Chapter 10
Sustainability Aspects in Mass Concrete

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Abstract This chapter addresses potential alternatives for base raw materials as well as potential solutions for sustainability in mass concrete. Issues like material selection and environment, material properties and mix design, durability, carbon footprint and life cycle analysis (LCA) of mass concretes are reviewed. The focus is put on recycling. Besides the use of conventional SCMs, non-conventional biomass pozzolans, based on combustion of renewable source of energy, like woody ashes, sugarcane bagasse ash and rice husk ash are covered. The synergic use of several mineral SCMs as a partial substituent of Portland cement is addressed. Furthermore, reuse of aggregates from construction–demolition waste as well as natural fiber alternatives to steel and synthetic reinforcements is discussed in detail. Materials selections and the consequence of it on the properties that affect the mix design and material properties specifically related to durability are summarized. An introduction on life cycle assessment (LCA) is given with its pros and cons, followed by its review on different mass concrete mixtures, separately addressing LCA of binders, aggregates, concretes and reinforced concrete structures with placement technologies. Limitations and further research directions are highlighted.

10.1 Introduction

Sustainability in mass concrete deals with designing of a sustainable concrete structure. Relevant issues in this respect are the environmental impacts occurred from raw materials extraction, through material production, transportation, construction, use, to the stages of disposal and recycling. All these elements together

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determine that the impact mass concrete has on the environmental footprint, including CO_2 emissions, energy use and generated waste.

Materials in view of sustainability in mass concrete are given in first section. The Materials section starts with a plain overview of potential materials that can be used for mass concrete with their purpose. Next, mass concrete properties are discussed considering different mix design possibilities using possible alternative materials. Lastly, a review on LCA is given covering typical scenarios occurring during a production of mass concrete structures.

10.2 Materials Selection

The current materials used in mass concretes and the potential more sustainable alternatives are reported in this section.

Supplementary cementitious materials (SCMs) are used to partly replace traditional Portland cement in concrete. By-products from industrial processes, such as steel slag, silica fume or fly ashes, have latent hydraulic characteristics; however, the development of green ecological concretes asks for SCMs originating from renewable base materials. A great deal of research has been conducted to examine the potential use of biomass pozzolans, based on combustion of renewable source of energy, like woody ash, sugarcane bagasse ash, rice husk ash, but also marble and granite residues are considered to act as a sustainable replacement in concrete. These efforts have generated lots of knowledge in the field of using sustainable SCMs as a replacement material. When combining this knowledge with the application of recycled aggregates originating from construction–demolition wastes (CDW), as well as natural fiber alternatives to steel and synthetic reinforcements the ingredients are available to develop the framework of an ecological concrete.

As concrete is one of the most widely employed construction materials, the use of recycled constituents, such as binders, aggregates, reinforcement and even water, to partially replace the 'natural' raw materials is of particular interest as a possible solution for the reduction of the environmental footprint of the mass concrete production.

10.2.1 Binders: Cement, Pozzolans and Filers

The major negative environmental impact of concrete is caused by cement clinker production that results in around 5–7% of anthropogenic global CO_2-emissions (Schneider et al. 2011; Lothenbach et al. 2008; Fennis 2011). Blending supplementary cementitious materials (SCMs) (Schneider et al. 2011; Lothenbach et al. 2008), as well as fillers like limestone, micronized sand or, marble and granite residues (Bacarji et al. 2013) to replace cement clinker is the most promising route towards sustainable construction materials. Replacing large quantities of Portland cement by pozzolans or fillers is a strategy that contributes largely to the reduction of traditional Portland cement in concrete, and with this, to reduced hydration heat development as well as reduced environmental footprint. Environmental impacts, such as CO_2 emission, natural resource usage, energy consumption and others, will all be positively influenced when replacing Portland cement by either a SCMs or non-reactive fillers. The challenge is to maintain equal performances for the cementitious composite as well as to minimize the environmental footprint by a maximum reuse of waste-like residuals.

An overview of SCMs and fillers is provided in Table 10.1. The main industrial SCMs are blast furnace slags, fly ash (FA, from coal combustion and co-fired with biomass), silica fume and ashes from combustion of biomass renewable energy sources like wood ash, sugar cane bagasse ash (SCBA) and rice husk ash (RHA).

Fly ash (FA) is fine particles that are collected in power plants running on combustion of coal or lignite, as well as co-fired by biomass, and are discussed in detail in Chap. 5.

Table 10.1 Overview of pozzolanic binders and fillers originating from primary waste streams

Type	Waste stream	Reactivity
Sugarcane bagasse ash	By-product of the sugar/ethanol agro-industry and is the microporous matter that remains after burning the sugarcane	Pozzolanic reactivity from amorphous SiO_2 and Al_2O_3
Rice husk ash	By-product of rice production and remains after burning the hard protecting coverings of rice grains	Pozzolanic reactivity from amorphous SiO_2
Sewage sludge ash	Residual, by drying and burning the semi-solid material left from industrial wastewater, or sewage treatment processes	Pozzolanic reactivity from partially crystalline SiO_2 and Al_2O_3
Fly ash (coal and biomass origin)	Fine residues generated in coal and/or biomass (co-)combustion of electricity plants	Pozzolanic reactivity from silicate glass containing Al_2O_3, Fe_2O_3 and alkali
Granulated blast furnace slag	Obtained by quenching molten iron slag (a by-product of iron and steel-making) from a blast furnace in water or steam	Cementitious material from silicate glass containing mainly CaO, MgO, Al_2O_3 and SiO_2
Silica fume	By-product of the induction arc furnaces in the silicon metal and ferrosilicon alloy industries	Pozzolanic reactivity from amorphous SiO_2
Metakaolin	Calcination of kaolinite clay	Reactivity from Al_2O_3 and SiO_2 dehydroxalated (amorphous nine parts)
Marble and granite residues	Residual waste product of the marble and granite industrial production plants	Non-reactive, acting as a filler material

The **biomass ashes** with the highest potential for use in mass concrete are the ones obtained by combustion of residues from timber industry and forest activities, the wastes from farms and agro-business and other plants deliberately grown for energetic purposes. The ash obtained by combustion of organic fraction of municipal solid wastes is not considered here.

Woody and agricultural biomass classes are among the highest biomass potentials for energy production in the EU and are considered as a CO_2 neutral and renewable source of energy as it releases less CO_2 by burning than it absorbs while growing. Therefore, biomass is increasingly being used as a sustainable fuel. The timber manufacturing and power generation industry is increasingly shifting towards the use of biomass waste from timber and forest processing for heat and electrical energy co-production. The use of energy from these renewable sources (Directive 2009/28/EC 'Promotion of the use of energy from renewable resources') will lead to the annual production of a foreseeable amount of 15.5 million tons of biomass ash in the EU-28 by 2020 (Carrasco-Hurtado et al. 2014; Obernberger and Supancic 2009). This will double the current annual amount. Presently, most ashes in Europe are landfilled, causing financial and material losses as well as an environmental burden. A possible application for biomass ash could be the replacement of cement and/or sand in cementitious materials (Carrasco-Hurtado et al. 2014; Obernberger and Supancic 2009; van Eijk et al. 2012; de la Grée et al. 2016; Berra et al. 2015; Cheah and Ramli 2011; Barbosa et al. 2013). Biomass is a renewable resource for raw materials and energy, so there is no concern over depleting limited supplies.

In general, biomass ash composition and properties are highly variable depending on:

(1) type of base-biomass feedstock (e.g. a spectrum of woody or agricultural biomass; different co-combustion combinations with peat, coal and/or another biomass type),
(2) geographical location (collection and handling process)
(3) combustion technology (e.g. fixed bed (grate), pulverized fuel or fluidized bed boilers).

Moreover, further classification of ashes is done by type of collection from a boiler:

(1) Bottom ash collected from the bottom of a combustion chamber,
(2) Relatively coarse fly ash collected from cyclones or boilers and
(3) Fine fly ash collected from electrostatic precipitators or bag house filters.

Particle size distribution of fly ash and cement is presented in Fig. 10.1. Results by Ukrainczyk et al. (2016) show that the ash is widening the particle size distribution of cement as it comprises particles smaller than 1 μm and larger than 100 μm. This shows to be a great potential of the biomass ash and may improve the packing density of the blends. Chemical composition of wood ash typically indicates a relative high level of CaO, MgO and alkali. Alkali oxides (Na_2O + K_2O)

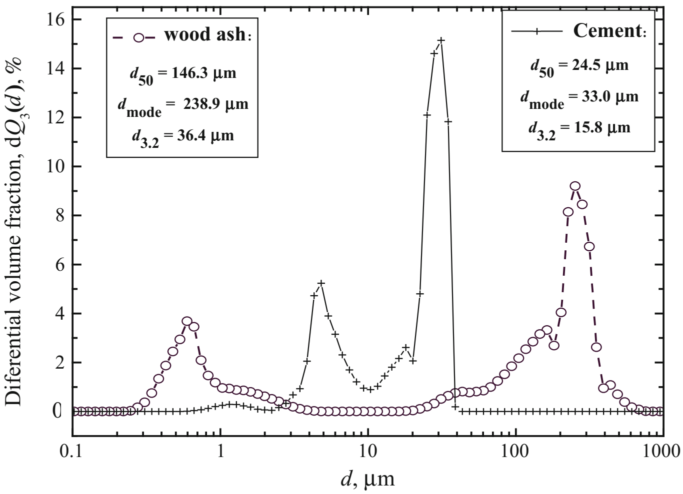

Fig. 10.1 Particle (volume) size distribution of woody ash and cement (adapted from Ukrainczyk et al. 2016)

may be considered acceptable in amounts up to 2% in cement and up to 5% in fly ash (EN 450-1). Alkali content in woody ash is around 5–10% which contributes with 0.75–1.5% for 15% replacement of the cement. This is then 1.75–2.5% of absolute (0.75–1.5% from ash + 1% from cement), which may thus become above the upper limit value for blended cements (2%).

Qualitative analysis of wood ash X-ray diffraction data (Fig. 10.2, Ukrainczyk et al. 2016) determined the main mineral phases of the sample as being lime (free CaO), MgO, larnite (2CaO SiO_2), calcium carbonate ($CaCO_3$), quartz (SiO_2), Brownmillerite (4CaO$_4$ $Al_2Fe_2O_6$) and calcium aluminosilicate (2CaO Al_2O_3 SiO_2).

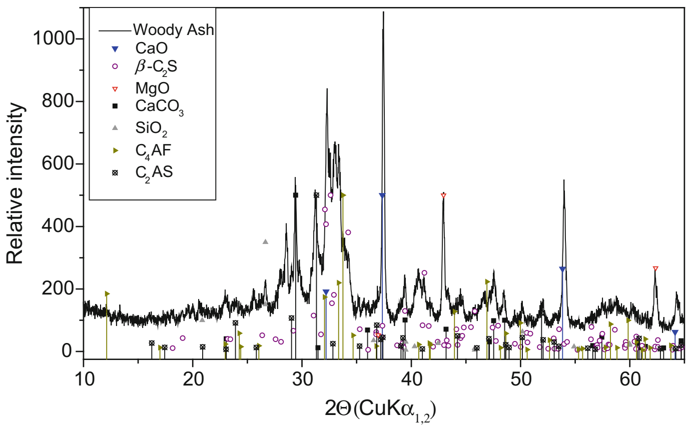

Fig. 10.2 Powder X-ray diffraction analysis of woody ash (adapted from Ukrainczyk et al. 2016)

When considering the properties of sugar cane bagasse ash (**SCBA**), which is a by-product of the sugar/ethanol agro-industry, its pozzolanic reactivity has shown great potential to act as a SCM in cement. With its base material used for ethanol production to replace petrol for cars (Cordeiro 2006; Fairbairn et al. 2010a, b), the burned remainings of sugarcane plant turned out to be suitable to act as a pozzolanic material that can partially replace cement.

RHA is obtained by combustion of an agricultural by-product material, which on burning, decompose cellulose and lignin to leave silica ash. The sensitivity of burning conditions is the primary reason that prevents the widespread use of this material as pozzolan (Hewlett 1998; Real et al. 1996). The X-ray data and chemical analyses of RHA produced under different burning conditions given by Hwang and Wu (1989) showed that the higher the burning temperature, the greater the percentage of silica in the ash. K, S, Ca, Mg as well as several other components were found to be volatile. Reactivity of RHA is attributed to its high content of amorphous silica and to its very large surface area governed by the porous structure of the particles (Cook 1984; Mehta 1992). Rice is the principal production in many developing countries where the cement needs are drastically increasing, it is probably the most promising vegetable ash. Note that 20 Mt annual generation of RHA is similar to GBFS and can absolutely not be compared to the 4000 Mt of cement that will be needed in 2050.

