0010 2.1 Introduction

p0010 On September 25, 2015, the United Nations established 17 sustainable development (SD) goals that have been adopted by many countries as a part of the new 2030 Agenda for Sustainable Development of our planet (United Nations, 2015), that officially came into force on January 1, 2016. Actions from governments, civil society, and private companies need to be pursued for these goals to be reached, and they relate also to the field of *green buildings*. How can they impact these goals? There are several ways in which green buildings may contribute to SD goals, as highlighted by the World Green Building Council. For instance, the application of circular economy principles, lowering environmental emissions from construction, and creating climate resilient infrastructures, highly durable over time, are viable methods to achieve sustainability of construction.

p0015 In this context, improving sustainability of construction materials is gaining increasing attention, and the objective of limiting the high impact of the construction industry becomes a challenge of paramount importance. Worldwide, the production of concrete and, more generally speaking, cement-based materials considerably exceeds 10 billion tonnes, with an increasing trend associated with the emerging markets from developing countries. There, the urbanization and industrialization are accompanied by an increasing demand for infrastructures. In 2012, about 3.8 Gton of cement, 17.5 Gton of aggregates, and over 2 Gton of water were consumed worldwide for concrete manufacture, leading to a contribution of 8.6% of the global anthropogenic carbon emissions (Miller, Horvath, & Monteiro, 2016). By far, concrete is acknowledged as the most produced manufactured material in the world by weight (Monteiro, Miller, & Horvath, 2017). The price to the environment of the widespread diffusion of concrete is great, and these effects are expected to impact developing countries more than others during the next years. Several concurrent causes that contribute to the environmental burdens of concrete can be summarized as

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- u0010 extraction of bulk natural resources (e.g., gravel, sand, minerals) that might induce local abiotic depletion and land consumption or transformation;
- u0015 environmental emissions due to transportation of resources and products;
- u0020 large consumption of energy, fossil resources, and water during cement production and concrete manufacture; and
- u0025 generation of a great amount of waste when the service life of structures is exhausted.

p0040 Abiotic depletion problems have been recorded in many territories, mainly in highly urbanized areas, that is, where the availability or accessibility of natural resources is scarce if compared to the high demand of resources (Habert, Bouzidi, Chen, & Jullien, 2010; Ioannidou, Nikias, Brièere, Zerbi, & Habert, 2015). In addition, typically the attitude of the population toward quarrying operation is negative, due to the disturbance that it causes (e.g., noise, dust, impact on land transformation). For such reasons, other activities are generally preferred in an urban area rather than a quarry, thus leading to an inverse relation between the urbanization of an area and the ease of access to bulk resources.

p0045 Local depletion of resources is directly related to transportation emissions, because distances to be covered are extended when raw materials are not easily accessible. Life cycle assessment (LCA) studies have shown how impacts due to transportation are of the same order of magnitude as those due to the whole supply chain of natural aggregates (Faleschini, Zanini, Pellegrino, & Pasinato, 2016). According to USGS (2018a), there is a shortage of quarries in some urban and industrialized areas of the United States, due to local zoning regulations and land development alternatives, and hence, for those areas, longer distances of travel for the delivery of material to the jobsite are required. For this reason a rise in prices in and near metropolitan areas is also observed. Differently from natural aggregates, often those coming from construction and demolition waste (C&DW) recycling are easily available in metropolitan areas, due to the presence of mobile recycling plants close to jobsites. Even though there is evidence of poor accessibility of natural aggregates in densely populated areas of the United States, the percentage of total aggregate supplied by recycled materials remained very small in 2017.

p0050 Cement is well known to be mainly responsible for the high carbon footprint of concrete. Indeed, the carbon footprint of cement can be quantified in the range of about 0.5−1 tonne CO_2/tonne of cement (Josa, Aguado, Cardim, & Byars, 2007), depending on the amount of clinker included in the blended binder. Portland cement is by far the least sustainable cement type, whereas blended cements including, for example, pozzolans such as rice husk ash (RHA) or coal fly ash permit significant emissions savings. It is worth recalling that in 2017, around 86.3 million metric tonnes of Portland cement was produced in the United States, in 98 plants located in 34 States, plus two plants in Puerto Rico, whereas the worldwide production is about 4100 million metric tonnes (USGS, 2018b). Even though great efforts to reduce the high environmental impact of concrete have been made during the last century, still cement production alone is responsible for more than 7% of CO_2 emissions, worldwide. For instance, in the United States, many plants have installed emissions-reduction technologies to comply with the 2010 National Emissions

Standards for Hazardous Air Pollutants limits, which went into effect in September 2015 (EPA, 2015). For the same reason, in 2017, precalciner dry kiln technology was added in two plants. However, the above strategies to improve the efficiency of the cement supply chain and emissions-reduction technologies cannot be pursued alone. In fact, a recent study has shown how concrete production was responsible for 9% of global industrial water withdrawals in 2012, this being a nonnegligible amount of water, if we consider that water consumption is growing at twice the rate of the global population. According to global concrete production projections, in 2050 it is expected that 75% of the water demand for concrete production will likely occur in regions that may experience water stress (Miller, Horvath, & Monteiro, 2018).

p0055 Lastly, great amounts of C&DWs are expected to be generated in the next years, due to the aging of the existing built environment in developed countries, and the need for new infrastructures in developing countries. Particularly, in the first case, the huge existing built stock is experiencing a constant decrease in its key-performance indicators, due to aging and, in some cases, lack of adequate maintenance. Moreover, the risk of failure or serviceability impairment due to disaster events (e.g., earthquakes) is severely increased in an obsolete built environment, whose fragility increases progressively. This potentially implies enormous burdens in terms of waste production, consumption of natural resources, and carbon footprint.

p0060 It is worth noting, however, that concrete does not have only negative impacts on the environment, because of its ability to recapture some CO_2 over time, due to carbonation.

p0065 The main results of the analysis of the above observations converge on identifying Portland cement as being mainly responsible for the high environmental emissions due to concrete production. To a lesser extent, natural aggregates and water consumption also negatively affect concrete sustainability. Accordingly, strategies to achieve *environmentally friendly concretes* can be identified, and they can be summarized as follows:

- u0030 Limit the content of Portland cement in favor of blended cements, through the increase in use of supplementary cementing materials (SCMs). Among them, those that are by-products of industrial processes, such as fly ash and ground granulated blast-furnace slag (GGBFS), should be preferred over natural pozzolans.
- u0035 Use recycled materials in place of natural resources. Since aggregate constitutes about 70% of concrete volume, an effective recycling strategy can substitute recycled for virgin materials to make the industry more sustainable. Among the recycled components to be included in the mix design, those characterized by the lowest delivery distance should be preferred, to limit transportation emissions and costs.
- u0040 Reuse wash water and limit water withdrawals. The recycling of wash water is readily achieved in practice and is already required by law in some countries.
- u0045 Improve concrete properties. An increase in mechanical strength and similar properties can lead to a reduction of materials needed. For example, doubling the concrete strength for compression-controlled members may cut the required amount of material in half.

In addition, improved concrete mechanical properties are often associated with enhanced durability.

u0050 - Improve durability. For example, by doubling the service life of our structures, we can cut in half the amount of materials needed for their replacement.

p0095 This chapter will address mainly the first two strategies, that is, the use of recycled components both as alternative binders and recycled aggregates. The research in this context has achieved significant progress in the last years, allowing the formulation of concretes with the same properties (or even better) than ordinary mixes containing natural materials only. In some countries, codes and standards have been proposed to regulate the use of recycled materials in concrete, identifying maximum replacement ratios depending on the application of the structure in which they will be placed. Hence, SCMs will first be discussed, such as fly ash and GGBFS, whose use in concrete is now well-established. Then, recycled aggregates coming from C&DWs will be described, highlighting how their use is regulated in some countries. Steelmaking by-products will be presented also, because their application in concrete is gaining increasing attention by researchers. Then recycled waste glass, fibers and recycled rubber from used tires, recycled plastics, coal, and municipal solid waste (MSW) incineration bottom ashes will be analyzed. Finally, the latest trends in current research will be presented.

s0015 2.2 Supplementary cementing materials

p0100 The role of SCMs is that of reducing the amount of cement in concrete mixes to achieve the desired compressive strength for use in construction projects, and at the same time reducing the carbon footprint of the material. These materials contribute to strength development when mixed with cement, through the development of hydraulic or pozzolanic activity. Pulverized fly ash (PFA), GGBFS, RHA, metakaolin (MK), and silica fumes (SF) are typically considered as alternative binders, which might be introduced into a concrete mix, for achieving the above goals. Table 2.1 lists the carbon footprint of some of these materials and of some blended binders, expressed in terms of kg of carbon equivalent per metric tonne of the final products, produced during the entire supply chain (i.e., during extraction, transportation of raw materials, and manufacture). Cement nomenclature follows EN 197-1 (2011).

s0020 *2.2.1 Fly ash*

p0105 The use of fly ash in cement-based materials has been well known for almost one century, even though its widespread application began only in the last 50 years, due to the dramatic rise of fly ash availability resulting from coal-fired power plants (Mindess, Young, & Darwin, 2003). Hence, the production of this material is directly related to the amount of coal-fueled electricity generation. The growth of the fly ash market still has a positive trend, due to growing urbanization in t0010 **Table 2.1** Carbon footprint of Portland cement, pulverized fly ash (PFA), ground granulated blast-furnace slag (GGBS), and limestone powder—data retrieved from UK Quality Ash Association (2015).

kg $CO_{2,eq}$/metric tonnes cement and SCM	
Portland cement type I (CEM I)	913 kg CO_2
PFA	4 kg CO_2
GGBS	67 kg CO_2
LP	75 kg CO_2
kg $CO_{2,eq}$/metric tonnes factory made cements	
Portland limestone cement (CEM II/A-LL or L)	745−859 kg CO_2
Portland fly-ash cement (CEM II/A−V)	746−859 kg CO_2
Portland fly-ash cement (CEM II/B−V)	615−728 kg CO_2
Portland slag-cement (CEM II/B−S)	639−743 kg CO_2
Blast-furnace cement (CEM III/A)	398−622 kg CO_2
Blast-furnace cement (CEM III/B)	277−381 kg CO_2
Pozzolanic (siliceous fly ash) cement (CEM IV/B−V)	441−598 kg CO_2

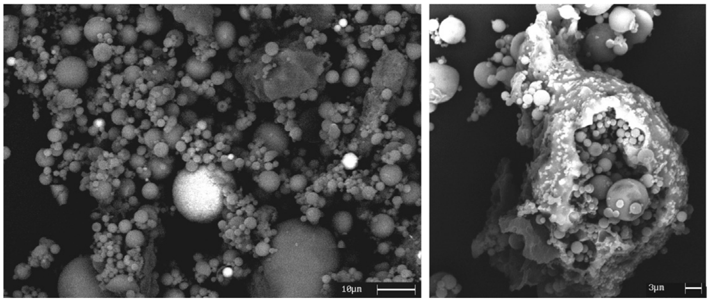
LP, Limestone powder; *SCM*, supplementary cementing material.

emerging economies and global increasing constructional activities. However, particularly in Europe, the future availability of this material is questionable, as a result of the Paris agreement signed by 26 of 28 member states that stated that they will no longer invest in new coal plants after 2020. Also in the United States, the competition from natural gas plants (and to a lesser extent, of renewable energies), accompanied with coal units retirements, will lead to a progressive fall in the availability of coal fly ash in the near future, which is expected starting after 2033. In 2013, the production of fly ash in the United States was about 48 million metric tonnes; about half of it was reused in concrete (American Road & Transportation Builders Association, 2015).