Non-renewable SCMs, i.e. with natural origin, are pyroclastic rocks rich in siliceous or siliceous and aluminous volcanic glass. Common silicate minerals are feldspar, mica, hornblende, pyroxene and quartz or olivine depending on the volcanic rock's chemical composition, but most of these minerals are easily alterable to form clays, zeolites, calcite and various amphiboles. Good natural pozzolan has in general low quantities of clays and zeolites (Habert et al. 2008). Natural SCMs may need a pre-treatment to enhance their pozzolanic activity, namely various mechano-chemical treatments (Habert et al. 2008) of volcanic rocks or calcined clays (Habert et al. 2009).

Huge amounts of mud and other residues are yearly being produced by various countries as a waste product by the **marble and granite** industry, causing serious threats to the environment, polluting soil and water, and when dry, turning into a fine dust that is harmful to the population. Most of the marble and granite residues are landfilled, and alternative solutions are being explored in many countries with the aim to turn this waste into a sustainable material. Bacarji et al. (2013) investigated the applicability of marble and granite residues as a sustainable alternative for cement replacement in production of concrete. Chemical analysis and particle size distribution showed that marble and granite residues (from three different sources) exhibit non-reactive properties but act as a filler. Replacement level of 5% (from only one source) showed only minor impact on the mechanical properties and rheology and could be considered as a promising sustainable alternative for cement.

10.2.2 Water

Water is a key ingredient needed not only to disperse and gradually dissolve cement particles but also is a reactant which is consumed in cement hydration reactions. The shortage of drinkable water resources forces concrete industry to find alternative water sources. The two main strategies for this are (1) recycling of wastewater produced in several human activities and (2) utilizing sources of water, derived by natural processes, which are not suitable for other uses.

Quality of water used in concrete must comply with the current norms, such as EN 1008:2002 (CEN 2002). Most common limitations deal with the content of the following species:

- Chlorides, maximum concentration is 1000 mg/l for concrete with metal reinforcement;
- Sulphates, maximum concentration of SO_4^{2-} ions is 2000 mg/l;
- Alkalis, maximum concentration of equivalent Na_2O is 1500 mg/l;
- Sugar (inhibits cement hydration process);
- Harmful pollutants, e.g. phosphates, nitrates, zinc and heavy metals.

The same norm makes the following classification of water:

- Potable water is suitable for use in concrete and needs no testing;
- Water recovered from processes in the concrete industry is usually suitable for use in concrete, but shall be tested;
- Water from underground sources may be suitable for use in concrete (shall be tested);
- Natural surface water and industrial wastewater may be suitable for use in concrete (shall be tested);
- Sea water or brackish water may be used for concrete without metal reinforcement but is in general not suitable for the production of reinforced or prestressed concrete: the permitted total chloride content in the concrete is the determining factor;
- Sewage water is not suitable for use in concrete.

10.2.3 Aggregates

Usage of natural aggregates is discussed in Chap. 5, and here the focus is put on its recycling. Reusing aggregates from construction–demolition waste (Fig. 10.3) asks for the development of an innovative mix design that deals with grading, with the properties in terms of hydration, strength and durability, and with the replacement procedure, affecting the workability of the mixtures. The question here is how to develop a mix design and an associated mix procedure for concretes with a partial replacement of natural aggregates by recycled aggregates. Recycled aggregates

Fig. 10.3 (Up) Demolition of hospital section, Ilha do Fundão, Rio de Janeiro, Brazil; (down left to right) homogenization process, grinding process with a crusher and autogenous cleaning

(RA) can only be considered as a serious sustainable alternative for natural aggregates (NA) if it leads to a concrete with predictable mechanical and durability properties, similar to those of ordinary concrete mixtures with natural aggregates. A controllable and predictable performance of RA, therefore, should be considered as a major issue that brings the use of recycled aggregates in the construction industry a step closer. Adding RA to the concrete matrix may affect the bearing capacity of the aggregate grain structure, and it may affect the morphological nature of the cementitious microstructure as well. RA, in general, consists of construction–demolition waste, i.e. of crushed concrete, which implicitly means that it contains both natural aggregate fractions, but also remainings of the former cement paste microstructure. This can be either fully hydrated C–S–H gel or anhydrous cement grains. These cement paste remainings are also partly responsible for the increased adsorption capacity of RA, which can be attributed to the relatively higher porosity of RA and the existence of surface and micro-cracks that have the ability to accumulate water. Saturation of these aggregates with water would increase their heat (absorption) capacity, which may be advantageously used in controlling the temperature gradients of mass concrete.

10.2.4 Fiber Reinforcement

Conventional design of steel reinforcement is detailed in Chap. 5, and here the focus is put on sustainable reinforcement alternatives with fibers. The micro- and macro-fracturing processes can be favourably modified by adding short, randomly distributed fibers of various suitable materials such as steel, carbon, cellulose, polypropylene, polyester, glass and nylon. Fibers not only suppress the formation of cracks due to early age self-heating problems, and loading but also abate their propagation and growth (Banthia et al. 2014).

An overview on properties of different types of fiber materials used as reinforcement is presented in Table 10.2. Although **asbestos** is an almost ideal fiber, it

Table 10.2 Physical and mechanical properties of synthetic and natural fibers (adapted from Sierra Beltran 2011 and Odler 2000)

Fibers	Properties					
	Length (l, mm)	Diameter (d, μm)	Aspect ratio (l/d)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation at break (%)
PE	12.7	38	335	2700	120	3–80
PVA	8–12	39	255	1620	42.8	6
PP	6	12	500	770–880	11.2–13.2	17.6–25.7
Asbestos	1–5	0.02–20		700–3000	170–200	2–3
Flax	10–40	11–33	1060	345–1035	28–45	1.3–3.3
Hemp	8.2–28	15–50	560	310–1000	30–60	1–4
Jute	2–5	16–200	75	250–750	25–30	1.5–2
Ramie	60–250	40–80	2310	400–1050	60	2–4
Hibiscus, Kenaf	2–6	200	10	930	53	1.6
Sugarcane	0.8–2.8	6.6–26	115	170–290	15–19	
Bamboo	2.8	10–40	280	350–500	7.3	11.3
Hardwood	0.3–2.5	10–60	35	200–1300	5–45	
Softwood	1.0–9.0	15–60	110	200–1500	40	15–40
Cotton	10–65	12–20	2040	300–600	4.5–12.6	7–9
Coir	0.9–1.2	16.2–19.5	60	130–175	4–6	10–25
Sisal	1–5	10–200	65	250–640	9–26	2–2.5
Banana	2.7–5.5	18–30	165	530–750	20–51	5–2
Cement paste				3–7		
Steel				3000–4000	200	
E-glass		10–20		1100–3900	70–80	
AR-Glass		10–20		3700	75	
Graphite PAN-based		7–8		3000–4000	250–400	
Graphite pitch-based		14–18		600–2000	30–200	
PAN		10–50		800		

is no more used due to health hazard. **Steel fibers** exhibit good composite properties, but only with binders that protect the fibers from corrosion (pore solution pH > 11). **Glass fibers** seem to be the main candidate to replace asbestos. Alkali resistant fibers with a high ZrO_2 content have been developed (AR-glass) as ordinary E-glass undergoes alkali corrosion and the tensile strengths decrease over time (Bentur 1989; Serbin et al. 1992). To improve poor bond of graphite fibers to cement matrix, and thus increase the composite tensile strength, micro-silica, methylcellulose, a SBR latex or a combination of these may be added (Fu et al. 1996), or even more effective is fiber pre-treatment by ozone (Fu et al. 1998).

Synthetic fibers like PE, PP, polyacrylamide (except polyester) fibers, generally have a sufficiently high resistance to the high pH values of the cement pore solution. However, they exhibit a poor fiber–paste bond, which does not improve distinctly with added micro-silica (Dyczek and Petri 1992). The fracture process is usually characterized by pull-out of the fibers. The bond is improved if fibrillated instead of straight fibers are used (such as PP) (Rice et al. 1988). Polyacrylonitrile (PAN) fibers have a significantly higher Young's modulus than conventional plastic fibers, providing a significant increase of the maximum strength (Odler 2000).

Cellulosic (e.g. wood and non-wood vegetable) fibers are being studied as reinforcement for cement-based materials because they are non-hazardous, renewable, low-cost alternative to synthetic fibers (Ardanuy et al. 2015; Sierra Beltran 2011). The development of new environmentally friendly materials to replace steel reinforcement for concrete structure applications is a good step to achieve sustainable concrete and structures. In the last few years, because of the increasing environmental concern, the utilization of fibers from natural resources (i.e. vegetable fibers) to replace synthetic carbon/glass fibers for fiber-reinforced polymer (FRP) composite application has gained popularity. Cellulose fibers exhibit a set of important advantages (Ardanuy et al. 2015), such as wide availability at relatively low cost, bio-renewability, ability to be recycled, biodegradability, non-hazardous nature, zero carbon footprint and interesting physical and mechanical properties, e.g. low density and well-balanced stiffness, toughness and strength. A combination of interesting mechanical and physical properties and their environmental benefits has been the main driver for their use as alternatives for conventional reinforcements. Compared to synthetic fibers, natural fibers are more easily available worldwide and they are friendlier to the environment since less energy is needed to produce them. They are also a renewable resource. Natural fibers, e.g. flax, hemp, jute, coir and sisal, are cost-effective, have good specific strength and specific stiffness and are readily available (Yan and Chouw 2013). However, the properties of natural fibers are not as constant as those of synthetic fibers and natural fibers have a lower tensile strength (Table 10.2). The main chemical components that form the physical fiber structure of wood cells are cellulose, hemicellulose and lignin. Wood fibers have high tensile strength and relatively high modulus of elasticity compared to other natural fibers, as can be seen in Table 10.2. In many occasions, published literature does not clearly specify if a natural fiber is a single cell fiber or a bundle of cell fibers. Therefore, a wide spectrum of properties for the same type of fiber can be found. A limited number of wood species are suitable as a reinforcing material, due to the negative interaction of the water-soluble oligosaccharides from the wood with the cement hydration process (Sierra Beltran 2011).

According to their origin and composition, cellulosic fibers are classified as non-wood and wood (lignocellulosic) fibers (Ardanuy et al. 2015). The main chemical components that form the physical fiber structure of wood cells are cellulose, hemicellulose and lignin. The two main groups of wood fibers are

(1) softwood fibers (obtained from pines, firs, etc.) and
(2) hardwood fibers (from the birch tree, eucalyptus, beech, etc.).

Non-wood fibers are grouped into four main groups depending on the part of the plant used to extract the fibers:

(1) bast fibers (hemp, jute, kenaf, flax, ramie and others),
(2) leaf fibers (sisal, henequen, pineapple, oil palm, banana or others),
(3) stalk fibers (straws—as rice, wheat and barley; reeds—as bamboo and grass—as esparto and elephant grass) and
(4) seed fibers (cotton, coir and others).

Stem or bast fibers come from the stalks of plants, and these fibers are usually obtained following a retting process that involves bacteria and moisture. These types of natural fibers are commonly not used as single fibers but in the form of bundles or strands, usually long ones.

Forms of the reinforcements based on cellulose fibers (Ardanuy et al. 2015) are

(1) strands (long fibers with lengths between around 20 and 100 cm),
(2) staple fibers (short length fibers which can be spun into yarns) or
(3) pulp (very short fibers of lengths around 1–10 mm which should be dispersed into water to separate them).

Recently, Ardanuy et al. (2015) presented a review on the research done in the last few years in the field of cement-based composites reinforced with cellulose fibers, focusing on their composition, preparation methods, mechanical properties and strategies to improve fiber–matrix bonding and composite durability. They concluded the following. Softwood and sisal pulps and sisal strands were the most commonly studied fibers for preparing fiber cementitious composites (FCCs). Adequate dispersion of the fibers in the matrix is crucial for obtaining FCC with good mechanical performance. This can be achieved by various production methods like various improvements of the traditional Hatscheck method (Ardanuy et al. 2015) or newer methods such as extrusion of pulp cement mixtures and laminates with long fibers or sheet-like structures. Different treatments used to improve the durability of cellulose cement composites include (1) pozzolanic additions, either directly introduced into the mass of cement or applied to the fibers and (2) refining the pulps, with hornification treatments or chemical surface treatments, like silanes.

10.3 Mix Design and Material Properties

The design of a suitable mass concrete composition is detailed in Chap. 5 and here extended to address it from sustainability (durability) point of view. Various chemical and physical processes involved in mass concrete placement affect not only the fresh concrete workability, i.e. rheology, hydration kinetics and mechanical properties but also development of porosity and thus the durability of hardened concrete in service.

At present, there are two principal standards to define the eligibility of pozzolans including ASTM C618 (ASTM, 2012) and EN 196 (BS-EN, 2013). Some standards prohibit use of biomass ash in concrete. Technical regulations and standards for coal and ashes obtained by co-firing of coal with up to 50% biomass share are used as a reference framework for ash producers and building industry customers. An example is the NEN 450-1: Fly ash in Concrete (2012) (Saraber et al. 2009), which gives a set of requirements to assess the quality of coal fly ash (co-firing percentages up to 50 mass% of clean wood) for use in concrete. These standards, however, do not apply to pure (non-coal) biomass ashes. On the one hand, this results in rising costs for biomass ash waste managers that force power plant owners to search for new opportunities how to recycle these ashes. On the other hand, blending cement with biomass ash could anticipate further improvements in concrete material performance while resulting in a lower environmental impact of the cement production as well as the biomass combustion. Vassilev and Vassileva (2007) proposed an unbiased method to define the eligibility of pozzolans which relies on the amorphous (glassy) content in ash to classify as high pozzolanic activity (PA, 82–100% of glass), medium PA (65–82%) and low PA (30–65%).

The use of high-volume SCMs (e.g. with a FA content of at least 50%) is general not directly allowed for more aggressive exposure environments, but only after its equivalent performance is proved in comparison to the eligible reference concrete (van den Heede and de Belie 2012).

Materials selections and the consequence of it on the properties that affect the mix design such as rheological, heat development, mechanical and durability properties are summarized in Table 10.3 and discussed further in this section. Here the focus is more on sustainability aspects, i.e. durability, while the mechanical properties e.g. elastic modulus are detailed in Chap. 5.

The rate and total amount of evolved heat in concrete generally decrease with decreasing C_3S and C_3A contents of cement. On the other hand, the pozzolanic reaction is slower than C_3S hydration and it produces less total potential heat than does cement hydration (Nili and Salehi 2010). Concrete containing SCMs generally exhibits low rate of hydration heat development and thus a small increase in material temperature due to self-heating. Schindler and Folliard (2003) showed that the use of FA and GGBFS retards the hydration process and reduces the amount of heat generated during the acceleration stage. Wang and Lee (2010) demonstrated

Table 10.3 General trend effects of SCMs and recycled aggregates (100% RAC) on concrete properties (adapted from Paris et al. 2016)

Concrete property		GBFS		FA class F		SF	
		Replacement (%)	Effect	Replacement (%)	Effect	Replacement (%)	Effect
Early age	Workability	30–50	Increased	10–40	Increased	>5	Decreased
	Bleeding and segregation	40–70	Increased	10–40	Increased	–	–
	Setting time	10–70	Increased		Increased	5–20	Increased
	Hydration enthalpy		Decreased		Decreased	10	Decreased
Mechanical	Compressive strength	30–50	28d Increased	10–50 (and sand replacement)	Increased	5–20	28d Increased
	Tensile strength	30	Increased	10–50	Increased	5–30	Increased
	Flexural strength	30–60	Increased	40–75	Increased	5–25	Increased
Durability	Permeability	33–50	Decreased	10–100	Increased	>5	Decreased
	SO_4/Cl^- resistance	10–50	Increased	<50	Increased	5–15	Increased
	Corrosion resistance	40	Increased	10–30	Increased	<20	Increased
	ASR resistance	30–60	Increased	20–40	Increased	4–20	Increased
	Freeze/Thaw resistance	10–60	Decreased	40–60	Increased	10–20	Increased

Concrete property		RHA		SCBA		RAC	
		Replacement (%)	Effect	Replacement (%)	Effect	Replacement (%)	Effect
Early age	Workability	10–40	Decreased	10–30	Decreased	100%	Decreased
	Bleeding and segregation		–	–	–		
	Initial set Final set	5–30 5–35	Increased Decreased	–	–		
	Hydration enthalpy			10–30	Decreased		
Mechanical	Compressive strength	5–30	Increased	10–30	Increased		Decreased 5–20%
	Tensile strength	5–30	Increased	5–15	Increased		Decreased 0–30%
	Flexural strength	5–20	Increased	–	–		
Durability	Permeability	7.5–40	Decreased	10–30	Decreased		Increased 40–50%
	SO_4/Cl^- resistance	7.5–40	Increased	5–30	Increased		Increased-Cl^- 50–70%
	Corrosion resistance	5–30	Increased	20	Increased		
	ASR resistance	4–15	Increased	–	–		
	Freeze/Thaw resistance	10	Increased	–	–		Decreased 0–10%

that FA is more effective in reducing the heat of hydration in concrete than GGBFS. Atis (2002) showed that 50% FA reduces the peak temperature of concrete by 23% as compared with OPC, indicating that the moderate levels (10–30%) of FA currently used in cement production may not provide sufficient reduction in the heat evolution of concrete. The use of large amounts of SCMs also significantly contributes to the sustainability of mass concrete (Yang et al. 2014, 2016) in terms of low CO_2 emissions, recycling of by-products and conservation of natural resources as well as the enhancement of workability and durability of concrete (Zhao et al. 2015).

An accurate model to simulate the heating process is essential for thermal stress analysis in mass concrete (Chap. 2). A reliable heat evolution kinetic model is still lacking in high-volume SCM concrete (Yang et al. 2016).

10.3.1 Ground Granulated Blast Furnace Slag (GGBFS)

The use of GGBFS as a substitute for cement clinker can improve technical properties, including workability, strength and durability (Shi and Qian 2000; Song and Saraswathy 2006).

GGBFS used in concrete can effectively reduce the pore sizes and cumulative pore volume (Basheer et al. 2002). Increased GGBFS replacement shows denser structure which prevents concrete from capillary water absorption. Densification of microstructure (lower porosity) comes from higher 'pozzolanic' C–S–H content related to higher GGBFS replacement which represents a higher durability of concrete. Luo et al. (2003) studied the pore structure of three types of concretes (mix ratios 1:1.7:3.29, w/b of 0.34) made with plain OPC and 70% GGBFS and 65% GGBFS/5% gypsum replacements. They demonstrated a great improvement in pore structure for 70% slag replacement, especially after 60 days. However, sulphates did not improve the pore structure of GGBFS. Gao et al. (2005) investigated the effect of slag on interface zone between aggregate–cement paste using XRD, SEM and micro-hardness measurements. They concluded that (a) the pozzolanic reaction rate was in direct proportion to the specific surface area of GGBFS, (b) GGBFS significantly decreased the content and the mean size of $Ca(OH)_2$ crystals in the aggregate–mortar ITZ, which made the microstructure of ITZ more dense, and (c) the ITZ weak zone almost vanished in concrete with 40% slag of 425 m^2/kg specific surface area, and completely vanished in concrete with 20% slag with 600 m^2/kg surface area, strengthening the cementitious matrix. The improvement in strength of concrete containing 20–60% GGBFS occurs only after 28 days of curing, where similar or higher long-term strength was obtained as compared with that of normal PC concrete (Aldea et al. 2000; Miura and Iwaki 2000). Babu and Kumar (2000) reported that 28-day compressive strength of concretes containing GGBFS up to 30% replacement was all slightly above that of normal concretes, and all other replacements (up to 80%) were below. Also, they observed that the variations due to the different percentages of slag replacement were smaller than the corresponding variations in the case of fly ash.

Cheng et al. (2005) also reported the beneficial influence of GGBFS on the rapid chloride permeability (RCPT) and water permeability of concrete. Khatib and Hibbert (2005) investigated the influence of incorporating GGBFS and metakaolin (MK) on the compressive strength of concrete.

Dhir et al. (1996) investigated the effect of GGBFS on chloride-binding capacity. With the increase in GGBFS percentage, the chloride-binding capacity increased for all chloride concentrations. For a GGBFS replacement level of 66.7%, the chloride-binding capacity was around five times that of the PC control for the case of 5 mol/L exposure chloride concentrations. At 28 days, despite the lower compressive strengths of the GGBFS concrete, the intrinsic permeability was similar. But, at 90 days when the strengths equalized, the intrinsic permeability of the GGBFS concrete was much better than PC reference. Moreover, with the increase in GGBFS replacement level, the coefficient of chloride diffusion steeply decreased. Luo et al. (2003) found that GGBFS increased the chloride-binding capability greatly, although sulphates and alkalinity also decreased it due to competing binding.

Carbonation rate of low fineness GGBFS (4500 cm^2/g) concrete increased with an increase in OPC replacement level (Sulapha et al. 2003). The reduction in portlandite content seemed to have more influence over pore morphology refinement and hence led to faster rates of carbonation. On the other hand, GGBFS of higher fineness (6.000 and 8.000 cm^2/g) reduced the carbonation rates compared to plain OPC concrete. The pore morphology modification, being more dominant than the change in portlandite content, appeared to control the carbonation rate. Ternary blended concrete containing 35% OPC, 55% GGBFS and 10% SF showed a higher carbonation rate than the plain OPC mixture and 10% SF concrete, but lower than 65% GGBFS concrete.

GGBFS at a level of 50% OPC replacement is effective in controlling ASR expansion (Hester et al. 2005). This is because (1) GGBFS reduces the alkalinity of the concrete and thus the alkali–silica ratio; (2) GGBFS reduces mobility (diffusivity) of alkalis in the concrete; and (3) GGBFS reduces free lime in the concrete which is regarded as an important factor for alkali–silica reaction. Yeau and Kim (2005) showed that the corroded areas of steel embedded in control concrete mixtures were about two times and three times larger than those of steel involved in 40% GGBFS concrete mixture and 55% GGBFS concrete mixture, respectively.

10.3.2 Coal Fly Ash (FA)

FA addition improved the corrosion resistance properties even up to 50% replacement level. The reduction in the water content and the good dispersing and the filler effect of the fly ash may contribute to the relatively good strength and permeability development of the fly ash concrete (Chindaprasirt et al. 2007).

With the use of finer fly ash, by sieve separation, the water content can be further reduced and the strength and durability of concrete enhanced. Shafiq and Cabrera (2004) showed that FA addition lowers porosity, oxygen gas and water permeability and investigated the influence of curing conditions on the porosity. For PC reference concrete (0%), 40% and 50% FA cement replaced concrete total porosity of dry-cured samples was 5–10%, 9–20% and 23–40% higher, respectively, than that of their corresponding wet cured samples. Oxygen and water permeability were 2–19 times higher for dry cured reference concrete, whereas 16–210 times greater for FA concretes. Inadequate (dry) curing of a 20 and 40% fly ash (cement replacement) concrete resulted in an increase of 20 and 60% in concrete sorptivity, respectively (Gopalan 1996).

Chloride diffusion value for paste with fly ash Portland cement was 14.7×10^{-9} cm^2/s compared to 44.7×10^{-9} cm^2/s for normal Portland cement paste (Short and Page 1982). Concrete mixtures were made with 15, 30 and 50% fly ash as cement replacements, exhibited reduction in the permeability values by 50, 60 and 86%, respectively (Thomas and Matthews 1992). Up to about seven days, the extent of concrete carbonation was higher for fly ash than the control concrete. However, after 90 days curing, the trend reversed in that the fly ash concrete exhibited less carbonation. The addition of fly ash (20–50%) seemed to improve the sulphate resistance of concretes when they are exposed to sulphates at 20 °C, while no effect at 8 °C was related to the retardation of pozzolanic reaction (Mulenga et al. 2003). Perry et al. (1987) found reduction in ASR expansion after one year in 5 to 81% at 20% replacement level, 34–89% at 30% replacement level and 47–92% at 40% replacement level. The alkalis present in fly ashes were less susceptible for reaction with aggregate, unlike the free and water-soluble alkalis of Portland cement. The chloride penetration was comparatively low and decreased with the increase of fly ash replacement (Chalee et al. 2007)

10.3.3 Woody Ash

High dosages of high calcium wood ash (>20%) may result in expansions which rapidly increases with further ash dosage (Ukrainczyk et al. 2016). This expansion is due to a delayed hydration of free and dead (hard) burned CaO and MgO. The potential of woody ash as an expansive additive to mitigate autogenous and thermal shrinkage problems of mass concretes represents a new research line worth investigating.

Regarding the pozzolanic reaction, Ukrainczyk et al. (2016) showed (Fig. 10.4) that plain ash hydration (no blending with cement) produces a maximal $Ca(OH)_2$ quantity at three days and decreases with further hydration demonstrating the pozzolanic activity of the ash. With increasing ash content, more $Ca(OH)_2$ is produced initially (at early ages) than for plain cement due to hydraulic properties

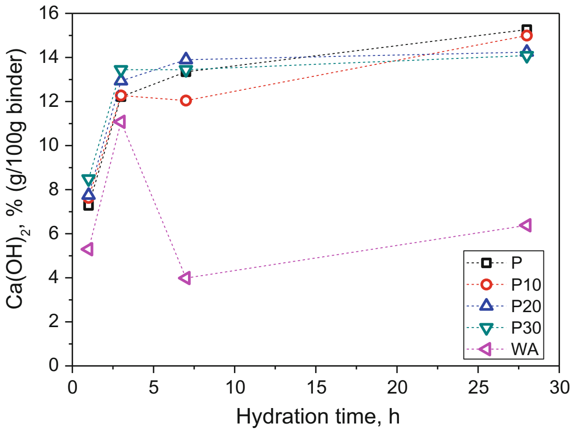

Fig. 10.4 Evolution of Ca $(OH)_2$ during hydration obtained from TG analysis: only 27 mass% of the woody ash (WA, with particles below 80 μm) was considered as a binder (adapted from Ukrainczyk et al. 2016)

of the ash with a relatively high content of reactive CaO, but at 28 days, inversely, there is less $Ca(OH)_2$ due to activated pozzolanic reaction. With increase in the cement replacement level, the hydration kinetics, workability, compressive and flexural strength reduced. Ukrainczyk et al. (2016) also found an optimum dosage of 15% woody ash, which replaces 5% of cement and 3.33% of the sand, still producing a structural grade mortar with acceptable workability and mechanical properties. Thus, potential reuse of woody ash could reduce landfilling and at the same time improve the sustainability perspective of cement production, reducing its energy needs, cutting back in CO_2 emissions and preserving natural resources (i.e. limestone) with no concern for depletion of biomass ash supplies.