p0110 Fly ash, which is commonly known also as PFA, is a coal combustion product made of fine particles with heterogenous composition, mainly depending on the type of coal burned, that has both crystalline and amorphous structures. Particles size is generally similar to that of cement grains, and fineness is directly correlated with fly ash reactivity. All fly ashes exhibit pozzolanic properties to some extent, which means that per se they have almost no or little cementing properties, but when they are finely ground and put in contact with water, they react with calcium hydroxide at ordinary temperatures to form a material with cementitious properties (ACI 232, 2018). The siliceous glass within the fly ash is the primary contributor for the pozzolanic activity, since it is the amorphous silica that combines with free lime (occurring from the hydration products of C_3S and C_2S) and water to form calcium silicate hydrate (C-S-H). Some fly ashes also display varying degrees of cementitious properties without the addition of $Ca(OH)_2$ or hydraulic cement. Fly ash may be introduced in a concrete mix either as a separately batched material or as a component of blended cement. When concrete containing fly ash is properly cured, the products of the fly ash reaction fill the spaces between hydrating cement particles, thus lowering concrete permeability, and ensuring enhanced strength and durability (Manmohan & Mehta, 1981).

p0115 The pozzolanic reaction of fly ash is relatively slow if compared to cement hydration, thus allowing for less heat generation, limiting a detrimental early temperature rise in massive structures. On the other hand, however, such relatively slow kinetics cause also a delayed rate of strength development of fly ash concrete, which represents a disadvantage in applications where high early strength is required. For such reasons, often, 56-day strength or 90-day strengths are used to characterize fly ash concrete compressive strength. In those cases, accelerators might be necessary to speed up hydration rates of fly ash concrete. It is worth recalling that in many situations, especially for mass concrete structures such as dams and heavy foundations, the structures are not loaded to their design values until months or even years after their placement; in those cases, it is quite common to specify 90-day strengths instead of the conventional 28-day strengths.

p0120 According to ASTM C618 (2017), two fly ash categories can be identified, depending on the chemical composition of their particles. The sum of iron, aluminum, and silica content (expressed as oxide content) is used to assess whether a fly ash is of type C (normally from subbituminous and lignite coals) or type F (normally from bituminous and anthracite coals). The sum of FeO, Al_2O_3, and SiO_2 exceeds 50% for fly ash of type C, which contains also large amount of CaO, that in some cases can be in the order of 15%. Noncrystalline silica exceeds 70% for fly ash of type F, which contains instead low amounts of CaO. In both cases, the largest fraction of fly ash (between 60% and 90%) consists of glassy spheres that could be solid or hollow (known as cenospheres), as shown in Fig. 2.1. Fly ashes characterized by high amounts of calcium-rich glassy phases are considerably more reactive than ones containing aluminosilicate glasses, typical of low-calcium fly ashes. The remaining fraction is made of a large variety of crystalline phases (crystalline matter ranges between 25% and 45%); approximately 316 individual minerals and 188 mineral groups have been identified in various ash samples (Yao et al., 2015). Low-calcium fly ashes typically contain only relatively chemically inactive



f0010 **Figure 2.1** Scanning electron microscope (SEM) images of circular-shaped and cenosphere fly ash particles, taken in the back-scattered electron mode.

crystalline phases, that is, quartz, mullite, ferrite spinel, and hematite; conversely, high-calcium fly ashes may contain also anhydrite, alkali sulfate, dicalcium silicate, tricalcium aluminate, lime, melilite, merwinite, periclase, and sodalite (McCarthy, Johansen, Steinwand, & Thedchanamoorthy, 1987). In addition, some unburned carbon may be present, which is the result of incomplete combustion of the coal and organic additives used. It is usually estimated through the loss of ignition (LOI), which should be carefully limited in fly ashes to maintain acceptable performance.

p0125 When fly ashes are used in concrete, generally the following objectives can be pursued:

- u0055 Reduce cement content, thus limiting both economic and environmental costs of the concrete.
- u0060 Reduce heat of hydration, especially in mass concrete structures, due to the delayed kinetics of the fly ash reaction.
- u0065 Improve concrete workability, due to the lubrication effect attained by using spherical glassy fly ash particles.
- u0070 Reduce bleeding and segregation, due to the increase in the solid:liquid ratio of the mix.
- u0075 Attain higher long-term strength, generally after 56 days, due to the prolonged strength gain over time of fly ash concrete.
- u0080 Reduce concrete permeability and enhance durability of fly ash concrete, due to the filling effect of fly ash particles in the matrix.
- u0085 Improve alkali-silica reaction (ASR) resistance, because the fly ash reaction consumes alkalis, thus reducing their availability for expansive reactions with reactive aggregates.
- u0090 Enhance sulfate resistance of concrete, because the fly ash reaction reduces the amount of free lime and reactive aluminates available to react with sulfate.

p0170 The main drawbacks that must be considered when using fly ashes are

- u0095 extension of setting time;
- u0100 necessity to vary the amount of air-entraining admixture (if necessary), depending on the type, fineness, and LOI parameter of the fly ash;
- u0105 delay in strength gain at early ages; and
- u0110 care should be taken when concreting at low temperatures, and when fly ash concrete is subject to freezing/thawing cycles at early ages, because of the delayed strength gain that may be insufficient to prevent cracking and scaling.

p0195 Concerning the optimal replacement level of fly ash in concrete, this is dependent on several variables that affect strength development to varying extents. Such variables include the type and characteristics of the fly ash, the type of cement, the mixture proportions, the ambient temperature, and the curing method. When fly ash concrete is proportioned on a strength basis, that is, aiming to attain the same strength as a reference concrete containing only ordinary cement, then the replacement level must be higher than 1:1, as observed by Lane and Best (1982). This means that more than one unit of fly ash is necessary to substitute an equivalent amount of cement, to maintain the same concrete strength, at a defined age. This consideration reveals the necessity to introduce a factor that accounts for the different reactivities amongst different fly ashes, and between fly ash and cement. This factor is known as the *efficiency factor* or *k*-value (Smith, 1967), and it was developed to determine when a mass of fly ash f can be considered as equivalent to a mass of cement $k \cdot f$, for its ability in influencing the strength development of the concrete. In other words, if a fly ash concrete is characterized by a ratio $w/(c + k \cdot f)$ equal to w/c of the reference mix (without fly ash), the two mixtures should have the same strength. In the above ratios, w is water, c is cement, k is the efficiency factor, and f is the fly ash, expressed in kg/m^3. Many researchers have evaluated k values for different types of fly ashes, ranging between 0.9 and 1.4 for high-calcium fly ashes (Papadakis & Tsimas, 2002) and about 0.5 for low-calcium fly ashes (Papadakis, 2000). However, in the existing standards that adopt the efficiency factor (i.e., EN 206, 2016) the highest k-value allowed is 0.4 for fly ash concrete made with cements CEM I and CEM II-A.

p0200 A serious problem that is often encountered when dealing with recycled materials relates to their great heterogeneity, which should be faced through strict quality-control protocols. Indeed, physical and chemical characteristics may vary considerably from plant to plant, not only due to differences in the original coal used in the power facility, but also due to different combustion processes. A parameter that is sensibly affected by variation during plant operations is the LOI, that is correlated to the amount of unburned carbon in the fly ash, which affects also the color of the material. Current standards identify conformity criteria, requirements, and test methods necessary to ensure that this material can be treated as a building product (such as EN 450-1, 2012), with repeatable characteristics and performances.

s0025 2.2.2 Ground granulated blast-furnace slag

p0205 Similar to fly ash cements, blast-furnace slag cements have also been used for a reasonably long period, due to the overall economy in their production as well as their improved performance characteristics in aggressive environments (Babu & Kumar, 2000). There are several examples of early applications of GGBFS in structures, such as the Hummer Bridge in the United Kingdom (Osborne, 1999). GGBFS is a by-product of the steelmaking industry in the manufacture of pig iron in the blast furnace, and it consists essentially of silicates and alumino-silicates of calcium plus other constituents, that are formed when molten iron blast-furnace slag is rapidly chilled (quenched) by immersion in water. This material appears as a glassy granular product with limited crystal formation, ground to a fine powder to improve its reactivity. The main components of GGBFS are SiO_2, CaO, MgO, and Al_2O_3 that constitute about 95% of the slag and allow it to develop pozzolanic properties; in addition, such granulated slag, when finely ground and combined with Portland cement, has been demonstrated to exhibit excellent cementitious properties (Pal, Mukherjee, & Pathak, 2003). This is due to a similar composition to that of cement, and it has been demonstrated that the main hydration product of GGBFS is the same of that of cement, that is, C-S-H (Smolczyk, 1978), even if its appearance seems more gel-like, thus improving the compactness of the paste itself. Table 2.2 lists the range of chemical composition of blast-furnace slags that can be found in North America, together with those of Portland cement and fly ash type F. GGBFS t0015 **Table 2.2** Range of chemical composition of fly ash, ground granulated blast-furnace slag (GGBFS) and Portland cement in North America (percentage by mass).

Chemical constituent (oxide)	Fly ash type F	GGBFS	Portland cement
SiO_2	>5	32–42	17–25
Al_2O_3	20–30	7–16	3–8
CaO	<5	32–45	60–67
MgO	–	5–15	0.5–4
S	–	0.7–2.2	–
Fe_2O_3	<20	0.1–1.5	0.5–6
MnO	–	0.2–1.0	–

cements have been commercially available for more than 100 years, and its replacement ratio in Portland blast-furnace slag cement can reach up to 70%.

p0210 The annual production of GGBFS is estimated to be approximately 2 million metric tonnes in North America. Almost all GGBFS currently produced in the United States is used as a partial substitute for Portland cement in concrete mixes or in blended cements, and its actual price per tonne is very close to that of cement (about 5% less than cement). Indeed, in recent years, the supply of GGBFS has been problematic in the United States, because of the closure and continued idling of a number of active blast furnaces (USGS, 2017). The long-term supply of steel will be increasingly reliant on electric arc furnaces (EAFs), which now contribute the majority of US steel production; a similar trend is exhibited in European countries. Likely, it is expected that in the long-term, the demand for GGBFS will increase because its use in concrete leads to enhanced performance for many applications, in addition to reducing the carbon footprint. However, the availability of this material in the face of this increasing market demand is a matter of discussion, and it may depend on imports only, either of ground or unground slag. If this is the case, imported GGBFS availability may be constrained by its increasing international demand (due to the same trend of steelmaking process conversions in other countries). In addition, the quality of the imported slag might be not the same.

p0215 The reactivity of slag is influenced by its properties, such as glass content, chemical composition, mineralogical composition, fineness, and the type of activation provided. The glass content of slag is generally considered as the most significant variable affecting the development of the hydraulic properties of GGBFS. This parameter depends mainly on the temperature reached during quenching and on the temperature at which the furnace is tapped. Accordingly, it can be stated that an appropriate control of the production process is of paramount importance to produce GGBFS yielding the desired target performances. Slowly cooled slags are predominately crystalline and do not possess relevant cementitious properties. Also, the grinding operation affects the reactivity of the slag. In the United Kingdom, GGBFS is marketed at a surface area of 375–425 m^2/kg Blaine; some commercially available slags in the United States have a surface area in the range of 450–550 m^2/kg; Canadian slags have about a 450 m^2/kg Blaine; this parameter was found to vary from 350 to 450 m^2/kg Blaine in Indian slags (Pal et al., 2003).

p0220 The effects of GGBFS use on concrete properties can be summarized as

- u0115 Improved fresh concrete workability.
- u0120 Extension of setting times, by about 0.5−1 hour at a temperature of 23°C.
- u0125 Concrete strength is affected in different ways, depending on the activity of the slag and the age. However, in the long term, consistent and stable strength gain has been observed in structures exposed to air-curing or moist curing.
- u0130 One of the peculiar characteristics of GGBFS concrete regards its color, both when slag is used in a blended mix or added separately to the mix. Indeed, between the second and the fourth day after concreting, a bluish-green color may appear; this coloration disappears progressively on the concrete surface with time, leading, at the end, to a slightly lighter color than that of Portland cement concrete. However, in the core, this coloration lasts for a prolonged period.
- u0135 Reduced heat of hydration can be obtained if GGBFS activity is not very high.
- u0140 Permeability of mature concrete can be significantly reduced, thus leading to enhanced durability performance of GGBFS concrete.
- u0145 Better sulfate resistance can be achieved when the replacement ratio exceeds 50%.
- u0150 Higher resistance to the ASR has been demonstrated.