Chowdhury et al. (2015) gave a review on the work done on the reuse of wood ash in concrete from 1991 to 2012. Work on ashes obtained from the combustion of forest waste wood and agricultural waste escalated (de la Grée et al. 2016; Cheah and Ramli 2011; Berra et al. 2015; Rajamma et al. 2012, 2015). de la Grée et al. (2016) indicated that a more contaminated biomass fly ash is obtained by combustion of treated waste wood rather than when forestry or agricultural waste is used as fuel. They investigated various treatment methods, at laboratory and pilot scale, for lowering the level of contaminants.

Review of the research results indicates that wood waste ash has potential for effective utilization as a cement replacement for production of blended cements (Cheah and Ramli 2011; Chowdhury et al. 2015). The inclusion of wood ash as partial cement replacement in blended cements has the following effects:

- longer setting times, but still within the standard limits.
- tend to have more soundness, i.e. volume changes after setting (due to excessive amounts of free lime or magnesia). However, the maximal soundness observed at 30% replacement level was still much lower than the maximum allowable soundness limit.
- a higher water requirement for a given level of mix workability of binder pastes.

- beneficial effects on microstructure.
- reduction in bulk density of the hardened binder.

Wood waste ash has high potential for effective utilization as a cement replacement for production of structural grade concretes and mortars of acceptable strength and durability performances (Cheah and Ramli 2011; Chowdhury et al. 2015). The inclusion of wood ash as partial cement replacement has the following effects on concrete properties:

- a higher water requirement for a given level of mix workability of mortars and concretes. However, at the same time there is a significant contribution towards the reduction of drying shrinkage induced micro-cracking of concrete, which could be attributed to a high porosity of ash particles that result in the beneficial internal curing effects (Naik et al. 2002).
- at replacement levels up to 10% by total binder weight can produce structural grade concrete or mortar with acceptable strength properties.
- generally increased magnitudes of concrete water absorption properties, but still far below maximum values allowed for construction material.
- no adverse effects on the resistance of concrete against deterioration by freeze–thaw action (Naik et al. 2002). However, there is a higher demand of air-entraining agents in order to achieve a specified volume of entrained air within the concrete mix.
- no adverse effects on the resistance of concrete against chloride penetration (at replacement levels up to 25% by total binder weight). Blends of 20% wood ash and 80% coal fly ash significantly enhances the resistance to chloride penetration (at cement replacement level of 25%).
- improved durability when exposed to the corrosive actions of monobasic acid solutions, but adverse effects under dibasic acid solutions.
- Mitigation of delirious expansion reaction in cement mortars due to ASR and sulphate attack.

High calcium wood ash (HCWA) can be effectively used in combination with other pozzolanic (SCM) binders to enhance the mechanical and durability performance of concrete (Cheah and Ramli 2014).

10.3.4 Sugarcane Bagasse Ash (SCBA)

At the UFRJ, extended research has been done to examine the properties of this class of SCMs in terms of grinding, burning, reactivity, morphology, chemistry and mechanical properties (Fig. 10.5) and also to evaluate its applicability in concrete (Cordeiro 2006; Cordeiro et al. 2008, 2009a; Fairbairn et al. 2010a, b). The morphological structure of such ashes is investigated directly after burning and after 4 h of grinding. The chemical results showed a SiO_2 content of about 78% (24% of

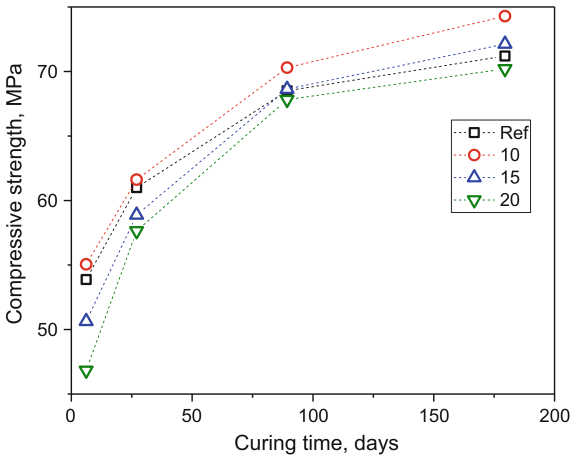

Fig. 10.5 Time evolution of compressive strength for concrete with cement replaced by SCBA (adapted from Cordeiro et al. 2008)

amorphous SiO_2), a density of 2530 kg/m^3 and a specific surface (Blaine) of 196 m^2/kg (Cordeiro et al. 2008). These properties show the potential of sugarcane bagasse ash to act as a sustainable replacement material for cement.

The pozzolanic activity tested by strength index is defined as the ratio between the compressive strengths of mortars with mineral admixture and a reference mortar. On the other hand, the pozzolanic activity Chapelle test measures consumption of CaO in diluted lime-pozzolanic dispersion. Cordeiro et al. (2008) systematically investigated the correlation among the grinding time, median particle size, Blaine fineness, by pozzolanic activity strengthen activity test and Ca^{2+} consumption capacity of SCBA (Fig. 10.6). A finer particle size (from 76.3 to 1.7 μm) consistently resulted in better pozzolanic activity (49–103%). The improvement of pozzolanic activity enhanced the strength of mortars via promoting CH consumption in the pozzolanic reaction (36–298 mg CaO/g).

Compressive strength tests (Fig. 10.5) have confirmed this, showing a high-performance concrete with a w/c ratio of 0.35 and a SCBA replacing ratio of 10, 15 and 20% (Cordeiro et al. 2009a). The results show that the replacement of cement by different percentages of SCBA leads to a similar strength capacity as the reference mixture. The addition of the SCBA also resulted in improvements in rheology of concrete in the fresh state (Cordeiro et al. 2009b). In relation to durability, the results of chloride-ion penetrability based on ASTM C1202-05 indicated that SCBA decreases by about 30% of passed charges for both conventional and high-performance concretes. It was also proven, by a case study for the south-eastern region of Brazil, that SCBA could be used at industrial scale, significantly reducing CO_2 emissions (Fairbairn et al. 2010a, b). The material can, therefore, be considered as a valuable substitute for the development of green and ecological mass concretes.

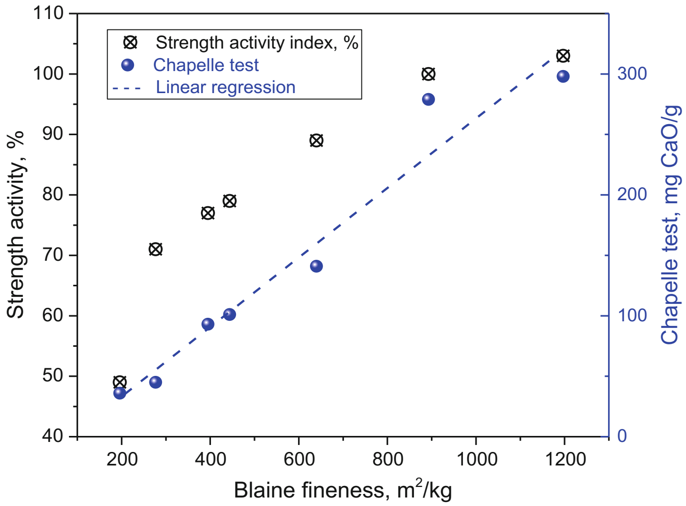

Fig. 10.6 Pozzolanic activity as quantified by Chapelle activity of consumed CaO in diluted lime-SCBA dispersion (right axis) and mortar strength index tests (left axis) as a function of Blaine fineness of SCBA (adapted from Cordeiro et al. 2008)

10.3.5 Rice Husk Ash (RHA)

Increase in RHA content in the paste results in higher water requirement to maintain the same normal consistency (Singh et al. 2002; Jaturapitakkul and Roongreung 2003). Zhang and Malhotra (1996) indicated that RHA concrete had a drying shrinkage of 638×10^{-6} after 448 days, which was similar to the strains for the control and silica fume concretes. Slump decreased with the increase in RHA content for same level of superplasticizer (Bui et al. 2005).

Bui et al. (2005) investigated the compressive strength of concrete mixtures made with two types of PC (Blain 2700 and 3759 cm^2/g) using w/c of 0.30, 0.32 and 0.34 with a cement replacement ratio of 10, 15 and 20%. They demonstrated that RHA can be used as a highly reactive pozzolanic material to improve the microstructure of the interfacial transition zone (ITZ) between the cement paste and the aggregate in high-performance concrete. Relative strength increase was higher for coarser cement (i.e. the gap-graded binder) due to improved particle packing structure accompanied by a decrease in porosity and particularly in particle spacing. Saraswathy and Song (2007) showed that cement replacements with 0, 5, 10, 15, 20, 25 and 30% RHA improved rapid chloride permeability (charge passed) through concretes: 1161, 1108, 653, 309, 265, 213 and 273 coulombs, respectively. Non-ground RHA did not significantly change the rapid chloride penetrability of concrete, whereas finely ground RHA, depending on the type and addition level, improved the RCM results (Nehdi et al. 2003) comparably to those achieved by SF. The results of air permeability by de Sensale (2006) revealed the significance of the filler and pozzolanic effect for the concretes with RHA. On the one hand, for the

RHA obtained by controlled burning (98.5% reactive SiO_2) the results are consistent with the compressive strength development at 28 days. On the other hand, in the concretes with RHA with 39.55% reactive SiO_2, lower air permeability was observed, which was attributed to the higher filler effect than the pozzolanic effect. Inclusion of RHA (0–15%) was very effective in controlling the ASR expansion of mortar (with quartzite and basalt reactive aggregates) at the age of 16 and 30 days.

Chindaprasirt et al. (2007) showed that sulphate resistance of mortars made with 20 and 40% PC (2900 cm^2/g) replacement levels by FA (6000 cm^2/g) and RHA (14,000 cm^2/g) is significantly improved compared to reference.

10.3.6 Synergy Effect of Multi-component Binder Blends

Yang et al. (2016) investigated the high volume (40, 80 and 90%, Table 10.4) use of varying combinations of fly ash, GGBFS and PC in order to control the hydration heat development in mass concrete and enhance its sustainability. The cumulatively evolved heat obtained by adiabatic hydration tests of the concrete was 370 (OPC), 280 (T4), 202 (T8) and 145 J/g (T9) (expressed per gram of binder), which were close to the values obtained by isothermal calorimeter: 350, 251, 198, 185 J/g, respectively. The theoretically calculated values were 507, 425, 369, 364 J/g binder. Isothermal heating rates show (Fig. 10.7 left) a significant decrease. The maximal heat rate (W/g) values decreased by 40% 69% and 67% for the T4, T8 and T9 paste, respectively, as compared with that of the OPC paste. These reductions were only minimally affected by temperature (13–33 °C). The heating rate curves (Fig. 10.7 left) also indicate to a relative increase in the second peak occurring due to the sequential reaction schemes of the aluminate phases (C_3A → etringite → monosulphate). This is probably due to a relative increase in aluminate content of the blended system. Typical Al_2O_3 mass fractions for fly ash, slag and OPC are 23, 12 and 7%. The compressive strength development of very high-volume SCM concrete (Fig. 10.7 right) could be reasonably correlated to the degree of hydration function determined from the calorimetry hydration tests (both isothermal and adiabatic).

Fairbairn et al. (2010a, b) performed experimental and numerical analyses based on a thermo-chemo-mechanical model. The model considered the coupling of hydration reactions of blended cements, exothermicity, thermo-activation, chemo-plasticity, with the evolution of thermal and mechanical properties, including also creep and relaxation. The authors emphasized the importance of high-performance finite element numerical models to simulate and predict such thermo-chemo-mechanical behaviour in real case scenarios. Sugar cane bagasse ash and rice husk ash are considered as potential mineral additions for constructing dams. The SCBA/RHA blended mixture had 60% of cement, 20% SCBA and 20% RHA while the reference concrete contains 100% of cement as cementitious materials. It was shown that besides the reduction of CO_2 emissions, the multi-component blended material had a thermo-chemo-mechanical behaviour more suitable for mass concrete than the reference material, yielding lower thermal and stress fields.

Table 10.4 Details of concrete mixture proportions and results for LCA studies (Yang et al. 2016; Crossin 2015) with the functional unit of 1 m^3 30 MPa concrete for 50 years (detailed strength development for concrete II-series is plotted in Fig. 10.7 left)

Concrete name	Source	Cement (kg/m^3)	FA (kg/m^3)	GGBFS (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel aggregate	Slump (mm)	Global warming
II	Yang et al. (2016)	350	0	0	175	873	873	185	100%
II-T4		240	100	60	165	814	886	210	65%
II-T8		78	156	156	140	802	945	220	22%
II-T9		40	164	206	140	792	933	225	14%
R	Crossin (2015)	374	0	0	157.6	685	1092	–	378.5 kg eq. CO_2/m^3
R-S7		112	0	262	149.5	703	1056	–	198.6 kg eq. CO_2/m^3

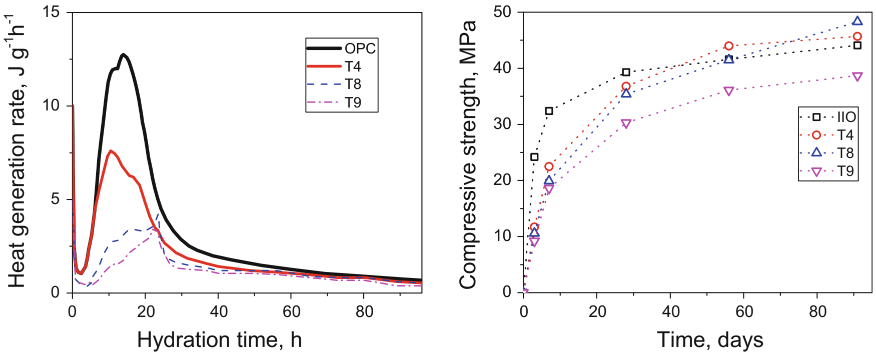

Fig. 10.7 High volume (40, 80 and 90%) use of fly ash and GGBFS (Table 10.4: Left) heat generation rate of paste samples with w/b = 0.50 at 23 °C; Right) concrete compressive strength development (adapted from Yang et al. 2016)

10.3.7 Recycled Aggregate Concrete (RAC)

Controlling the compressive strength of RAC boils down to the control of the mechanical properties, the adsorption capacity, the grading and morphology of the RA (Figs. 10.8, 10.9 and 10.10). Koenders et al. (2014) proposed a model to predict the hydration kinetics and the mechanical behaviour of recycled aggregate concrete (RAC). Particularly, it reports the possible influence of two key parameters, such as w/c ratio and moisture conditions of recycled concrete aggregates (RCAs), on the hydration reactions and on the time evolution of the compressive strength for four different mixtures with recycled aggregates (Table 10.5). The time monitoring of the temperature developed inside the hardening concrete has led to the indirect identification of a model with which the hydration processes for various mixes considered in that study can be described. The simulation of the setting and hardening process in the concrete samples tested in compression showed clear linear correlation between degree of hydration and compressive strength. Such a correlation is strongly affected by both w/c ratio (as already known for ordinary concrete mixes) and moisture conditions of recycled aggregates. The linear correlation emerged between degree of hydration and compressive strength indicates a possible design approach for the type of concrete under consideration.

The RCA can fully or partially replace NA, however, the high water absorption of the fine material smaller than 150 µm, lowers the strength and increases the concrete shrinkage significantly. As higher water demand significantly complicates concrete quality control, some standards do not allow the use of fine RCA in recycled aggregate concrete for structural use (DAfStb 2004; En 206-1 2006). As the origin of RCA is usually unknown, care should take about RAC chemical

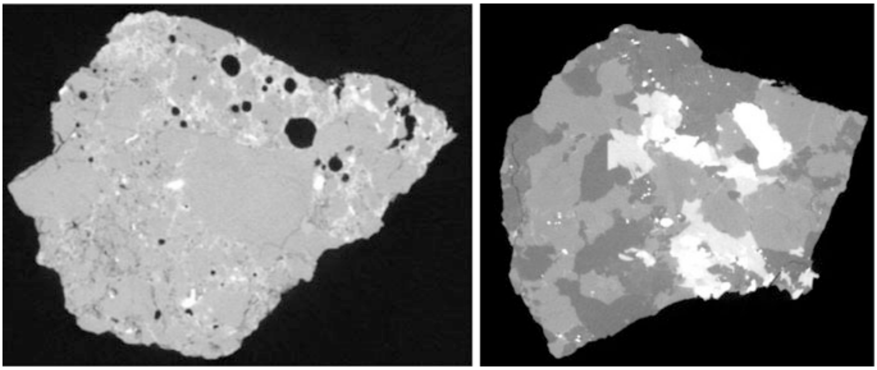

Fig. 10.8 Cross-section of 3D computerized tomography micro-scans for the recycled (left) and natural aggregates (right)

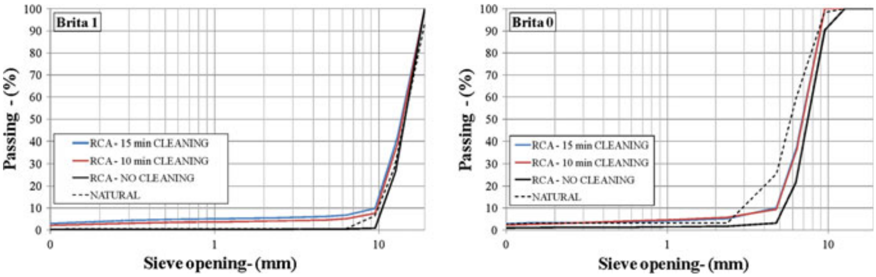

Fig. 10.9 Grain size distribution comparison for natural and recycled aggregates (adapted from Koenders et al. 2014)

Fig. 10.10 Compressive strength development for the five mixtures as presented in Table 10.5 (adapted from Koenders et al. 2014)

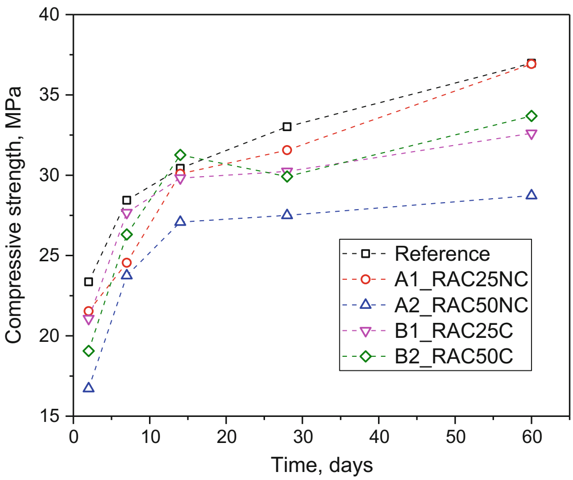

Table 10.5 Mix design prepared for ecological concrete with recycled aggregates (kg/m^3) (adapted from Koenders et al. 2014)

Concrete type	Cem	Water	Superplast	Natural components			RCA without cleaning		RCA with cleaning		Slump (mm)
				Sand	Brita 0	Brita 1	Brita 0	Brita 1	Brita 0	Brita 1	
Reference	300	191	4.02	9523	439.9	470.2	–	–	–	–	160
A1_RAC25NC	300	205	4.02	952	439.5	–	–	404.5	–	–	160
A2_RAC50NC	300	232	4.02	950	–	–	346.6	404.0	–	–	240
B1_RAC25C	300	202	4.02	952	439.8	–	–	–	–	415.3	190
B2_RAC50C	300	110	4.02	951	–	–	–	–	403.1	415.1	220

properties, like the content of chlorides, sulphates and alkali–silica reactivity. Pryce-Jenkins (2011) performed a comparative analysis of 103 studies on RAC (100% coarse aggregate replacement) use in structural concrete and showed following typical effects. Compressive and tensile strength is 5–20% and 0–30% lower, respectively, with little effect below 30% and 50% replacement level. Modulus of elasticity is 15–30% lower, little effect below 20% replacement. Shrinkage is increased by 10–20%, creep +25–50%, water absorption +40–50%, no effect or improved resistance to carbonation, 0–10% decreased freezing and thawing resistance, 50–70% increased chloride penetration resistance. This typical reduction in concrete properties shows that RCA has a good potential to replace natural aggregates in low-to-medium strength structural concrete.

Although the Revised Waste Framework Directive (WFD) 2008/98/EC (EU 2008) established that by 2020, the minimum recycling percentage of ‘non-hazardous’ construction and demolition wastes should be at least 70% by weight (Pacheco-Torgal et al. 2013), it is still not clearly defined to whom the benefits of recycling should be credited: to the primary producer or to the user of recycled materials (Chen et al. 2010).

10.3.8 Fiber Reinforcement

The tensile strength of the fiber-reinforced concrete is determined by the strength properties of the matrix and the fibers, the amount and the geometry (and aliment) of the fibers and amount of the fiber–matrix bond. There is an optimum fiber–matrix bond strength at which the fracture energy (for complete failure) of the material attains its maximum value, and the material’s behaviour is the least brittle. One of the main reasons to add fibers to cement-based materials is the possibility of improving the toughness and ductility of the composite and therefore overcomes the inherent disadvantages of brittle cementitious materials. Both ductility and toughness are concepts that describe the mechanical behaviour of concrete composite in the post-cracking stage.

10.3.8.1 Wood Fibers

Adding fibers to a cement-based mixture increases the surface area and therefore decreases the workability. In praxis, all fiber-reinforced concretes have a higher water/cement ratio, lower coarse aggregate content and smaller size of aggregates compared with conventional concretes (Sierra Beltran 2011). Sugar is a main inhibitor of cement setting, and it is present in the chemical components of fibers, mainly in lignin and in hemicellulose. Because of its chemical composition and extractives hardwood is therefore more an inhibitor to cement setting than softwood fibers (Blankenhorn et al. 2001).

The addition of fibers can reduce plastic shrinkage because they stop the spread of micro-cracks and increase the tensile strength of concrete (Soroushian and Marikunte 1991). Because of their hygroscopic properties wood fibers keep concrete moist for a longer time so that drying of the concrete surface starts later (Sierra Beltran 2011).

Following Rapoport and Shah (2005) in a cementitious matrix, fibers can be distributed in three fundamental modes: uniform, random or clumped. A uniform distribution is ideal while in cast-in-place concrete a random distribution is the best that one can obtain. In their study, cellulose fibers do disperse well under normal mixing circumstances. Processing the secondary fibers into fibrous form improves their dispersion in the cement matrix (Blankenhorn et al. 1999). Pulp fibers have the tendency to clump together in water and fiber clumps become weak spots in concrete.

Wood-reinforced cement composites have lower compressive strength than fiberless mortar or concrete (Sierra Beltran 2011; Blankenhorn et al. 2001; Pehanich et al. 2004), consistent with the higher water/cement ratio of the fiber composites.

Pulp fibers significantly increase the fracture toughness. Wood fiber-reinforced composites have higher values of flexural strength and toughness than fiberless cement samples (Blankenhorn et al. 2001; Pehanich et al. 2004). The authors consider that the origin of fracture toughness comes mainly from the work dissipated in pulling out the cellulose fibers from the cement mortar matrix. Long fibers enhance even more the toughness of the composites because they have a bigger surface area in contact with the cement matrix enabling them to resist fiber pull-out. Additionally, it can also make a more effective bridge of the micro-cracks. Fiber and cement matrix bond depends on many factors like the physical characteristics of the fibers: geometry, type, surface characteristics, orientation, volume and distribution, the chemical composition of the fiber, but also the treatment of the fiber and additives in the cement mixture.

Tonoli et al. (2009) reported decrease of flexural toughness, deflection and modulus of rupture after 200 wet/dry ageing cycles. The decrease of final deflection was bigger for untreated cellulose fibers than for treated ones.

10.3.8.2 Non-wood Natural Fibers

As with wood fibers, the addition of other natural fibers to cementitious matrices decreases the compressive strength. In concrete reinforced with palm trees fibers, the compressive strength decreases with increasing fiber percentage and with increasing fiber length (Kriker et al. 2005). Mortar samples prepared with coir, sisal, jute and hibiscus cannabinus also exhibit lower compressive strengths than mortar without fibers (Ramakrishna and Sundararajan 2005).

Fibers from agave sisalana (sisal) benefit the flexural behaviour if the composite is prepared by slurry de-watering instead of cast-in-place (Savastano et al. 2003, 2005).

Natural fibers enhance the flexural toughness of cement-based materials, even in cases where the bending strength was lower than samples without fibers (Kriker et al. 2005). Savastano et al. (2003) report higher values of fracture toughness for composites with kraft banana (Musa cavendishii) and composites with sisal fibers that were obtained through different pulping processes. The toughening in the natural fiber-reinforced composites occurs as a result of crack bridging. When comparing the behaviour of the different sisal fibers, it is evident that the pulping process affects the fiber failure mechanism. Mechanical pulp fibers tend to pull-out and have little fracture. As a consequence, the mortar samples with these fibers develop higher toughness.