p0265 Concerning the current regulations available for GGBFS application, ASTM C989 (2018) defines three strength grades of slags (Grades 120, 100, and 80), defined on the basis of the slag-activity index, calculated by comparing the strength of mortars made with GGBFS, and a reference made with Portland cement only. Blended cements, in which the GGBFS is combined with Portland cement, are covered by ASTM C595 (2018). Three types of such cements are defined, being a slag-modified Portland cement (known as Type I SM), in which the GGBFS is less than 25% of the total mass; a Portland blast-furnace slag cement (known as Type IS), which contains 25%−70% GGBFS; and a slag cement (known as Type S), which contains more than 70% of GGBFS. In Europe, blended cements with GGBFS are regulated according to EN 197-1 (2011) and are known as cement II/A-S, cement II/B-S, cement III (type A, B, C), or cement V/A and cement V/B, depending on the amount of the slag.

p0270 Although the steel industry represents by far the main source of slags that might be used as SCM, there are also other metallurgical slags currently produced that are still being mostly stockpiled, landfilled, or downcycled into low-value applications. It is worth recalling that even within the same steel slags, there are by-products which currently do not find a valuable application, and in some cases, waste management protocols are very expensive. Mehta (2000) suggests that the concrete industry offers ideal conditions for the beneficial use of such slags and ashes, because the harmful metals can be immobilized in a stable matrix, as they will be safely incorporated into the hydration products of cement. Recent studies have dealt with the application of copper slags (Shi, Meyer, & Behnood, 2008), ladle furnace slags (Manso, Losañez, Polanco, & Gonzalez, 2005), and other dusts such as the EAF dust (da Silva Magalhães, Faleschini, Pellegrino, & Brunelli, 2017), obtaining promising results that will foster future research in this field.

s0030 2.3 Recycled aggregates

p0275 The second method to improve concrete sustainability relates to replacing natural aggregates with recycled components. Such a strategy might seem not as effective as replacing cement with SCMs, due to the lower impact that aggregates have on the carbon footprint of concrete. However, it is worth recalling that indicators for land use are rarely applied in LCA, thus resulting in underestimating environmental problems linked to soil depletion and topography alteration, which are directly correlated to aggregate consumption. In addition, typically aggregates account for about 70% of the overall concrete volume, hence representing a nonnegligible amount of material, which can be potentially saved through appropriate recycling policies.

p0280 Recycled aggregates are produced from C&DW, which is one of the most voluminous types of waste generated worldwide. C&DW includes a large variety of materials that may be derived from different processes, for example, construction, renovation, demolition, land-clearing, and even after natural disasters. Difficulties are often experienced when trying to estimate the volume of C&DW produced yearly in one state, or even worldwide, because of the absence of a universal definition of its constituents. For this reason, it is hard to obtain reliable estimates of this waste stream; further difficulties are encountered when attempting to identify the recycling rate of this material. When C&DW is generated after the occurrence of a disaster, for example, after an earthquake, tsunami, tornado, this single event may be responsible for about 5−15 times the annual waste generation rate of the hit region (Reinhart & McCreanor, 1999). In those cases, the composition of the waste depends mostly on the structural type affected by the disaster and by the event itself. As an example, waste generated by hurricanes is usually quite mixed, whereas waste produced by an earthquake in a historic center is principally made up of stone or brick masonry. For instance, Hurricane Katrina and Hurricane Rita together severely damaged or destroyed over 275,000 homes, which corresponds to more than the total number of residential units demolished in an entire year across the United States (Faleschini, Zanini, Hofer, Zampieri, & Pellegrino, 2017a). Such considerations make the estimation of C&DW streams more and more complex. However, according to EPA (2016), the amount of C&DW generated in the United States during 2014 can be estimated as about 480 million tonnes, whose composition is made of concrete (70%), asphalt concrete (14%), wood products (7%), drywall and plasters (3%), asphalt shingles (3%), brick, clay, and tiles (2%), and steel (1%). At the same time, in 2017 about 390 million tonnes of construction sand and gravel were produced in the United States and used as concrete aggregate (USGS, 2018c), plus 1 billion tonnes of crushed stone used as construction material (USGS, 2018d). According to USGS (2018c), the percentage of total aggregate supplied by recycled materials remained very small in 2017, meaning that a large amount of material was simply landfilled. In Europe, instead, the C&DW production in 2014 can be estimated as about 868 million tonnes, representing about 34.7% of the overall waste streams, with a composition varying significantly country by country. Currently, the rate of recycling and material recovery of C&DW differs also among the state members (between less than 10% and over 90%), even though it is expected that, in the near future, the recycling rate will be about the same for all the European countries. Indeed, Article 11.2 of the Waste Framework Directive (2008) 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 [. . .] shall be prepared for reuse, recycled or undergo other material recovery." However, due to the general availability of virgin aggregates (at least at the regional or national scale), often most of the recycled C&D debris is used as road base or subbase material, as recycled aggregates are generally less expensive or "valuable" than high-quality concrete aggregate. To favor the use of recycled aggregate, and to enhance the recycling rate of C&DW, Green Public Procurement (GPP) has been introduced in Europe, as a voluntary instrument that helps to stimulate a critical mass of demand for more sustainable goods and services, which otherwise would be difficult to get into the market. For instance, in Italy concrete structures built under a GPP should contain at least 5% by weight of recycled constituents (i.e., 120 kg/m^3), and "0-km" products should be preferred over others.

p0285 Recycled aggregates are produced by transforming C&DW in treatment plants that can be stationary or mobile, and equipped with screens, crushers, and magnetic separators, aimed at reducing debris dimensions, separating ferrous elements and other contaminants, and lastly achieving the required grading. From the technical point of view, a huge amount of research has been carried out to establish how the use of recycled aggregates impacts on concrete performance. First, it is necessary to clarify which kind of recycled aggregates can be produced, on the basis of their composition and grading:

- u0155 recycled concrete aggregate (RCA), mainly composed of coarse particles of concrete;
- u0160 recycled masonry aggregate, mainly composed of coarse particles of brick; and
- u0165 mixed aggregates (MA), composed of a mix of coarse particles of concrete and brick; fine aggregate (FA), made up of fine particles only (maximum size less than 4 mm).

p0305 Such a distinction is necessary because the composition of recycled aggregate and its grading have a great effect on recycled concrete properties. A number of standards exist to regulate the use of recycled aggregates in concrete, such as EN 12620 (2008) and EN 206 (2016). Table 2.3 lists, as an indicative example, the maximum replacement ratio allowed per EN 206 (2016), depending on the aggregate type and concrete exposure class. It is significant to note that FA is excluded from any applications in structural concrete, regardless of the strength class and exposure of the structure. In Table 2.3, Type A aggregates are made of RCA, containing a very limited quantity of contaminants (e.g., glass, organic floating materials, asphalt), whereas Type B aggregates are made of RCA and MA, with a lower content of concrete particles and low quantities of contaminants. The nomenclature used in Table 2.3 is that of EN 12620 (2008). As one would guess, the maximum allowable replacement ratio decreases as the exposure class becomes more aggressive.

t0020 **Table 2.3** Maximum percentage of replacement of coarse aggregates (% by mass) according to EN 206 (2016).

Recycled aggregate type	**Exposure class**			
	X0 (%)	**XC1, XC2 (%)**	**XC3, XC4, XF1, XA1, XD1 (%)**	**All other exposure classes (%)**
Type A: (Rc90, Rcu95, Rb10-, Ra1-, FL2-, XRg1-)	50	30	30	0
Type B: (Rc50, Rcu70, Rb30-, Ra5-, FL2-, XRg2-)	50	20	0	0

Type A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%. Type B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.

p0310 Those limits on the replacement ratio reflect the effects of recycled aggregate on concrete that have been experimentally observed in past research studies. Indeed, the main technical problems evidenced when recycled aggregates are used depend on the quality of the aggregates (e.g., for MA, or when the attached mortar content is high), on the great heterogeneity of recycled aggregates, and on the use of fine recycled sand, which is typically rich in contaminants. Reliable indicators of recycled aggregate quality include aggregate density, water absorption, and the amount of attached mortar, which can be estimated through various methods (chemically, through thermal shock, etc.). The density of recycled aggregates is generally slightly lower than that of virgin materials, and it is lower for lower quality aggregates. Conversely, water absorption increases for lower quality of the aggregates, and for increased amounts of old attached mortar. Fig. 2.2 shows particles of RCA with varying contents of old attached mortars and, accordingly, different qualities.

p0315 The use of recycled aggregate, in general terms, causes a reduction in concrete strength (Poon, Shui, Lam, Fok, & Kou, 2004) and elastic modulus, larger creep, and shrinkage deformations (Domingo-Cabo et al., 2009), as well as higher permeability of the concrete (Gómez-Soberón, 2002). In sum, concrete produced with RCA is generally of lower quality than natural concrete. However, when replacement ratios are limited and concern only the coarse fraction, and the quality of recycled aggregate is good, such a reduction of concrete performance is acceptable. In addition, there are methods for the design of recycled concrete that allow one to produce concrete with the same target properties of an ordinary mix, containing natural materials only. For instance, a novel method for concrete design, recently introduced by Fathifazl et al. (2009), called equivalent mortar volume (EMV), has been used to prevent the strength losses often reported in the literature when using recycled concrete. The EMV method has been applied for RCA only, and it considers the recycled aggregate as a two-phase material, consisting of the natural

f0015 **Figure 2.2** Recycled concrete aggregate (RCA) particles with different content of old attached mortar.

aggregate and the mortar attached to it, which must be quantified and included in the proportions of the mix, as a source of cement and sand. This allows the recycled concrete mix to be designed with a similar internal structure to that of the natural concrete used as a reference. The mixing water compensation method (Ferreira, de Brito, & Barra, 2012) for designing concrete is based instead on adding extra water in the mix that will be absorbed by the recycled aggregate, to adjust the effective water/cement ratio of the mix, and hence allow for improved fresh concrete workability. There is also evidence about the practicability of designing high strength concretes containing recycled aggregates, with replacement ratios up to 30%, that do not display any strength loss, just by adjusting the effective water/cement ratio inside the mix (Limbachiya, Leelawat, & Dhir, 2000). Other techniques to improve RCA quality before their use, and therefore limiting possible deficiencies of the recycled concrete, are currently available, such as the autogenous cleaning procedure (Pepe, Toledo Filho, Koenders, & Martinelli, 2014). This method, that has been applied satisfactorily at the laboratory scale, gives positive results enhancing the properties of crushed concrete particles, especially in terms of a reduction of the attached mortar content and, consequently, on their water absorption.

p0320 With regard to concrete durability, generally the reduced properties of recycled aggregates, that is, their lower density and mechanical strength, along with the higher absorption and porosity, make recycled concrete less durable against carbonation, chloride penetration, permeation, and freezing/thawing resistance. However, some contradictory results are also present in the literature. Some research has indicated that carbonation resistance of recycled concrete is slightly inferior to that of natural concrete, due to the increased porosity resulting from the high quantity of attached mortar (Otsuki, Miyazato, & Yodsudjai, 2003). Conversely, other researchers have found that when the recycling rate reaches 100%, carbonation resistance is enhanced (Kou & Poon, 2013).

p0325 It is worth recalling that, for a great number of applications, high-performances concrete is not required. Although there are some limitations that may induce practitioners to be suspicious of recycled concrete, there are many cases in which recycled aggregates might be used safely, as the target performances asked of these concretes are within the range of recycled concrete properties. In those cases, the use of recycled aggregates makes strong economic and technical sense. Blends of virgin aggregates and recycled aggregates can be developed, maintaining the replacement ratio below the limits recommended by the standards for the required applications, thus ensuring little impact of recycled aggregate on the concrete mix. One major success story in the United States is the recycling of Denver's former Stapleton International Airport (Yelton, 2004). Instead of hauling the 6.5 million tonnes of concrete and hardscape (enough aggregate to build the Hoover Dam) to landfills, the Recycled Materials Company, Inc., was able to recycle or reuse all of this material. The company claims this project to be the world's largest recycling project and completed it at no cost to the City of Denver within 6 years (Meyer, 2008). There are also some other exemplary cases of efficient use of recycled concrete that are worth mentioning. These are the Allianz Stadium (also known as Juventus Stadium), which at the time of its construction was the first *recycled stadium*, and the ice rink in Torino, both in Italy. For the Allianz Stadium, about 50,000 tonnes of concrete have been recycled, which came from the original bleachers of the previous structure and were then used for the basement of the new facility. The use of recycled materials other than concrete (5000 tonnes of steel, 2000 m^2 of glass, and 300 metric tonnes of aluminum were saved and recycled) allowed for €2 million savings, according to Legambiente (2017). The ice rink of Turin, built for the Winter Olympic Games of 2006, was built using 20,000 tonnes of recycled aggregates, again used for constructing the basement.