The flexural toughness increased with increasing fiber content of curaua fibers (D'Almeida et al. 2010). For the same fiber content, samples with longer fibers exhibited higher toughness.

Cement composites reinforced with some natural fibers show loss of bending strength after either accelerated weather tests or natural weathering. Samples prepared using a slurry vacuum de-watering technique and reinforced with 8 wt% of sisal were tested after two years of external exposure to tropical weather. They exhibited a considerable reduction in bending strength since the modulus of rupture of the composite decreased to 70% (Savastano et al. 2009). Likewise, the toughness reduced from 0.85 kJ/m^2 at 28 days to 0.62 kJ/m^2 after two years of external exposure. The loss in mechanical strength of the composites was attributed to the degradation of both the vegetable fibers and the cementitious matrix.

10.4 Life Cycle Assessment (LCA)

First an introduction on life cycle assessment (LCA) is given, followed by its review on different mass concrete mixtures and placement technologies.

10.4.1 LCA Background

Life cycle assessment (LCA) is a systematic approach to evaluate the environmental impacts and other sustainability indicators (Fig. 10.11) (Schau et al. 2011; Gencturk et al. 2016) of processes and products during their life cycle. According to ISO standards 14040 (2006a) and 14044 (2006b), this is performed in four steps (explained in more details latter): (1) planning: goal and scope definition which describes the product system boundaries and the functional unit; (2) life cycle inventory (LCI): compiling an inventory of relevant energy and material inputs with corresponding environmental releases; (3) evaluating the potential environmental impacts associated with identified inputs and releases; and (4) interpreting the results leading to more informed decisions. LCA includes various stages of producing a product (Fig. 10.11), from raw materials extraction, through material production, transportation, construction, use, to the stages of disposal and recycling. A life cycle approach identifies energy use, material inputs and waste generated from the time raw materials are obtained to the final disposal of the product. This provides a global

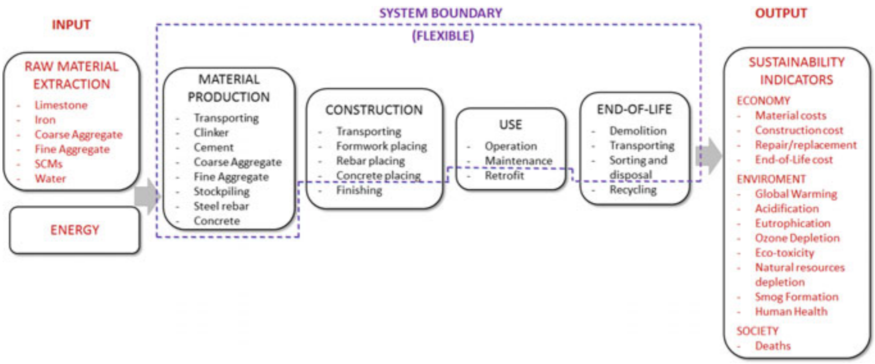

Fig. 10.11 Life cycle assessment (LCA) system for reinforced concrete structure defined by a flexible system boundary with input and output flows of materials, energy, pollutants and economic values

and objective basis for comparisons. Capital goods, including plant and infrastructure, are usually excluded from the system boundary. Although LCA originally aimed at considering every stage of the product's life cycle, known as *cradle-to-grave*, many studies narrow the system boundary. For example, the LCA system boundary usually comprises the raw materials production and the construction only, known as *cradle-to-gate*, where the effects of the concrete structure use and it's end-of-life processes are not included.

When comparing different concrete mix designs, the calculated environmental impact depends on the adopted functional unit, which should incorporate differences in strength, durability and service life. How the concrete service life influences the results of most LCA studies have seldom been included. To consider both strength and durability of concrete structure, the functional unit should contain the amount of concrete needed to produce a structural element designed to carry a particular mechanical load over a particular service lifetime. To evaluate the concrete structure, service life requires employment of service life (probabilistic) prediction models based on experimental durability tests corresponding to specific exposure conditions.

Once the functional unit and system boundary are defined, the second step is the inventory analysis. This means time-intensive collecting and validating the data, calculating and allocating the inputs and outputs. The data quality depends on the access to manufacturer data, regional inventory databases, literature, estimates and judgments of the researchers. At the world level the *Ecoinvent* proprietary database is the largest and most complete database for life cycle inventory. Furthermore, a growing number of regional and national databases are emerging that can facilitate data collection (Finnveden et al. 2009). Very careful attention must be paid when combining databases (Lasvaux et al. 2014).

The third step is the impact assessment which provides quantified information on the environmental impact of the studied products or processes. In LCA, when a process produces more than one product (i.e. a by-product such as fly ash or slag), the environmental impact of this process needs to be allocated between the product and the by-product. If the by-product can be considered as waste, all impacts are allocated to the main product, but if this by-product can be considered a co-product of the process, then environmental impacts have to be shared between the main and co-products.

The last step is the interpretation and conclusion of the implications of the life cycle assessment that involves the evaluation of principal issues, limitations and recommendations. In relation to the interpretation, the focus is on uncertainty analysis. Explicit description of the uncertainties should be of great importance here, however, only few LCA studies report it. The uncertainty in an LCA can be obtained by various statistical methods, e.g. parameter variation and scenario analysis, Monte Carlo simulations, analytical methods based on first-order propagation and qualitative uncertainty methods based on quality indicators (Finnveden et al. 2009).

The LCA standard ISO 14040-44 is quite generalized and non-specific in its requirements and offers little help to the LCA practitioner in making choices. There are various tools for performing LCA or for supporting the different phases and applications of LCA. Most tools include databases, some more comprehensive than others. Table 10.6 shows a list of existing LCA tools with some main characteristics. Most tools are designed for experts, and only few for non-specialists (Lehtinen et al. 2011).

Table 10.6 List of some LCA tools

Name	Developer	Main database	Application	Open source	Web page
BEES 4.0	National Institute of Standards and Technology (NIST)	Bees	Construction industry	Yes	http://www.nist.gov/el/economics/BEESSoftware.cfm
CCaLC Tool	The University of Manchester	CCaLC and EcoInvent	General	Yes	http://www.ccalc.org.uk/index.php
Eco-Bat 2.1	Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud	Eco-Bat	Construction industry	No	http://www.eco-bat.ch/index.php?option=com_content&view=frontpage&Itemid=1&lang=en
Environmental Impact Estimator V3.0.2	Athena Sustainable Materials Institute	Own	Construction industry	No	http://www.athenasmi.org/
GaBi 4	PE International GmbH University of Stuttgart, LBP-GaBi	Gabi	General	No	http://www.gabi-software.com/index.php?id=85&L=0&redirect=1
LEGEP 1.4	LEGEP Software GmbH		Construction industry	No	http://www.legep.de/index.php?AktivId=1125
OpenLCA	GreenDeltaTC GmbH		General	Yes	http://www.openlca.org
SimaPro 7	PRé Consultants B.V.	SimaPro	General	No	http://www.pre.nl/

10.4.2 LCA Limitations

The broad scope of analysing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects (Guinée et al. 2004). A core challenge of LCA is the comparability of different concrete studies, due to different methods and assumptions. Currently, available indicators for assessing resource consumption are generally based on global scale and are thus not fully adapted to the concrete industry (Habert et al. 2010; van den Heede and de Belie 2012), where the resource availability and accessibility should account regional specific conditions. The inventories and results are based on supply chain and time specific data. Databases are being developed in various countries, and although the format for databases is being standardized, in practice data are frequently obsolete, incomparable, or of unknown quality (Guinée et al. 2004). LCA case studies on commonly used concretes have been carried out in developed countries but there are insufficient studies in developing countries using local data. Furthermore, LCA is typically a steady state, rather than a dynamic approach. However, improvements are increasingly being taken into account in more detailed LCA studies. Although LCA is a tool based on linear modelling (Guinée et al. 2004), some progress is being made in reducing this limitation. The results of available concrete studies are not fully comparable due to different study scopes and system boundaries. Great caution needs to be taken in generalizing any LCA findings or transferring it to different cases.

10.4.3 LCA of Binders

The environmental impact related to the class of potential binders that can be used for mass concretes will be discussed in this section.

Some indicative LCA data sources for embodied carbon in typical binders used for making concrete are shown in Table 10.7. Embodied carbon for cement production can be split to raw material (chemical) decarbonation contribution (mainly $CaCO_3$), which amounts about 47%, and energy use which amounts 53% of the total CO_2 emissions. It is important to note that significant differences exist between cement plants which should be considered to improve accuracy of environmental evaluation (van den Heede and de Belie 2012). Table 10.7 indicates that the CO_2 emissions range from 930 kg per tonne of CEM I to 230 kg per tonne of CEM III/B comprising 80% GGBFS content. The embodied CO_2 values for blended cements taken from (MPA 2011) (Table 10.7) are based on the CEM I and SCM ingredients and the range of supplemented proportion. The calculations consider CEM I with supplement combined at concrete plant. For such combinations, the CO_2 value for CEM I is used together with the values for limestone, fly ash and GGBFS (shown in Table 10.8, MPA 2011) in the appropriate proportions. Therefore, the values can be interpolated for proportions between the minimum and maximum SCM addition.

Table 10.7 Some indicative LCA data sources for embodied carbon in typical binders used for making concrete

Material	Type	kg CO_2/tonne	Source (and comments)
Cement	Raw material decarbonation	425	Gartner (2004)
	Energy use	470	
	Total	895	
	OPC	844	Ecoinvent database v2, Frischknecht and Jungblut (2001)
Blended cement	CEM I (95% clinker, 5% gypsum)	930	MPA (2011)
	CEM II: 6–20% limestone	880–750	MPA (2011) (CO_2 values for blends can be interpolated between the min and max SCM addition)
	CEM II: 6–20% fly ash	870–750	
	CEM II: 21–35% fly ash	730–610	
	CEM II: 21–35% GGBFS	740–620	
	CEM III: 36–65% GGBFS	610–360	
	CEM III: 66–80% GGBFS	340–230	
	CEM IV: 36–55% Siliceous fly ash	590–420	

For example, using values for the end member components, namely CEM I has 930 kg CO_2/t while GGBFS 52 kg CO_2/t, then linear interpolation for CEM III in the range of 36–65% GGBFS gives CO_2 impacts of 610–360 kg CO_2/t. More specifically, $360 = 0.65 * 52 + 930 * (1 - 0.65)$. Likewise, any interpolated value can be used to estimate the impact for any blend.

Some relevant environmental impact factors from proprietary Ecoinvent database v2 (Frischknecht and Jungbluth 2001) are given in Table 10.8. There the ground blast furnace slag, fly ash and silica fume were considered as reused waste from other industries, thus without consideration of allocation and treatment (as detailed in Chen et al. 2010). Usual practice is to assume SCMs as waste, i.e. to assign them a null environmental impact. However, industrial sectors may have to share these environmental loads. This is very relevant to the use of SCMs such as blast furnace slags and fly ash, which now has to be regarded as a by-product because they fulfil three conditions specified by European Union Directive (EU 2008). Regarding to the first condition, they are used entirely, e.g. in Europe. Secondly, both SCMs are produced as an integral part of a production process,

Table 10.8 Some indicative LCA data sources for embodied carbon in typical SCMs and other additions used for making concrete

Material	kg CO_2/tonne	Source (and comments)
GGBFS	16.9	Ecoinvent database v2, Frischknecht and Jungblut (2001)
Fly ash	5.3	
Limestone filler	35.1	
Silica fume	0.313	
Metakaolin	92.4	
Kaolinite	2.93	
Superplasticizer	750	
Water	0.155	
GGBFS	52	MPA (2011)
Fly ash	4	
Limestone filler	32	

Table 10.9 Mass and economic allocation coefficients for FA and GGBFS (van den Heede and de Belie 2012)

Product	Produced amount	Market price	Mass allocation (%)	Economic allocation (%)
Electricity	2.7 kW h/ (kg of hard coal)	0.1 €/ (kW h)	87.6	99.0
FA	0.14 kg	20 €/t	12.4	1.0
Steel	1 kg	400 €/t	80.6	97.7
GGBFS	0.24 kg	40 €/t	19.4	2.3

and thirdly, they can be used directly without any further processing other than normal industrial practice. GBFS and FA used in the cement industry fulfil existing standards that consider their suitability in terms of mechanical performance, risk for concrete durability and risk for the environment, e.g. according to EN 450-1 standard for FA (EN 2007) and EN 197-1 for GBFS (EN 2001). When mass allocation is applied (Table 10.9), the FA and GGBFS environmental burdens become higher than for OPC. Therefore, an economic allocation (Table 10.9) is recommended, which results in an order of magnitude lower impacts of FA and BFS (van den Heede and de Belie 2012). The main problem with the economic allocation is the question of price variability (van den Heede and de Belie 2012). The allocation method, based on the European Union GHG emission trading system (EU-ETS), is calculated so that the economic gains and losses are the same for all of the industries involved in the trading of by-products, which underlines the overall environmental benefit of the exchanges (Habert et al. 2013). For natural SCMs, e.g. volcanic rocks or (calcined) clays, there is no allocation problem and their environmental impact results only from the energy used during their processing, which is always much lower than cement.

Table 10.10 Normalized values describing the sustainability profile of concretes incorporating coal and/or biomass-based fly ash (adapted from Teixeira et al. 2016)

	FA0	CFA60	BFA60	CBFA60
Material input (kg/m^3 of concrete)				
Portland cement	350	140	140	140
Gravel	1100	1100	1100	1100
Sand	750	750	750	750
Water	175	175	175	175
Superplasticizer	8.8	8.8	8.8	8.8
Coal fly ash		210		105
Biomass fly ash			210	105
Transportation (tkm)				
Portland cement	14.4	5.7	5.7	5.7
Sand and gravel	577.2	577.2	577.2	577.2
Superplasticizer	2.9	2.9	2.9	2.9
Coal fly ash		34.7		17.3
Biomass fly ash			30.2	15.1
Global warming (kg CO_2 eq.)	784	416	413	415
Relative overall sustainability index	0	0.98	1.00	0.99

Yang et al. (2016) investigated the high volume (40, 80 and 90%) use of varying combinations of fly ash, slag and PC in order to control the hydration heat development in mass concrete and enhance its sustainability. The studied system boundary included the following phases: (1) procurement of all constituents in a materials inventory (Korean LCI database, Yang et al. 2014) taken from cradle-to-gate, (2) transportation of the constituents to a ready-mixed concrete plant and (3) in-plant mixing of concrete. The reduction percentage in the global warming, photochemical oxidation and abiotic depletion categories, as compared with the reference OPC concrete, was 35%, 36% and 34%, respectively, for the T4 (25%FA + 15%GGBFS) concrete, 75%, 80% and 73% for the T8 (40%FA + 40% GGBFS) concrete and 86%, 89% and 82% for the T9 (40%FA + 50%GGBFS) concrete.

Use of biomass ash as a binder shows a capability to reduce the environmental impacts of conventional concrete (Table 10.10). Using LCA analysis Teixeira et al. (2016) showed that the most sustainable concrete was the one in which 60% of cement is replaced by biomass fly ashes. Nevertheless, with such a concrete it was possible to achieve satisfactory mechanical properties. The incorporation of biomass fly ashes could solve a problem of ash disposal while contributing to the development of concretes with improved environmental performance. However, these results should be complemented by experimental studies aimed at assessing both strength and durability of concretes affected by variability in biomass ash quality. If biomass fly ashes are considered as a waste product without economic value (true in most EU countries, Berra et al. 2015; de la Grée et al. 2016;

Ukrainczyk et al. 2016), then there are no flows from the biomass power plant allocated to its production. On the other hand, coal fly ashes have a market value and consequently a percentage of the power plant's flows are allocated to their productions (García-Gusano et al. 2015).

The amount of superplasticizer used in concrete is almost negligible, thus its emissions, which are approaching cement values (shown in Table 10.8), do not contribute significantly to the overall environmental impact. On the other hand, application of superplasticizer can even reduce the overall concrete CO_2 emissions by 26% (Purnell and Black 2012) due to reduced cement content while achieving same targeted workability and strength.

10.4.4 LCA of Aggregates

Aggregates are the major component of concrete and are inherently a low carbon product (Table 10.11). Most are naturally occurring materials requiring little processing. Besides the type of aggregate, its regional availability and accessibility are of importance. They are generally local sourced, due to the associated impact of transport costs and CO_2 emissions. For example, the transport of aggregates doubles its price (per t) every 30 km. Table 10.11 shows that the CO_2 impact for crushed (virgin) aggregates increases from 6.6 kg CO_2/t for cradle-to-gate system boundary (extraction and production only), for additional 2.7 kg CO_2/t due to transportation delivery and return distance of 58.5 km by road. Reported GHG emissions, including production and average transport values, for crushed aggregates are 45.9 kg CO_2 equivalents/t of granite/hornfels and 35.7 kg CO_2 equivalents/t of basalt, while for sand it is lower, 13.9 kg CO_2 equivalents/t of sand (Flower and Sanjayan 2007) as it does not involve crushing process. Emissions and energy consumption per metric ton of glacier rock produced by a Nordberg HP400 SX rock crusher (55 de Belie) are 0.6465 kg CO_2/t and 9.8192 MJ/t, respectively.

CO_2 emissions for recycled aggregates are compared with virgin aggregate in Table 10.11. It can be seen that for transport distances longer than about 15 km, the CO_2 emissions may become higher than for virgin aggregates with 58.5 km transportation distance (Table 10.11). For the same transport distance of 58.5 km, contributing for 2.7 kg CO_2/t, the resulting total value for RA is 15% higher than for virgin (crushed) aggregate. Therefore, recycled aggregates should only be used if they are locally available and can be demonstrated to reduce overall CO_2 impact. However, to estimate the overall CO_2 impact, benefits in preservation of natural bulk resources and reduction of landfill space as well as CO_2 uptake of crushed concrete should also be considered. This is discussed further in next section (concrete).

Table 10.11 Some indicative LCA data sources for embodied energy and carbon in aggregates, including transportation, used for making concrete

Material	Type	Energy, MJ/tonne	kg CO_2/tonne	Source (and comments)
Sand, fine aggregates			2.4	Ecoinvent database v2, Frischknecht and Jungblut (2001)
Coarse aggregates			4.3	
Aggregate	Virgin (gravel)	23.8	4	MPA (2011)
	Virgin (crushed)	30.2	6.6	
	+58.5 km delivery by road		9.3	
Recycled aggregate from concrete demolition	0 km transport by road	62.1	7.9	MPA (2011)
	+15 km transport		9.3	
	+58.5 km transport		10.6	

10.4.5 LCA of Concrete

Absolute contributions of CO_2 emissions for each of the individual materials and processes relevant for placement of 40 MPa grade concrete are shown in Table 10.12 (Turner and Collins 2013) which in descending relative terms amounts: 76% for cement, 14.4% coarse agg., 3.1% sand, 2.5% transport, 2.5% placement, 0.85% batching, 0.3% admixtures and 0.3% curing. The contribution of the cement production phase varied from 75% to 94% of the total impact, depending on the category indicator and the concrete type. This result is in agreement with Braunschweig et al. (2011).

Although GGBFS has higher material emission factor than fly ash (about 13 times, Table 10.8), it can generally replace more cement (40%) than fly ash (25%) due to its self-cementing properties, which may lead to better reductions in total emissions, 22% for GGBFS instead of 13–15% for FA, respectively, for typical 25 and 32 MPa concrete mixes (Flower and Sanjayan 2007). Some typical CO_2 impacts for OPC and GGBFS and FA concretes are shown in Table 10.12. Baseline GHG emission reductions of between 22 and 40% (Crossin 2015; Flower and Sanjayan 2007) have been reported, while Blankendaal et al. (2014) suggest a total environmental impact reduction of up to 39%.

In different life cycle studies on GGBFS, Flower and Sanjayan (2007), Lee and Park (2005), Kellenberger et al. (2007) and Heidrich et al. (2005) include the emissions associated with processing and transport of GGBFS, but excluded emissions associated with the blast furnace operation.

Table 10.12 Some indicative LCA data sources for embodied energy and carbon in materials and processes for building concrete structures

Material	Type	Energy (MJ/tonne)	kg CO_2/tonne	Source (and comments)
OPC concrete	40 MPa, Coarse agg. 1242 kg/m^3, sand 781 kg/m^3, OPC 328 kg/m^3, water 190 kg/m^3		112(Cement) + 21.3 (coarse agg.) + 4.6(sand) + 0.4(admix.) + 1.3 (Batching) + 3.8 (Transport) + 3.8 (Placement) + 0.4 (Curing) = 147.5	Turner and Collins (2013) (concrete density 2400 kg/m^3 assumed)
Concrete	Structural	1111	159	Hammond and Jones (2011) (density of 2400 kg/m^3 assumed for unit conversion)
	RC40 with 25% PFA	970	132	
	RC40 with 50% GGBFS	880	101	
Concrete	30 MPa (Table 10.4) PC		164	Crossin (2015)
	70% slag (Table 10.4)		87	
Reinforcement			427	MPA (2011)
Reinforced concrete	C28/35 unreinforced (w:c:a = 0.55:1:6.4)		95	(density of 2380 kg/m^3 assumed for unit conversion)
	C28/35 (w:c:a = 0.55:1:6.4) with steel bars 110 kg/m^3		110	
	Mass foundation GEN1 d_{agg} < 70 mm, unreinforced	CEM I	75	MPA (2011) (concrete density of 2300 kg/m^3 assumed for unit conversion)
		30% FA	54	
		50% slag	43	
	Trench foundation GEN1 d_{agg} < 120 mm, with steel bars 25 kg/m^3	CEM I	80	
		30% FA	62	
		50% slag	47	
	Reinforced foundation RC30 d_{agg} < 70 mm, with 100 steel bars kg/m^3	CEM I	138	
		30% FA	116	
		50% slag	87	
	Ground floors RC35 d_{agg} < 70 mm, with steel bars 30 kg/m^3	CEM I	137	
		30% FA	113	
		50% slag	81	
	Structural walls RC40 d_{agg} < 70 mm, with 100 kg/m^3 steel bars	CEM I	162	
		30% FA	138	
		50% slag	103	
	High strength RC50 d_{agg} < 70 mm, with steel bars 100 kg/m^3	CEM I	190	
		30% FA	155	
		50% slag	120	
	N. agg. (Table 10.13)	668	142 (CO_2 eq.)	Marinkovic et al. (2014) (excluding agg. transportation)
	Natural crushed aggregate (NCA, Table 10.13)	752	160 (CO_2 eq.)	
	Recycled agg. replacing 50% NCA (Table 10.13)	666	142 (CO_2 eq.)	
	Recycled agg. fully replacing NCA (Table 10.13)	724	152 (CO_2 eq.)	

(continued)

Table 10.12 (continued)

Material	Type	Energy (MJ/tonne)	kg CO_2/tonne	Source (and comments)
Concrete batching and pumping			2.35 (CO_2 eq.)	Crossin (2015) (concrete density of 2300 kg/m^3 assumed for unit conversion)
Transport of concrete to site			0.3 per km	
Concrete mixer truck	12 tonne	2.06 (per km)	0.154 (CO_2 eq. per km)	Hong et al. (2014), Akbarnezhad and Nadoushani (2014)
Truck	16.5 tonne	0.94 (per km)	0.065 (CO_2 eq. per km)	
Excavator	0.2 m^3	107.5 (per h)	13.12 (CO_2 eq. per h)	
Truck crane	25 tonne	215.3 (per h)	16.01 (CO_2 eq. per h)	
Loader	1.77 tonne	899.6 (per h)	35.07 (CO_2 eq. per h)	
Crawler crane	50–80 tonne	607.2 (per h)	45.23 (CO_2 eq. per h)	
Concrete pump	80 m^3/h	1094.3 (per h)	81.37 (CO_2 eq. per h)	
Concrete vibrator	2.5 m^3/h	34.9 (per h)	2.59 (CO_2 eq. per h)	
Air compressor	425 m^3/h	968.8 (per h)	37.77 (CO_2 eq. per h)	
Concrete structure	15 stories building, 3375 m^2 of total floor area, 30 MPa concrete 985 kg/m^2 and rebar 57 kg/m^2		189(Material extraction) + 13.4(Transport) + 14.2 (Construction) = 216.4	Nadoushani et al. (2015) (unit adapted from per m^2 of floor area to per tonne of concrete structure)

Crossin (2015) investigated two utilization scenarios: (1) GGBFS is readily available in the marketplace and is not fully utilized and (2) the supply of GGBFS is constrained. Life cycle modelling was undertaken using SimaPro 7.2.4, with background datasets taken from ecoinvent 2.2 (Frischknecht and Jungblut 2001) and the Australasian Unit Process Life Cycle Inventory. In the assessment, they included the full fuel cycle for all energy consumption processes, but excluded the steel reinforcement. The results showed that the impacts of concrete were dominated by GHG emissions from the production of cement and blended cement, contributing to 85% and 73%, respectively of the total impact. The use of GGBFS as a cement substitute in concrete resulted in a 47.5% reduction of GHG emissions provided that the supply of GGBFS is not constrained. Conclusive determinations of supply constraints, and subsequently the establishment of potential environmental benefits, require the better provision and access to market data, including price information. GGBFS prices have increased from 2005 to 2011, while cement prices peaked in 2008. The unit price for GGBFS is higher from CEM I cement from 2009 to 2011 (van Oss USGS Mineral info 2006–2011 cited in Crossin 2015).

In order to achieve the same strength characteristics, the total cementitious content of GGBFS concrete mixes needs to be higher than for concrete mixes without GGBFS (Richardson 2006; Shariq et al. 2008; Babu and Kumar 2000). GGBFS concretes typically require increase in binder content of about 5–10 kg/m^3 up to replacement levels of 50% to achieve equivalent 28-day strength (MPA 2011). These changes would likely result in a minor increase in the greenhouse gas impacts reported in that study. For concrete containing 40% fly ash, the total binder content may be around 15% higher than a reference concrete containing CEM I only.