s0035 2.4 Electric arc furnace slag

p0330 Among the steelmaking slags, EAF slag is worth mentioning, as its application as aggregate for concrete is gaining increasing attention. Euroslag, which is an international organization dealing with iron and steel slag matters, has estimated that about 25.9% of steel slags produced in Europe are EAF slags from carbon steel production (EAFC- EAF carbon steel), and 5.9% are EAF slag from stainless or high alloy steel production (EAFS- EAF stainless steel). In particular, the amount of the former, that is, EAFC, is expected to rise dramatically in the near future, due to the conversion of many steel processing plants into EAF technology that is more environmentally sustainable. During the melting process of the steel in this type of furnace, EAF slag (known also as black slag) is generated after the addition of certain admixtures (limestone, slag correction agents such as bauxites, and slag formers) in the molten bath of the steel, in amounts between 120 and 180 kg/tonne of manufactured steel.

p0335 After cooling from 1560°C, EAF slag becomes a stony, cohesive, slightly porous, heavy, hard, and tough material that appears as a black or dark-gray crushed aggregate. Generally, it has very good mechanical properties, as it is made up of particles with a hard, dense, and angular shape. It has high abrasion resistance, low aggregate crushing value, and excellent resistance to fragmentation. In addition, it is typically characterized by a heavier weight than natural aggregates, which depends on the amount of heavy metal oxides included in its composition and that varies slag by slag. Its chemical composition is principally Fe_2O_3, CaO, SiO_2, and Al_2O_3, with minor amounts of MnO and MgO. Constituent materials (e.g., scraps and additions in the furnace) significantly influence slag composition and structure, as well as the cooling method, which can be rapid (through water spraying) or slow (solidification in open air). The density of the EAF slag is an important parameter that helps to identify how heterogeneous the slag might be, depending on each steelmaking process. Indeed, it has been recorded as varying within the range of $3000-4000\ kg/m^3$, due to differences in the content of metallic iron ($\rho \approx 8000\ kg/m^3$), iron and manganese oxides ($\rho \approx 5000\ kg/m^3$), and the internal porosity. EAF slag typically has a crystalline nature, where the principal minerals that can be detected are wustite, hematite, magnetite, merwinite, larnite, etc.

p0340 The above properties make EAF slag a good candidate for use in many areas of construction, including as a (heavyweight) aggregate for concrete. For this reason, gravity structures, hydraulic protection structures, mass concrete, and all other applications in which the heavyweight of the slag is advantageous can be identified as the best markets for EAF concrete. An interesting potential application is as radiation-shielding concrete, as an environmentally friendly substitute of natural aggregates such as barite, hematite, or limonite. One of the first attempts to assess the feasibility of using EAF slag in concrete was carried out by Al-Negheimish, Al-Sugair, and Al-Zaid (1997), who tested the main mechanical properties of EAF concrete mixtures. Subsequent research has shown that the mechanical properties and durability of concretes manufactured with this slag are well known and are similar, or even better, than those of concretes manufactured with traditional natural aggregates (Faleschini et al., 2015a; Manso, Polanco, Losanez, & Gonzalez, 2006). Almost all studies point to the positive contribution of EAF slag on concrete compressive strength, tensile strength, elastic properties, durability against carbonation, chloride penetration, and freezing/thawing cycles (Arribas, Santamaría, Ruiz, Ortega-López, & Manso, 2015). Poor performance is obtained only in the fresh concrete, due to the angular shape of the slag, that could be easily overcome using water-reducing admixtures in the mix. As an example, self-compacting concrete made with EAF slag has been successfully produced (Santamaría et al., 2017). However, most studies show the necessity of limiting the use of the fine slag fraction, which generally cannot exceed 50% as the natural sand replacement ratio (Pellegrino, Cavagnis, Faleschini, & Brunelli, 2013).

p0345 Before being used in concrete, EAF slag must be stabilized to prevent the potential swelling that has been observed which may exceed 2% in volume. Some of the causes of this swelling include free lime hydroxylation and subsequent carbonation, which is acknowledged as the main cause of EAF slag potential expansion, the hydroxylation and carbonation of free MgO, the long-term oxidation of metallic iron from iron +2 to iron +3, and lastly the transformation of β-silicate to γ-silicate. To prevent slag swelling, a simple stabilization treatment that does not involve any transformation of the material can be carried out, consisting of prolonged weathering in outdoor exposure, which should last about 3 months. After this, the slag can be processed as an aggregate, and when it reaches the required grading, it should be sprayed with water for 3–6 days, providing alternate wetting/drying conditions. The reliability of this method has been demonstrated (Pellegrino & Gaddo, 2009). Another environmental obstacle that has discouraged the use of some slags in construction until now is the potential leaching of hazardous compounds and heavy metals. This risk seems particularly relevant for some EAFS from stainless steelmaking that contain a high quantity of chromium. 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. The pretreatment operation discussed above is often effective not only to reduce potential swelling phenomena, but also to reduce the concentrations of harmful substances or the high leaching levels of these elements. Water used to stabilize the slag should of course be collected and treated to maximize the sustainability of the slag production plant.

p0350 Laboratory tests were also conducted to prove the suitability of using EAF slag as aggregate in reinforced concrete structures, to assess whether its heterogeneity, its high density and its poorer workability represent an obstacle for designing and constructing full-scale structures. The results obtained were positive: adjusting the mix with water reducers, it was possible to obtain both pumpable and self-compacting concrete, with appropriate flowability even in highly reinforced structural elements (Fig. 2.3). The structural response of beams subject to four-point

f0020 **Figure 2.3** Casting operations of concrete with electric arc furnaces (EAF) slag aggregate.

loading was even better than for reference beams made with natural concrete, both when flexural-bending failure and shear-failure were induced (Pellegrino & Faleschini, 2013). Bond between steel and concrete is enhanced significantly when EAF slag is used as coarse aggregate, with a positive contribution for developing mechanical interlock and frictional bond mechanisms (Faleschini, Santamaria, Zanini, San José, & Pellegrino, 2017b). Tests were also carried out to evaluate the response of full-scale corner beam-column joints, subject to seismic-like action and gravity, to simulate one of the most stressed regions of a multistory reinforced concrete building. Results in this case also demonstrated a superior response of the elements made with EAF slag concrete, which dissipated more energy, had enhanced ultimate capacity, and remained more intact after the failure (Faleschini, Hofer, Zanini, Dalla Benetta, & Pellegrino, 2017c). A single specimen made with EAF concrete demonstrated the most important and unexpected result: it attained enhanced performances compared to the reference, but it was designed with 20% less cement, and a higher water/cement ratio, thus being significantly more environmentally sustainable than the reference. Results were also extended to other test configurations through a numerical approach, demonstrating always improved performance of the joints made with EAF slag (Faleschini, Bragolusi, Zanini, Zampieri, & Pellegrino, 2017d).

p0355 These results have encouraged some producers to use EAF slag concrete in real construction projects, even though there is still not a standard which clearly supports its use, at least in Europe. One of the most important examples of the application of the EAF slag concrete in a real structure is the basement elements of the Tecnalia experimental building KUBIK, sited in Derio, Bizkaia, on the Northern coast of Spain, which were made of premixed reinforced concrete containing up to 75% (by weight) of EAF slag aggregate. The amount of EAF concrete used was about 140 m^3, necessary to construct both basement walls and foundation slabs, which were manufactured in 2008. EAF concrete was poured on-site continuously with a concrete pump. Concrete strength evolution was monitored constantly for 180 days after concreting, displaying high strength development, which achieved on average 60 MPa for both slabs and walls. After more than 10 years from its construction, no durability problems or swelling phenomena have been recorded. In 2015, the Port of Bilbao used EAF slag to manufacture blocks to protect the “Punta Lucero” dock and to build the new “Punta Sollana” dock, employing a large amount of this material for building these maritime structures (Santamaria, 2017). However, in the past, unsuccessful stories of EAF slag use in concrete have been also recorded, due to the incorrect management of this material, that was often mixed with the white slag (i.e., ladle furnace slag), which is very prone to swelling when in contact with water. The European standard EN 12620 (2008) considers EAF slag as an artificial aggregate, which can be used for many civil engineering applications, including as an aggregate for concrete. However, no details about the technical requirements are defined either in this standard or in other national regulations. Several research groups around the world are working on the standardization of the EAF slag in hydraulic mixes; in Europe, groups from Spain, Italy, and Greece stand out, among others. Other countries, such as Japan, have already concluded this process of standardization, and have proper standards that include this material officially as an aggregate for concrete (JIS A 5011-4, 2013).

s0040 2.5 Recycled waste glass

p0360 According to the EPA (2014), in 2012 Americans generated about 227 million metric tonnes of MSW, of which 4.5% was glass waste, which corresponds to about 10.2 million metric tonnes. Only about 34% of glass containers were recycled, primarily to produce new bottles. Even though glass is easily recycled and can be recycled endlessly without loss in quality or purity, a matter of concern is related to colored glass, which generally is not accepted to produce new containers, because once glass is colored with a coloring agent, the color cannot be removed. Therefore colored glass can only be recycled into glass of the original color. The situation in Europe is very different, and according to FEVE (2015), the average recycling rate for glass packaging reaches 73%, meaning that over 25 billion glass containers continue to be recycled in a bottle to bottle closed loop. There are many options for glass recycling, though most of them may be considered as *downcycling*, because the value of the material for its secondary use is less than in its original form. Most of them involve crushing the glass into cullet or FAs. Some areas in which glass can be recycled include soil applications, construction and road building, and even art and decoration. The fact that much of the waste glass is already broken when collected is one reason that limits or even hinders its use for certain applications. Examples of lower value uses are applications as aggregate for fill, drainage, filtration, road base, pipe bedding, and sand blasting. Since the early 1970s, several transportation departments have used glass as partial replacement of aggregate for asphalt paving, producing the so-called “glasphalt,” but for various reasons, this application never became really widespread. By far the most important waste recycling program is that undertaken by the City of New York’s Department of Transportation, where from 1990 until 1995 approximately 225,000 metric tonnes of glass have been used in resurfacing paving projects (FHWA, 1997). Crushed recycled glass can be used also as FA replacement in concrete, while finely ground glass (powder) has been acknowledged to have pozzolanic properties. Recycled glass aggregate fits also within the definition of manufactured aggregate given in EN 12620 (2008), similar to EAF slag.

p0365 When waste glass is to be used in concrete, it is important that it is crushed using high-velocity impact equipment to avoid sharp edges, which would make its handling hazardous. If properly crushed, the aggregate can be handled just like ordinary sand and crushed stone, without any danger of injury. The glass dust generated by the crushing operation has not been shown to present a quantifiable health hazard, even if prudence calls for collection of the dust at the source. Very finely ground glass particles (below 10 μm) have also been shown to have pozzolanic properties and can serve as an excellent filler material to produce high-performance concrete. The finer the glass powder is, the higher its pozzolanic activity. The activation of these pozzolanic properties can also be accelerated by using higher curing temperatures, causing a rapid strength gain at early ages. In addition, it has been demonstrated that glass powder additions can also reduce the ASR expansion potential, even though to a lesser extent than adding fly ash to the concrete mix (Shi, Wu, Riefler, & Wang, 2005).

p0370 The use of glass as an aggregate for concrete had already been contemplated decades ago (Phillips & Chan, 1972; Johnson, 1974), but the ASR caused an insurmountable problem at that time. ASR is a phenomenon that is well known in concrete, because it can also occur with natural aggregates that contain certain kinds of reactive (amorphous) silica. In the presence of moisture, ASR gel swells, thus creating microcracking in the cementitious matrix, with deleterious strength losses. The main obstacle to the study of ASR phenomena in concrete is its long-term nature, because the resulting damage that might be experienced by concrete can usually be seen only after many years. However, according to the chemical composition of the glass, it can easily be determined if a high risk for ASR potential exists. For instance, soda-lime glass, which is the most prevalent type of glass, used for windowpanes and glass containers for beverages, food, and some commodity items, has very high-risk potential to display ASR if it is used as aggregate in concrete. In addition, one can identify a pessimum size, which is the particle size causing the maximum expansion, that has been demonstrated to depend upon glass type and color. With increasing glass ASR-reactivity, the pessimum shifts toward smaller particle sizes. Clear soda-lime glass is the most reactive, followed by amber glass; green glass caused less expansion than even the reference aggregate. This surprising finding was explained by the presence of chromium oxide that manufacturers add for the green color (Jin, Meyer, & Baxter, 2000). However, a proper evaluation of the reactivity cannot be performed on the basis of glass coloration only, as some recent research has highlighted opposite results about the reactivity of green emerald glass (Park, Lee, & Kim, 2004).

p0375 As ASR has serious consequences on concrete performance, special caution must be taken when dealing with potentially reactive aggregates, such as recycled glass. Each concrete product and glass source needs to be evaluated and tested thoroughly to ensure an acceptable quality and durability. Moreover, accelerated tests such as ASTM C1260 (2014) may be insufficient to guarantee durability, and it may be necessary to conduct longer term tests such as ASTM C1293 (2015), for additional assurance that ASR will not occur. Among the tools available to counteract the detrimental effects of ASR in concrete, it is worth mentioning the following:

- u0170 grind the glass fine enough to pass at least United States standard mesh #100;
- u0175 use mineral admixtures such as MK, fly ash, or GGBFS that consume alkali available for the ASR reaction;
- u0180 apply a protective coating to the glass particles (e.g., zirconium);
- u0185 modify the glass chemistry to make it less reactive;
- u0190 seal the concrete to prevent moisture ingress;
- u0195 use low-alkali cement; and
- u0200 develop a special ASR-resistant cement.

p0415 Concerning the effects of glass aggregate use in concrete, first it is worth noting its almost null water absorption, which is an advantage, because it does not need to be considered when defining the effective water/cement ratio of the mix. Because of the lack of water absorption and the smooth surfaces of glass particles, the flow properties of fresh concrete with glass aggregate are enhanced compared to that of natural aggregate concrete, without the necessity of using water-reducing admixtures. This leads to reduced costs, higher strength, and enhanced durability, even in aggressive environments. Another advantage of glass particles is their excellent hardness and abrasion resistance, which makes them suitable aggregates for paving stones, floor tiles, and other applications subject to high wear and tear (Meyer, Egosi, & Andela, 2001). At elevated temperatures, its use at low replacement ratios provides enhanced concrete strength. The esthetic potential of color-sorted glass, not to mention specialty glass, has barely been explored at all and offers numerous novel applications. A key is to use white cement instead of regular Portland cement, because it requires much smaller quantities of (relatively expensive) color pigments. The possibilities of light reflections and refractions, together with the various color combinations, give architects and other design professionals an important new tool to experiment with. A final advantage of using waste glass as aggregate for concrete is the environmental aspect, because it has the potential of a noticeable impact on the solid waste streams of major metropolitan areas.

p0420 From the marketing point of view, commodity products such as paving stones and concrete masonry units are typically very competitive, with low profit margins. Therefore the economic benefit obtained when substituting glass for natural aggregate is marginal at best. Glass does need to be cleaned, crushed, and graded to specifications, and the producer needs to have a dependable source of glass. If the added cost of ASR-suppressing admixtures is to be avoided, the glass needs to be ground sufficiently fine. But, in this case, it is invisible to the naked eye so that the potential esthetic advantages of glass cannot be utilized. Instead, for value-added products, the purpose of the glass substitution is to exploit the special properties of the glass itself, and thereby add value to a material that, otherwise, would be a waste. Hence, for *upcycling* purposes, pretreatments might be required, to ensure achieving the target performances. For instance, glass might be sorted by color and then it might be coordinated with the color of the cement matrix, aiming at achieving novel esthetic effects, which can be further enhanced with appropriate surface treatments. In order to be visible, glass particles need to be of a certain minimum size, for example, size #8 or #4, which however increases its vulnerability against ASR expansion.

s0045 2.6 Recycled tires

p0425 In 2003, the United States generated approximately 290 million scrap tires. Historically, this waste was simply stockpiled and then landfilled, but over recent years, significant investment has been made in terms of R&D to develop new end markets for exhausted tires, which are constantly increasing in numbers. In 2003, these markets consumed about 233 million scrap tires, that is, about 80.4% of the annual waste production. Of these, 130 million (44.7%) were used as fuel; 56 million (19.4%) were recycled or used in civil engineering projects; 18 million (7.8%) were converted into ground rubber and recycled into products; 12 million (4.3%) were converted into ground rubber and used in rubber-modified asphalt; 9 million (3.1%) were exported; 6.5 million (2.0 %) were recycled into cut/stamped/punched products; and 3 million (1.7%) were used in agricultural and miscellaneous uses. Another 16.5 million scrap tires were retreaded (EPA, 2010). In 2013 in Europe the estimated production of scrap tires was about 3.6 million metric tonnes, of which after sorting, 2.7 million metric tonnes were recovered and recycled, which represents a treatment rate of 96%. This is a commendable result compared to other waste streams in Europe (ETRMA, 2015). Great progress has been recorded in the last 10 years in improving such recycling rates, because of the large environmental problems observed in the past as a consequence of illegal dumping or even burning. There are even countries where the recycling rate attains 100%, such as France, Germany, Italy, Spain, Sweden, and the Netherlands.

p0430 Several materials can be recycled starting from scrap tires; tire-derived materials are typically rubber/elastomers, carbon black, metals, textile, zinc oxide, sulfur, additives, and other carbon-based materials. Cement production is a key market for exhausted tires, where they are used as alternative fuel in cement kilns. Such use is widespread throughout the United States and Europe (Davies & Worthington, 2001), even though it is considered as an example of downcycling, because the value of scrap tires as fuel is considerably less than that of the original material. Alternatively, there are many other potential applications in constructions, for example, in hot mix asphalt or as crumb rubber for modifying binders in asphalt pavements (Navarro, Partal, Martinez-Boza, & Gallegos, 2005; Pasquini, Canestrari, Cardone, & Santagata, 2011). Recycling rubber in cement composites and concrete can also be seen as a downcycling of the scrap, if they are simply replacing natural aggregates without attempting to improve some concrete characteristics. A common way to introduce recycled rubber is through its use as shredded, chipped, ground, or crumb rubber, with sizes ranging from shredded pieces as large as 450 mm to powder particles as small as 75 μm, to produce the so-called "rubberized concrete." The main aim of rubber incorporation in concrete is to lighten the structures and increase some performance characteristics such as strain capacity, ductility, and energy dissipation capacity (Eldin & Senouci, 1993). Indeed, the peculiar difference between recycled rubber and natural aggregates is the large differences in Young's moduli. When recycled rubber is used as aggregate replacement, often losses in compressive and tensile strength as well as stiffness are recorded with increasing rubber content. For this reason, it is suggested that rubber contents should not exceed 20% of the total aggregate volume, to avoid consistent losses in mechanical performance. Instead, rubberized concrete with large amounts of rubber aggregates may be suitable for many other applications, for example, for nonstructural purposes such as lightweight concrete walls, building facades, and architectural units, if a load-bearing structure is separately present. It could also be used as aggregate for cement bases under flexible pavements (Khatib & Bayomy, 1999). Other potential advantages that can be achieved when using rubberized concrete derive from the sound absorption of rubber and its thermal properties. For instance, Farcimar S.A. has concluded the R&D process regarding the use of recycled rubber to produce sound barriers with high acoustic performance, which have been supplied to Vinci Construction Terrassement, for the RN24 site in St. Thurial, France. The sound barriers were 28 cm thick, composed of 10 cm of structural concrete, and 18 cm of rubbercrete, with heights varying between 1 and 4 m.

p0435 However, tires also yield other materials; both textile and steel fibers can be extracted from used tires. There is an ongoing research into the use of textiles from tires as reinforcement in concrete, which has been funded by the E.U. within the LIFE Projects (LIFE14ENV/IT/000160 “Recycling of textile fibers from end-of-life tires for production of new asphalts and plastic compounds”). Steel fibers are also recovered, to be used in fiber-reinforced concrete (FRC); this application has a great potential, as it is estimated that more than 500,000 tonnes of high-quality steel fibers could be recovered annually from used tires in Europe alone (Centonze, Leone, & Aiello, 2012; Pilakoutas, Neocleous, & Tlemat, 2004). There are also other applications which can take advantage of the ductility of rubber. For instance, it has been used to develop seismic base isolation pads and recycled rubber−fiber-reinforced bearings, with comparable performances to reference counterparts (Calabrese, Spizzuoco, Serino, Della Corte, & Maddaloni, 2014; Turer & Özden, 2008).

s0050 2.7 Recycled plastics

p0440 The effects of the huge worldwide plastic consumption are in the eyes of everyone. Plastic debris is accumulating in the oceans, on the coastlines, under the glaciers of the entire planet, jeopardizing the environment worldwide. Since World War II, the ensuing rapid growth in plastics production has been extraordinary, surpassing that of most other man-made materials. Plastics have been used for many purposes, including packaging, automotive and industrial applications, water desalination, land/soil conservation, housing, flood prevention, medical delivery systems, artificial implants, other healthcare applications, preservation and distribution of food, communication materials, security systems, and so on. The vast majority of monomers used to produce plastics, such as ethylene and propylene, are derived from fossil hydrocarbons. The durability of plastic that makes it such an attractive material to use is also the cause of the great environmental concerns about its end-of-life management, because it is highly resistant to degradation. It may take centuries for such materials to break down and decompose (Barnes, Galgani, Thompson, & Barlaz, 2009), and hence near-permanent contamination of the natural environment with plastic waste is a serious risk. While some plastic waste is recycled, the majority ends up in landfills; a huge amount of the material is also subject to indiscriminate disposal, that ends up with the introduction of plastic into the marine environment (Gregory, 2009). It has been estimated that 8300 million metric tonnes of virgin plastics have been produced up to 2017, with an annual production rate of resins and fibers (alone) that increased from 2 million tonnes in 1950 to 380 million tonnes in 2015. By 2015, approximately 6300 million metric tonnes of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or in the natural environment (Geyer, Jambeck, & Lavender Law, 2017).

p0445 The potential reuse of plastics in concrete and cement composites is a subject of great interest, due to the huge amount of waste that should find an alternative to end-of-life other than disposal. Typically, the largest component of the plastic waste stream is low-density polyethylene (LDPE)/linear LDPE, followed by high-density polyethylene, polypropylene (PP), polystyrene (PS/extended PS), polyvinyl chloride, polyethylene terephthalate (PET), and then other miscellaneous types (Siddique, Khatib, & Kaur, 2008). On one hand, recycled plastic has been attempted to be included in concrete as recycled aggregate; on the other, recycled plastic fibers have been developed to be used in FRC. With regard to the first application, research has demonstrated that postconsumer plastic aggregates can be successfully utilized to replace conventional aggregates, even though typically plastic aggregates have a poor bond with the matrix, thus reducing the mechanical properties of the concrete. Indeed, the interfacial transition zone of concrete with recycled plastic aggregates differs from that of conventional concrete, because the plastic surface is smooth and has a hydrophobic nature; as a consequence, poor anchoring between the plastic surface and the cement matrix develops (Choi, Moon, Chung, & Cho, 2005). Most techniques aimed at incorporating recycled plastics in concrete focus on replacing FA with plastic fines. There exist several patented processes to treat the plastic particles thermally or otherwise to improve the bond properties. The use of recycled plastic reduces the overall concrete bulk density; the compressive strength, elastic modulus, splitting tensile strength, and flexural strength of the concrete decrease too, with the increase of the substitution ratio, and depending on the plastic type. For instance, PET aggregates decrease the elastic modulus less significantly than the other plastic types. These properties are further negatively affected when nonuniformly shaped plastic aggregates are used (Gu & Ozbakkaloglu, 2016). Shrinkage increases also with the replacement ratio, and durability generally decreases, because the concrete becomes more porous and with a more open structure. However, ductility is enhanced, even though the peak stress is lower than in the reference concrete, and workability is generally improved.

p0450 When recycled plastic fibers are used in concrete to provide internal reinforcement in FRC applications, the workability of the fresh concrete is reduced, depending on the amount of the addition. Concrete with a low content of plastic fibers (less than 1%) has higher compressive, splitting tensile, and flexural strengths than those of conventional concrete; a further increase in the fiber content leads instead to a deterioration in the mechanical properties of concrete. Such improvements are more visible when PP fibers are used rather than PET fibers.

p0455 Further research is needed to develop methods to replace larger volumes of aggregate with recycled plastics. This goal could be accomplished by improving the bond with the concrete matrix. One possibility is to combine a foaming agent with the use of bioplastic as a coating of plastic aggregate. Bioplastic in its most elementary form is an agricultural waste product (starch). If mixed with water and some oil for workability, it can easily biodegrade in warm wet environments and is therefore highly unstable. When the plastic aggregate is introduced into the wet concrete, the bioplastic coating begins to biodegrade. This process is accelerated by any heat of hydration liberated during curing of the concrete. Once the bioplastic has degraded sufficiently, a chemical foaming agent is activated and causes bubbles to form in the concrete. In addition, the aggregate can be made easily pliable or extremely rigid. The aggregate's bond to the concrete can be designed and varied. All of these features of plastic's incorporation into concrete are engineering problems—as the aggregate itself becomes an engineered product within the concrete matrix. Compared with recycled glass, the chemical interaction with the concrete matrix is benign in its simplest form. One of the most promising aspects of using recycled plastic in concrete (whether raw, modified, or in a bioplastic composition) is the potential change in the visual appearance of the aggregate and concrete matrix. For example, the plastic in the aggregate can be exposed or hidden. The visual impact on the concrete translates into a slight change in the surface color of the mix, as can be seen, for example, in the Plascrete blocks produced by Conigliaro Industries (2007), which consist of commingled waste plastic used as aggregate, at compressive strengths ranging from 2 to 12 MPa.

s0055 2.8 Other recycled materials

p0460 Many other materials have been proposed as substitutes for conventional constituents of concrete. Here the focus is on those materials that are considered as by-products of other productive processes, or even waste, that is, for which a market still does not exist. Most important among these are ashes of many different kinds, as briefly mentioned in Section 2.2 of this chapter. Indeed, there are other kinds of ashes with more or less pronounced pozzolanic properties, which could be potentially applied as a partial replacement of Portland cement. In addition, it is worth recalling that the demand for SCMs is increasing, and both fly ash and GGBFS production might be insufficient in the near future to satisfy it. Other than natural pozzolans, and by-products such as SF (which however, due to its great value, could be considered as a standalone product), co-combustion ashes are gaining increasing importance, because of the current trend of adding refuse-derived fuels in power plants, together with coal (Faleschini, Zanini, Brunelli, & Pellegrino, 2015b). Such additions to the fuel of the power plants might change significantly the composition of the fly ashes generated, which would then need to be properly qualified before a possible use as SCM.

p0465 Most metropolitan areas in the United States and in Europe are also facing major solid waste disposal problems. This is particularly true for New York City, which probably generates more solid waste than any other city in the world, including those that are much bigger. To solve such scarcity of land for waste disposal, waste-to-energy facilities represent currently one of the principal strategies MSW management. However, the disposal of the ash even in conventional landfills is problematic, because this particular fly ash from incineration [MSW incineration (MSWI) fly ash] is typically considered as a hazardous material, because it may contain unacceptable levels of toxic elements. Rather than landfilling such ash, it is possible to exploit its cementitious properties, while encapsulating the heavy metals in the ash in such a way that they cannot leach out. Hence, for this material, a considerable research literature is developing. However, before such technologies can be applied in actual practice, additional research is needed (Ferreira, Ribeiro, & Ottosen, 2003), because of the necessity to identify proper pretreatment operation to remove chlorides and heavy metals, which might negatively affect several cement and concrete properties, including setting time, workability, strength, and durability.

p0470 Coal bottom ash is another material mainly composed of fused coarser ash particles, which are quite porous and look like volcanic lava. Generally, this material is employed in concrete as structural fill, even though there is an existing literature exploring the possibility of coal bottom ash being used as substitute/replacement of FA (Singh & Siddique, 2013). When used as sand replacement, it influences the workability, setting times, loss of water through bleeding, bleeding rate and plastic shrinkage of fresh concrete and density, strength, porosity, and durability of the hardened conglomerate. Such influences are typically negative, as it decreases concrete strength due to higher porosity and higher water demand than natural sand. However, more research is needed to address important aspects regarding effects on concrete durability and to identify strategies for limiting the observed strength losses.

p0475 The application of MSWI bottom ash in concrete has also been explored. Bottom ash is made up of heterogeneous particles consisting of glass, magnetic and paramagnetic metals, minerals, synthetic and natural ceramics, and unburned materials. Freshly quenched bottom ash contains reactive silica and lime, and hence it is considered reactive. The most widespread practice to reuse MSWI bottom ash is as an aggregate substitute for road bases, even though research indicates that it can be also employed as aggregate for concrete. However, when the replacement ratio exceeds 50%, the durability and strength of the concrete are severely affected. Other research has indicated that it can also be used as a cement replacement. However, the most important limit that might hinder its application in constructions is that freshly quenched MSWI bottom ash tends to suffer expansive reactions, that could create swelling problems, even at later ages; these are related to the presence of metallic aluminum or aluminum compounds (Ginés, Chimenos, Vizcarro, Formosa, & Rosell, 2009). In addition, it may also suffer ASR related problems. For such reasons, researchers are attempting to identify suitable washing and pretreatment operations aimed at reducing the above problems; also, their aim is to find optimum combination of MSWI bottom ash with other recycled components that should balance the above deficiencies of this ash.

p0480 RHA is another suitable candidate as a SCM, because it has been shown to have valuable cementitious properties (Mehta, 1992; Nehdi, Duquette, & Damatty, 2003; Zhang & Malhotra, 1996). It is the residue from burning rice husks, an agricultural by-product of the production of rice. For every 1000 kg of rice paddy milled, about 50 kg of RHA is produced (Siddique, 2008), which translates into millions of tonnes worldwide each year. Existing research has demonstrated the feasibility of producing blended cements with RHA that are extremely competitive in terms of economic price, sustainability, and technical performances. An optimum level of strength and durability properties has been observed, generally reached with addition of up to 20% of RHA; beyond that, a slight decrease in compressive and tensile strength is observed, though negligible effects on strength can be obtained at up to 40% replacement ratio. However, the pozzolanic activity index of this ash depends on the degree of grinding, the burning temperature, and the content of reactive silica. It has been found that RHA is extremely sensitive to fineness changes; thus, the higher the fineness, the more active the ash, and its contribution to strength gain is improved (Antiohos, Papadakis, & Tsimas, 2014). Its beneficial effect is primarily achieved at 28 days, being lower at the early ages. A good ability of RHA to consume available lime is recorded, that is comparable or even higher than that of fly ash. If the efficiency value is used to design concrete, the RHA k-value has been estimated as being about 0.8 at 28 days, which is even better than low-calcium fly ashes ($k = 0.5-0.7$), but worse than SF ($k = 2.5-3$). In general terms, the incorporation of RHA in concrete up to a 25% replacement ratio of cement contributes to low chloride ion penetration and reduces also water absorption.

p0485 The combustion of wood results in about 6%−10% ash, the characteristics of which vary widely with the type of wood, its cleanliness, the combustion temperature, etc. Typical wood burnt for fuel at pulp and paper mills and wood products industries may consist of sawdust, wood chips, bark, and saw mill scraps, etc. (Siddique, 2008). The suitability of the ash as a cementitious material has been shown (Naik, 1999; Naik & Kraus, 2000).

p0490 Hempcrete is a light composite building material with building lime as its binding agent and containing hemp shives (wood core) and fibers (with high tensile strength). The process for separating fibers from shives is generally complex and costly, and thus this application needs to find a viable market for both together. However, at present this material can be used only in combination with a load-bearing structure, due to the insufficient mechanical properties of hempcrete (de Bruijn, Jeppsson, Sandin, & Nilsson, 2009).

p0495 Self-healing concrete is a novel type of cement-based material characterized by the ability of the concrete to self-seal cracks occurring due to external loading and/or exposure in aggressive environments, with chemical products within the concrete, with the aid of rainwater and carbon dioxide in the air (Roig-Flores, Moscato, Serna, & Ferrara, 2015). Together with self-sensing concrete, these two materials have been the object of increasing interest over the last two decades, acknowledging their potential application in the field of structural health-monitoring and repair of existing structures. Self-sensing properties are characteristics that allow the material to develop a capability to sense the strain, stress cracking, or damage, while maintaining its mechanical properties (Han, Ding, & Yu, 2015).

p0500 Fiber-reinforced concrete is increasingly being used. The addition of large numbers of short, uniformly dispersed fibers has the effect of modifying the properties of the concrete matrix. The main benefits are improved ductility, toughness, and energy dissipation capacity, which have been exhaustively documented in the literature. Even more significant is the role that fibers play in controlling the cracking of the concrete matrix. By preventing cracks from opening up, the permeability of concrete can be preserved, which translates into improved durability. The most common types of fiber are steel and PPE, and alkali-resistant glass fibers are widespread in the precast concrete industry. All of these fibers are usually manufactured out of virgin material. However, studies have been reported on substituting fibers manufactured out of recycled carpets. Millions of tonnes of old carpets need to be disposed of each year, constituting another sizeable fraction of solid waste. Since carpet fibers are typically made of nylon, recycled fibers have been shown to improve some mechanical properties of concrete (Wang, 1999).

s0060 2.9 Future trends

p0505 There are some key strategies that define mandatory steps toward a circular economy in the construction sector, that also contribute to achieving some of the SD goals defined by the new 2030 Agenda for Sustainable Development of our planet (United Nations, 2015). Among them, #11, that is, make cities inclusive, safe, resilient, and sustainable, is one of the most important for the construction sector. Of course, when dealing with the sustainability of construction, this is not the only goal that could be pursued, as reducing the impacts of the construction industry permits also achieving further SD goals that are listed in Table 2.4.

p0510 Such strategies include the reuse and upscaling of as much waste as possible to produce valuable new products that can be introduced into the concrete market. The future of using recycled materials in concrete only makes sense if it is economically attractive, meaning that recycling markets must function properly, and a real upscaling of waste is attained. In a free market economy, the price of a service or commodity is determined by supply and demand. But government can and regularly does intervene with incentives (e.g., in the form of tax write-offs) and disincentives, such as fees, penalties, or outright prohibition, if this is considered to be in the best interest of the public. This is what governments are currently doing, using a wide variety of measures to promote recycling. Unfortunately, there is some evidence that markets for some recyclable materials are still subject to important failures and barriers, thus in practice limiting the possible high recycling rate of some wastes.

p0515 An interesting tool that has been introduced recently in Italy (and in other EU countries) to achieve increasing replacement rates in construction is GPP, which states that some minimum environmental criteria must be followed in a public project. Such criteria vary depending on the project type, and within them, on the t0025 **Table 2.4** Impact of "green constructions" on sustainable development (SD) goals.

SD goal (United Nation, 2015)	Impact of construction sector	Reason
#1: No poverty	No	–
#2: Zero hunger	No	–
#3: Good health and well-being	Yes	Green buildings can improve people's health and well-being
#4: Quality education	No	–
#5: Gender equality	No	–
#6: Clear water and sanitation	No	–
#7: Affordable and clean energy	Yes	Renewable energy should be preferred for developing green buildings, they will become cheaper to run
#8: Decent work and economic growth	Yes	The new markets generated in the field of waste and by-product recycling and valorization
#9: Industry, innovation, and infrastructure	Yes	Green building design can foster innovation, contributing to climate and disaster-resilient infrastructures
#10: Reduced inequalities	No	–
#11: Sustainable cities and communities	Yes	Reduction of environmental impacts, natural resources preservation, avoidance of waste production
#12: Responsible consumption and production	Yes	Application of circular economy principles, through the concept of urban mining, where waste becomes a resource to be valorized in new products with an added-value
#13: Climate action	Yes	Green buildings should be designed to achieve lower impact emissions throughout their life cycle, from cradle-to-grave
#14: Life below water	Yes	Green buildings might contain recycled plastics that currently is accumulating into water bodies
#15: Life on land	Yes	Green buildings consume less natural resources (including water), and thus protects land consumption and deforestation
#16: Peace, justice, and strong institutions	No	–
#17: Partnerships for the goals	Yes	Strong, global collaboration that might arise for developing green buildings around the planet

material type. For instance, recently new criteria have been adopted for the construction of buildings, and some of them are precast concrete structures should contain at least 5% by weight of recycled materials or industrial by-products; masonry blocks should contain, as a minimum, recycled materials between 5% and 15%, depending on their applications; steel coming from EAF productive process should contain at least 70% of recycled material (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2017).

p0520 Equally important is a general shift in public attitude. Whereas Europeans and Japanese have long been used to material shortages, Americans have been raised much more on the principles of conspicuous consumption and wasteful use of natural resources. But that is now changing, and there is increasing public attention to solid waste management and environmental problems. Environmental consciousness is growing worldwide: for instance, according to Eurobarometer (2005), the large majority of European citizens (about 85%) would like policy makers to consider the environment to be just as important as economic or social policies. For such reasons, stable SD is considered one of the main objectives of the European Parliament. Then community residents and government officials have the possibility to see the potential returns on investment in recycling, and people tend to respond positively to the benefits both to themselves and their communities. Due to the continually increasing amount of solid waste being generated, and the limited space and capacity of waste treatment facilities, particularly in and near metropolitan areas, overall the willingness of people to bear the costs of a proper recycling policy increases, as well their attitude to recycling. Such an attitude promotes keeping people inspired, motivated, educated, and informed.

References

ACI 232. (2018). *Report on the use of fly ash in concrete*. Farmington Hills, MI: American Concrete Institute.

Al-Negheimish, A. I., Al-Sugair, F. H., & Al-Zaid, R. Z. (1997). Utilization of local steel making slag in concrete. *Journal of King Saud University Engineering Science*, *9*, 39–55.

American Road & Transportation Builders Association. (2015). *Production and use of coal combustion products in the U.S. – Market forecast through 2033*. Available from https://www.acaa-usa.org/Portals/9/Files/PDFs/ReferenceLibrary/ARTBA-final-forecast.compressed.pdf.

Antiohos, S. K., Papadakis, V. G., & Tsimas, S. (2014). Rice husk ash (RHA) effectiveness in cement and concrete as a function of reactive silica and fineness. *Cement and Concrete Research*, *61–62*, 20–27.

Arribas, I., Santamaría, A., Ruiz, E., Ortega-López, V., & Manso, J. M. (2015). Electric arc furnace slag and its use in hydraulic concrete. *Construction and Building Materials*, *90*, 68–79.

ASTM C1260. (2014). *Standard test method for potential alkali reactivity of aggregates (Mortar-Bar method)*. West Conshohocken, PA: ASTM International.

ASTM C1293. (2015). *Standard test method for determination of length change of concrete due to alkali-silica reaction*. West Conshohocken, PA: ASTM International.

ASTM C595. (2018). *Standard specification for blended hydraulic cements*. West Conshohocken, PA: ASTM International.

ASTM C618. (2017). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. West Conshohocken, PA: ASTM International.

ASTM C989. (2018). *Standard specification for slag cement for use in concrete and mortars*. West Conshohocken, PA: ASTM International.

Babu, K. G., & Kumar, V. S. R. (2000). Efficiency of GGBS in concrete. *Cement and Concrete Research*, *30/8*, 1031–1036.

Barnes, D. K. A., Galgani, F., Thompson, R. C., & Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 1985–1998.

da Silva Magalhães, M., Faleschini, F., Pellegrino, C., & Brunelli, K. (2017). Cementing efficiency of electric arc furnace dust in mortars. *Construction and Building Materials*, *157*, 141–150.

de Bruijn, P. B., Jeppsson, K.-H., Sandin, K., & Nilsson, C. (2009). Mechanical properties of lime–hemp concrete containing shives and fibres. *Biosystems Engineering*, *103*, 474–479.

Calabrese, A., Spizzuoco, M., Serino, G., Della Corte, G., & Maddaloni, G. (2014). Shaking table investigation of a novel, low-cost, base isolation technology using recycled rubber. *Structural Control Health Monitoring*, *22*(1), 107–122.

Centonze, G., Leone, M., & Aiello, M. A. (2012). Steel fibers from waste tires as reinforcement in concrete: A mechanical characterization. *Construction and Buildings Materials*, *36*, 46–57.

Choi, Y.-W., Moon, D.-J., Chung, J.-S., & Cho, S.-K. (2005). Effects of waste PET bottles aggregate on the properties of concrete. *Cement and Concrete Research*, *35*(4), 776–781.

Conigliaro Industries, 71 Waverly Street, Framingham, MA 01702, 2007. Available from http://www.conigliaro.com/products/plascrete.cfm.

Davies, R. W., & Worthington, G. S. (2001). Use of scrap tyre as a fuel in the cement manufacturing process. In R. K. Dhir, et al. (Eds.), *Recycling and use of used tyres*. London: Thomas Telford.

Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction and Building Materials*, *23*(7), 2545–2553.

Eldin, N. N., & Senouci, A. B. (1993). Rubber-tire particles as concrete aggregate. *Journal of Materials in Civil Engineering – ASCE*, *5*(4), 478–496.

EN 12620. (2008). *Aggregates for concrete*. Brussels, Belgium: Comité Européen de Normalisation.

EN 197-1. (2011). *Cement—Part 1: Composition, specifications and conformity criteria for common cements*. Brussels, Belgium: Comité Européen de Normalisation.

EN 206. (2016). *Concrete. Specification, performance, production and conformity*. Brussels, Belgium: Comité Européen de Normalisation.

EN 450-1. (2012). *Fly ash for concrete. Definition, specifications and conformity criteria*. Brussels, Belgium: Comité Européen de Normalisation.

EPA. (2010). *Scrap tires: Handbook on recycling applications and management for the U.S. and Mexico*. Available from: https://archive.epa.gov/epawaste/conserve/materials/tires/web/html/publications.html.

EPA. (2014). *Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2012*. Available from https://archive.epa.gov/epawaste/nonhaz/municipal/web/pdf/2012_msw_fs.pdf.

EPA. (2015). *National emission standards for hazardous air pollutants (NESHAP)*. Environmental Protection Agency. Available from https://www.epa.gov/stationary-sources-air-pollution/national-emission-standards-hazardous-air-pollutants-neshap-9.

EPA. (2016). *Construction and demolition debris generation in the United States, 2014*. Available from https://www.epa.gov/sites/production/files/2016-12/documents/construction_and_demolition_debris_generation_2014_11302016_508.pdf.

ETRMA. (2015). *End-of-life tyre REPORT 2015*. Available from http://www.etrma.org/uploads/Modules/Documentsmanager/elt-report-v9a---final.pdf.

Eurobarometer. (2005). *The attitudes of European citizens towards environment*. Available from http://ec.europa.eu/commfrontoffice/publicopinion/archives/ebs/ebs_217_sum_en.pdf.

Faleschini, F., Bragolusi, P., Zanini, M. A., Zampieri, P., & Pellegrino, C. (2017d). Experimental and numerical investigation on the cyclic behavior of RC beam column joints with EAF slag concrete. *Engineering Structure*, *152*, 335−347.

Faleschini, F., Fernández-Ruíz, A. M., Zanini, M. A., Brunelli, K., Pellegrino, C., & Hernández-Montes, E. (2015a). High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties. *Construction and Building Materials*, *101*, 113−121.

Faleschini, F., Hofer, L., Zanini, M. A., Dalla Benetta, M., & Pellegrino, C. (2017c). Experimental behavior of beam-column joints made with EAF concrete under cyclic loading. *Engineering Structures*, *139*, 81−95.

Faleschini, F., Santamaria, A., Zanini, M. A., San José, J.-T., & Pellegrino, C. (2017b). Bond between steel reinforcement bars and Electric Arc Furnace slag concrete. *Materials and Structures*, *50*(3), 170.

Faleschini, F., Zanini, M. A., Brunelli, K., & Pellegrino, C. (2015b). Valorization of co-combustion fly ashes in concrete. *Materials and Design*, *85*, 687−694.

Faleschini, F., Zanini, M. A., Hofer, L., Zampieri, P., & Pellegrino, C. (2017a). Sustainable management of demolition waste in post-quake recovery processes: The Italian experience. *International Journal of Disaster Risk Reduction*, *24*, 172−182.

Faleschini, F., Zanini, M. A., Pellegrino, C., & Pasinato, S. (2016). Sustainable management and supply of natural and recycled aggregates in a medium-size integrated plant. *Waste Management*, *49*, 146−155.

Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., & Foo, S. (2009). New mixture proportioning method for concrete made with coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *21*, 601−611.

Ferreira, L., de Brito, J., & Barra, M. (2012). Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Magazine of Concrete Research*, *63*, 617−627.

Ferreira, L., Ribeiro, L., & Ottosen, L. (2003). Possible applications for municipal solid waste fly ash. *Journal of Hazardous Materials*, *96*(2−3), 201−216.

FEVE. (2015). *European container glass federation PRESS RELEASE – GLASS RECYCLING HITS 73 IN THE EU*. Available from http://feve.org/wp-content/uploads/2016/04/Press-Release-EU.pdf.

FHWA. (1997). User guidelines for waste and byproduct materials in pavement construction. In: *Federal Highway Administration Research and Technology Report no. FHWA-RD-97-148*. Available from https://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/wg2.cfm.

Geyer, R., Jambeck, J. R., & Lavender Law, K. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782.

Ginés, O., Chimenos, J. M., Vizcarro, A., Formosa, J., & Rosell, J. R. (2009). Combined use of MSWI bottom ash and fly ash as aggregate in concrete formulation: Environmental and mechanical considerations. *Journal of Hazardous Materials*, *169*(1−3), 643−650.

Gómez-Soberón, J. M. V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate. An experimental study. *Cement and Concrete Research*, *2069*, 1−11.

Gregory, M. R. (2009). Environmental implications of plastic debris in marine settings: Entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*, 2013−2025.

Gu, L., & Ozbakkaloglu, T. (2016). Use of recycled plastics in concrete: A critical review. *Waste Management*, *51*, 19−42.

Habert, G., Bouzidi, Y., Chen, C., & Jullien, A. (2010). Development of a depletion indicator for natural resources used in concrete. *Resources, Conservation, Recycling*, *54*, 364−376.

Han, B., Ding, S., & Yu, X. (2015). Intrinsic self-sensing concrete and structures: A review. *Measurement*, *59*, 110−128.

Ioannidou, D., Nikias, V., Brièere, R., Zerbi, S., & Habert, G. (2015). Land-cover-based indicator to assess the accessibility of resources used in the construction sector. *Resources, Conservation and Recycling*, *94*, 80−91.

Jin, W., Meyer, C., & Baxter, S. (2000). Glascrete − Concrete with glass aggregate. *ACI Materials Journal*, *2000*, 208−213.

JIS A 5011-4. (2013). *Slag aggregate for concrete—Part 4: Electric arc furnace oxidizing slag aggregate*. Tokyo, Japan: Japanese Industrial Standards Committee.

Johnson, C. D. (1974). Waste glass as coarse aggregate for concrete. *Journal of Testing and Evaluation*, *2*(5), 344−350.

Josa, A., Aguado, A., Cardim, A., & Byars, E. (2007). Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. *Cement and Concrete Research*, *37*, 781−788.

Khatib, Z. K., & Bayomy, F. M. (1999). Rubberized Portland cement concrete. *Journal of Materials in Civil Engineering − ASCE*, *11*(3), 206−213.

Kou, S. C., & Poon, C. S. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement Concrete Composites*, *37*, 12−19.

Lane, R. O., & Best, J. F. (1982). Properties and use of fly ash in Portland cement concrete. *Concrete International*, *4*(7), 81−92.

Legambiente. (2017). L'economia circolare nel settore delle costruzioni. *Rapporto dell'osservatorio Recycle* (in Italian).

Limbachiya, M. C., Leelawat, T., & Dhir, R. K. (2000). Use of recycled concrete aggregates in high-strength concretes. *Materials and Structures*, *33*, 574−580.

Manmohan, D., & Mehta, P. (1981). Influence of pozzolanic, slag, and chemical admixtures on pore size distribution and permeability of hardened cement pastes. *Cement, Concrete and Aggregates*, *3*(1), 63−67.

Manso, J. M., Losañez, M., Polanco, J. A., & Gonzalez, J. J. (2005). Ladle furnace slag in construction. *Journal of Materials in Civil Engineering − ASCE*, *17*(5), 513−518.

Manso, J. M., Polanco, J. A., Losanez, M., & Gonzalez, J. J. (2006). Durability of concrete made with EAF slag as aggregate. *Cement and Concrete Composites*, *28*, 528−534.

McCarthy G. J, Johansen D. M., Steinwand S. J., Thedchanamoorthy A. (1987). X-ray diffraction analysis of fly ash. In: *Advances in X-ray analysis 31*, 331−342, *Cambridge University Press.*

Mehta P. K. (1992). Rice husk ash − A unique supplementary cementing material. In: *Proceeding of the international symposium on advances in concrete technology* (pp. 113−122), Athens, Greece.

Mehta, P. K. (2000). Concrete technology for sustainable development − Overview of essential elements. In O. E. Gjørv, & K. Sakai (Eds.), *Concrete technology for a sustainable development in the 21st century* (pp. 83−94). London: E & FN Spon.

Meyer, C. (2008). Recycled materials in concrete. In S. Mindess (Ed.), *Developments in the formulation and reinforcement of concrete*. Cambridge: Woodhead Publishing limited.

Meyer, C., Egosi, N., & Andela C. (2001). Concrete with waste glass as aggregate. In: R. K. Dhir, T. D. Dyer, & M. C. Limbachiya (Eds.), *Recycling and re-use of glass cullet. Proceedings of the international symposium concrete technology unit of ASCE and University of Dundee*, March 19−20, 2001.

Miller, S. A., Horvath, A., & Monteiro, P. J. M. (2016). Readily implementable techniques can cut annual CO_2 emissions from the production of concrete by over 20%. *Environmental Research Letters*, *11*, 074029.

Miller, S. A., Horvath, A., & Monteiro, P. J. M. (2018). Impacts of booming concrete production on water resources worldwide. *Nature Sustainability*, *1*, 69−76.

Mindess, S., Young, J. F., & Darwin, D. (2003). *Concrete* (2nd ed.). Englewood Cliffs, NJ: Prentice Hall.

Ministero dell'Ambiente e della Tutela del Territorio e del Mare. (2017). *Piano d'azione nazionale sul Green Public Procurement (PANGPP) − CAM Edilizia, 6/11/2017* (in Italian).

Monteiro, P. J. M., Miller, S. A., & Horvath, A. (2017). Towards sustainable concrete. *Nature Materials*, *16*, 698−699.

Naik, T. R. (1999). *Tests of wood ash as a potential source for construction materials. Report No. CBU-1999-09*. Milwaukee: UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin − Milwaukee.

Naik, T. R., & Kraus, R. N. (2000). *Use of wood ash for structural concrete and flowable CLSM. Report No. CBU-2000-31*. Milwaukee: UWM Center for By-Products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin − Milwaukee. Final Report Submitted to the University of Wisconsin System, Solid Waste Management and Research Program.

Navarro, F. J., Partal, P., Martinez-Boza, F., & Gallegos, C. (2005). Influence of crumb rubber concentration on the rheological behavior of crumb rubber modified bitumen. *Energy and Fuels*, *19*, 1984−1990.

Nehdi, M., Duquette, J., & Damatty, A. E. (2003). Performance of rice husk ash produced using a new technology as a mineral admixture in concrete. *Cement and Concrete Research*, *33*, 1203−1210.

Osborne, G. J. (1999). Durability of Portland blast furnace slag cement concrete. *Cement and Concrete Composites*, *21*, 11−21.

Otsuki, N., Miyazato, S. I., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. *Journal of Materials in Civil Engineering*, *15*(5), 443−451.

Pal, S. C., Mukherjee, A., & Pathak, S. R. (2003). Investigation of hydraulic activity of ground granulated blast furnace slag in concrete. *Cement and Concrete Research*, *33*(9), 1481−1486.

Papadakis, V. G. (2000). Efficiency factors (k-values) for supplementary cementing materials regarding carbonation and chloride penetration. *ACI Special Publication*, *192*, 173−188.

Papadakis, V. G., & Tsimas, S. (2002). Supplementary cementing materials in concrete: Part I: Efficiency and design. *Cement and Concrete Research*, *32*(10), 525−532.

Park, S. B., Lee, B. C., & Kim, J. H. (2004). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, *34*(12), 2181−2189.

Pasquini, E., Canestrari, F., Cardone, F., & Santagata, F. A. (2011). Performance evaluation of gap graded Asphalt Rubber mixtures. *Construction and Building Materials*, *25*(4), 2014−2022.

Pellegrino, C., Cavagnis, P., Faleschini, F., & Brunelli, K. (2013). Properties of concretes with black/oxidizing electric arc furnace slag aggregate. *Cement and Concrete Composites*, *37*, 232−240.

Pellegrino, C., & Faleschini, F. (2013). Experimental behavior of reinforced concrete beams with electric arc furnace slag as recycled aggregate. *ACI Materials Journal*, *110*, 197−206.

Pellegrino, C., & Gaddo, V. (2009). Mechanical and durability characteristics of concrete containing EAF slag as aggregate. *Cement and Concrete Composites*, *31*, 663−671.

Pepe, M., Toledo Filho, R. D., Koenders, E. A. B., & Martinelli, E. (2014). Alternative processing procedures for recycled aggregates in structural concrete. *Construction and Building Materials*, *69*, 124−132.

Phillips, J. C., & Chan, D. S. (1972). Refuse glass aggregate in Portland cement concrete. In: *Proceedings, third mineral waste utilization symposium*, Chicago, March 1972. U.S. Bureau of Mines and IIT Research Institute.

Pilakoutas, K., Neocleous, K., & Tlemat, H. (2004). Reuse of tyre steel fibres as concrete reinforcement. *Proceedings of the ICE - Engineering Sustainability*, *157*(3), 131−138.

Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, *34*(1), 31−36.

Reinhart, D. R., McCreanor, P. T. (1999). *Disaster debris management − Planning Tools*. US Environmental Protection Agency Region IV, Final Report.

Roig-Flores, M., Moscato, S., Serna, P., & Ferrara, L. (2015). Self-healing capability of concrete with crystalline admixtures in different environments. *Construction and Building Materials*, *86*, 1−11.

Santamaria, A. (2017). *Development of cementitious matrix materials, with improved performance, incorporating by-products from the steelmaking industry* (Ph.D. thesis). Spain: University of Basque Country.

Santamaría, A., Orbe, A., Losañez, M. M., Skaf, M., Ortega-Lopez, V., & González, J. J. (2017). Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate. *Materials and Design*, *115*, 179−193.

Shi, C., Meyer, C., & Behnood, A. (2008). Utilization of copper slag in cement and concrete. *Resources, Conservation and Recycling*, *52*(10), 1115−1120.

Shi, C., Wu, Y., Riefler, C., & Wang, H. (2005). Characteristics and pozzolanic reactivity of glass powders. *Cement and Concrete Research*, *35*(5), 987−993.

Siddique, R. (2008). *Waste materials and by-products in concrete*. Berlin: Springer.

Siddique, R., Khatib, J., & Kaur, I. (2008). Use of recycled plastic in concrete: A review. *Waste Management*, *28*(10), 1835−1852.

Singh, M., & Siddique, R. (2013). Effect of coal bottom ash as partial replacement of sand on properties of concrete. *Resources, Conservation and Recycling*, *72*, 20−32.

Smith, I. A. (1967). Design of fly ash concretes. *Proceeding of the Institution of Civil Engineering*, *36*, 769–790.

Smolczyk, H. G. (1978). The effect of the chemistry of slag on the strength of blast-furnace cements. *Zement-Kalk-Gips (Wiesbaden)*, *31*(6), 294–296.

Turer, A., & Özden, B. (2008). Seismic base isolation using low-cost Scrap Tire Pads (STP). *Materials and Structures*, *41*(5), 891–908.

UK Quality Ash Association. (2015). *Embodied CO_2e of UK cement, additions and cementitious material. Fact Sheet 18*. Available from http://cement.mineralproducts.org/documents/Factsheet_18.pdf.

United Nations. (2015). *Resolution adopted by the General Assembly on 25 September 2015. 70/1. Transforming our world: the 2030 Agenda for Sustainable Development*.

USGS. (2017). *U.S. Geological Survey, Mineral Commodity Summaries, January 2017*. Available from https://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel_slag/mcs-2017-fesla.pdf.

USGS. (2018a). *U.S. Geological Survey, Mineral Commodity Summaries, January 2018*. Available from https://minerals.usgs.gov/minerals/pubs/commodity/sand_&_gravel_construction/mcs-2018-sandc.pdf.

USGS. (2018b). *Geological Survey, Mineral Commodity Summaries, January 2018*. Available from https://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2018-cemen.pdf.

USGS. (2018c). *Geological Survey, Mineral Commodity Summaries, January 2018*. Available from https://minerals.usgs.gov/minerals/pubs/commodity/sand_&_gravel_construction/mcs-2018-sandc.pdf.

USGS. (2018d). *Geological Survey, Mineral Commodity Summaries, January 2018*. Available from https://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/mcs-2018-stonc.pdf.

Wang, Y. (1999). Utilization of recycled carpet waste fibers for reinforcement of concrete and soil. *Polymer-Plastics Technology and Engineering*, *38*(3), 533–546.

Waste Framework Directive. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. *Official Journal of the European Union*. L312/3, 28p. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri = CELEX:32008L0098.

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth Science Reviews*, *141*, 105–121.

Yelton, R. (2004). Concrete recycling takes off. *The Concrete Producer*, 28–31, Publication #J04I028, Hanley Wood, LLC.

Zhang, M. H., & Malhotra, V. M. (1996). High-performance concrete incorporating rice husk ash as a supplementary cementing material. *ACI Materials Journal*, *93*(6), 629–636.

NON-PRINT ITEM

Abstract

This chapter reviews the main recycled materials that can be introduced in concrete mix design to achieve the sustainability goals asked for by the construction industry. Outcomes from the most recent research work about the use of recycled components in concrete are reported. First, the use of supplementary cementing materials such as fly ash and ground granulated blast-furnace slag is discussed. Then, the application of recycled materials as aggregates is analyzed, paying special attention to recycled aggregates coming from construction and demolition waste, whose use is already regulated in almost all of the developed countries. By-products will also be presented, because their application in concrete is gaining increasing attention by researchers, such as in the case of steel slags. Lastly, some innovative research results about other recycled materials are included, such as recycled glass and plastics, scrap tires, hemp fibers, and ashes from incinerator facilities.

Keywords: Fly ash; recycled aggregates; recycled fibers; supplementary cementing materials; steel slags; sustainable development goals