10.4.5.1 Recycled Aggregates Concrete (RAC)

Replacing natural aggregates with recycled concrete aggregates can decrease concrete environmental impact by preserving natural resources and minimizing waste disposals. LCA benefits of concrete with replaced NA by RAC are given in FIB TG3.6 (2008), Hájek et al. (2011) and Marinkovic (2013, 2014). Braunschweig et al. (2011) showed that environmental impacts of NAC and concrete with 25% recycled aggregate are similar, considering the increase of cement amount in RAC is below few per cent. Blankendaal et al. (2014) concluded that the recycling of concrete does neither contribute nor harm the environmental impact. Weil et al. (2006) compared NAC to RAC with 35 and 50% of recycled concrete aggregate and different cement content. Marinkovic et al. (2014) investigated the effect of three different types of aggregate: natural gravel, natural crushed and recycled concrete aggregate (Table 10.13) on the transport phase and CO_2 uptake during the life cycle of concrete. Within the limits of that case study, based on Serbian LCI data and typical conditions, brought the conclusion that RCA application in structural concrete can bring environmental benefits over gravel aggregate, and certainly over crushed aggregate, but this depends on transport conditions and types of natural and recycled aggregate.

The impairment in sustainability of NCA relative to NA ranged from 12% to 18% in all category indicators (namely energy use, global warming, eutrophication, acidification, photochemical oxidant creation) due to 9% higher cement content, needed to maintain workability and strength in NAC and different transportation types: truck and ship, respectively. The 50% and 100% replacement ratio of NCA, i.e. RA50 and RA100, relative to NA (Table 10.13) showed a negligible effect of below 2 and 3%, respectively, on the indicators for all impact categories of the concrete. However, for RA concretes there is a clear benefit in avoiding the landfilling of 1071 kg of concrete waste and extraction of 1071 kg of natural aggregate per 1 m^3 of RAC100. This indicates that additional special indicators should be developed to quantify benefits in (a) preservation of natural bulk resources (e.g. natural resource depletion indicator as shown in Fig. 10.11) and (b) reduction of landfill space.

Table 10.13 Mix proportions and properties of concretes made by NA and RA (adapted from Marinkovic et al. 2014)

Concrete short name	Concrete with	Cement (kg/m^3)	Water (kg/m^3)	Aggregate			Slump (cm)	Comp. strength at 28 days (MPa)	CO_2 eq. (kg/m^3)	Energy (MJ/m^3)
				Fine (kg/m^3)	Coarse (kg/m^3)					
					Natural	Recycled				
NA	Natural aggregate	354	185	600	1164	0	8.0	43.7	328	1538
NCA	Natural crushed aggregate	384	201	592	1165	0	8.8	41.5	356	1677
RA50	Recycled agg. replacing 50% NCA	354	178	598	555	555	9.7	44.2	333	1559
RA100	Recycled agg. fully replacing NCA	365	218	576	0	1071	9.7	42.5	356	1623

The contribution of the aggregate production phase is very small, ranging between 0.8 and 5.4%. Therein, RCA concretes have higher contribution than NA concretes due to higher energy requirement for the production of RCA (62.1 MJ/t) than NA (23.8 MJ/t) or NCA (30.2 MJ/t). However, the different energy requirement for production of different aggregate types affects the total impacts by up to a few per cent only. The contribution of the concrete production phase is also small and varies from 0.1 to 5.1%, depending primarily on the category indicator. The transport phase contributed from 3 to 20%, wherein was largest for NCA due to the case assumption that 100 km transport was made by a truck, a much more polluting means than by a ship. This emphases that the results of the concrete LCA studies depend primarily on the concrete mix design, i.e. the amount of cement used, and secondly on the assumed transportation means and distances. For transport distances longer than about 15 km, CO_2 emissions for recycled aggregates may become higher than for virgin aggregates (Table 10.11).

Another benefit of concrete recycling is CO_2 uptake of crushed concrete. During its stockpiling for a certain period of time, a revealed surface area, and thus CO_2 uptake, is much greater than for landfilled concrete waste which is not that finely crushed. Literature results show that CO_2 uptake in post-use phase can be significant, depending on the concrete structure, namely concrete CO_2 uptake normalized to CO_2 emission from calcination during service life is 8.6% (Gajda 2001), which is much smaller than CO_2 uptake during secondary life when demolished concrete is crushed into RCA and reused in the construction: 33–57% (Kjellsen et al. 2005) or 86% (Collins 2010). Dodoo et al. (2009) showed that the uptake of CO_2 during the concrete building service life for 100 years was 23% of the clinker calcination emissions. However, when the concrete was crushed, after demolition, and exposed to air for four months, the CO_2 uptake was 43% of the calcination emissions. Collins (2010) indicated that during the concrete building service life for 100 years CO_2 uptake was only 3% of the calcination emissions, while when the concrete was crushed, after demolition, into RCA and used in the construction of a new bridge for another 30 years, CO_2 absorption is as high as 55 and 86% of the clinker calcination emissions, depending on RCA application. The amount of this CO_2 uptake should then be allocated between the product that generates waste and the product which receives it.

Beside partial replacement of cement with SCMs, or recycling of aggregates, another option to improve sustainability in mass concrete would be to reduce the concrete volume or decrease maintenance burdens by enhancing the concrete performance. Habert et al. (2013, 2014) highlighted that significant saving can be achieved with high-performance concretes, which are at the same time less environmental friendly than conventional concrete. However, the gain prevails when concrete is designed to be used in much smaller amounts (lower cross sections) or for much longer time.

10.4.6 LCA of Reinforced Concrete Structure

The composite combination of concrete and rebar employs tensile and compressive qualities, respectively. Steel reinforcement is used to deliver tensile capacity, a week property of concrete alone needed (1) to minimize the thermal induced cracking problems and/or ensure tensile loadings during structural use. Efficient use of reinforcing steel is dependent on good structural design and on the material's chemical composition, mechanical properties and rib geometry, as well as accurate cutting, bending and fixing.

Rebar contents in reinforced concrete may vary, and this will affect the embodied CO_2. Rebar amount of 110 kg per m^3 of concrete will increase CO_2 emissions by 16%, as shown in Table 10.12 for C28/35 concrete (MPA 2011). Rebars can be recovered, recycled and reused at the end of a structure's service life.

Nadoushani and Akbarnezhad (2015) investigated concrete structural systems designed for 3, 10 and 15 stories buildings including moment resisting frames, braced frames and shear walls systems. The CO_2 footprint of each individual design is estimated by considering the emissions incurred in: (1) material extraction, (2) transportation, (3) construction, (4) operation and (5) end-of-life phases. The cradle-to-gate embodied CO_2 was estimated for per square metre of different structural systems, which was converted into per tonne of concrete structure and shown in Table 10.12. This unit conversion was done by averaging the amount of concrete and rebar used in the whole building. The results show that the cradle-to-gate for reinforced concrete materials extraction embodied majority (87.3%) of the total CO_2 for the whole structure. Transportation of the high amount of the materials accounted for 6.2% of the total CO_2 impact. The use of energy consuming vehicles and equipment such as concrete truck mixers and concrete pumps in construction process, to complete concrete frames, resulted in 6.6% of total CO_2 embodiment. Table 10.12 includes also the energy consumption and GHG emission factor for transportation vehicles and construction equipment. This also gives a rough estimate on the specific technologies applied for mass concrete, namely occurred for additional construction processes for (1) controlling the lift thickness and the time intervals between lifts placing, to allow hydration heat to dissipate and (2) reducing the temperature of concrete, either by pre-cooling the mix and/or its ingredients or by post-cooling the mix after placement.

10.4.6.1 Fibers

Currently, there are insufficient efforts in applying LCA to fiber-reinforced concrete composites. To provide an even starting point for environmental comparisons, functional units should be developed to consider an appropriated lifespan and similar mechanical responses.

Natural fiber production has superior environmental impacts compared to glass fiber production (Joshi et al 2004). However, this is compromised by a lower operating service life compared to glass fiber components (Beltran, Romildo). Significant environmental savings, of about 48%, can be achieved compared to steel reinforced concrete, when using only 3 vol% of bamboo (Zea Escamilla and Wallbaum 2011). The replacement of traditional reinforcements brings both a significant environmental and economical saving for the production of concrete.

10.5 Conclusion

Based on this review, chapter on sustainability in mass concrete following points may be recommended and/or summarized.

(1) LCA should be performed when improving mass concrete mix design and placement technology, following the outlined approach and recent studies. An objective functional comparison criteria should be used, for example the equivalent mechanical strength, volume of binder paste and/or replaced aggregate, but also it is crucial to consider durability criteria. A more advanced rational approach is required to include durability and service life of mass concrete in the LCA assessment. Further research on the compromise between longer concrete service life and increase in initial input value of raw materials is recommended, as it is crucial to find optimal environmental solutions over the entire life cycle of mass concrete structure. However, the broad scope of analysing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects. A core challenge of LCA is the comparability of different concrete sustainability studies, due to different methods and simplifying assumptions. At least the extended cradle-to-gate system boundary conditions should be performed, which define the amount of mass concrete needed to maintain the structure during well-specified service life, with required repairs and maintenance.

(1.1) The quality of LCA results depends significantly on the quality of life cycle inventory input data. An LCA should be performed locally, to include the local conditions and impact of transport, and make it comparable to the result with other studies.

(2) Contributions of CO_2 emissions relevant for placement of conventional (40 MPa) concrete in descending relative terms amounts: 76% for cement (varies from 75 to 94% depending on the concrete type), 14.4% coarse agg., 3.1% sand, 2.5% transport, 2.5% placement, 0.85% batching, 0.3% admixtures and 0.3% curing. The cradle-to-gate LCA for reinforced concrete structure indicates following CO_2 contributions for typical stages: 87.3% for materials extraction, 6.2% for transportation and 6.6% for the use of energy consuming vehicles and equipment (Table 10.12). This also gives an order of magnitude estimate ($\sim$<5%) for the possible contribution of the specific technologies

applied for mass concrete, namely for controlling the lift thickness and the time intervals between lifts placing and for pre-cooling or post-cooling the mix.

(3) The use of non-conventional wastes and/or a high volume of conventional SCMs is general not directly allowed to be used in concrete, but only after its equivalent performance is proved in comparison to the eligible reference concrete.

The SCMs with the highest potential for improving the sustainability in mass concrete are the biomass ash obtained by combustion of residues from timber industry and forest activities (woody ash), the wastes from farms and agro-business (sugar cane bagasse and rice husk ash), and other plants grown for energetic purposes. The utilization of biomass ash in production of mass concrete is an environmentally motivated choice. It will save costs for ash disposal, decrease energy requirement mainly related to cement clinker production, preserve natural resources, i.e. quarried limestone, sand and natural aggregates which consume also huge amounts of non-renewable and pre-treated natural raw materials and decrease greenhouse gas emissions by cement clinker substitution. The challenge is to maintain equal performances of the produced mass concrete while minimizing the environmental footprint by a maximum reuse of waste-like residuals.

(4) Using of recycled aggregates in mass concrete can make a big contribution to accomplish the Revised Waste Framework Directive (WFD) 2008/98/EC (EU 2008) which established that by 2020, the minimum recycling percentage of 'non-hazardous' construction, and demolition wastes should be at least 70% by weight. Indeed, RCA has a good potential to replace natural aggregates in low-to-medium strength structural concrete. However, recycled aggregates should only be used when they are locally available and can be demonstrated to reduce overall CO_2 impact. For impact estimation, benefits in preservation of natural bulk resources and reduction of landfill space as well as CO_2 uptake of crushed concrete should be included.

(5) To derive value from various wastes, namely various ashes from biomass (wood, sugar cane bagasse and rice husks) combustion and/or construction and demolition wastes, capable of satisfying the technical needs of mass concrete manufacture industry within the framework of sustainable development, still several requirements need to be fulfilled. Currently, there are limitations in technical and regulatory (standard) specifications as well as logistics. The main reasons for this situation relate to waste quality variations, environment and sustainability. To overcome these barriers for a more widespread waste utilization in the mass concrete production, a quality control systems and demonstrations from both different locations and on the various mass concrete application options are needed. These actions will also stimulate cooperation between producers and end-users and increase awareness among market actors.

(6) Natural fibers present several advantages such as lower environmental impact, production costs and weight as well as the higher sustainability of the materials, although the bending strength and ductility by reinforcing concrete with natural

fibers is lower than some other fiber reinforcements. Despite all these advantages, the industrial production of natural fiber-reinforced concrete composites is currently limited by the long-term durability of these materials, which needs to be evaluated in detail. In general, the durability problem is associated with an increase in fiber–matrix performance due to a combination of the weakening of the fibers by alkali attack, fiber mineralization by diffusion of hydration products to lumens and volume variation due to their high water absorption. This causes the material to have a reduction in post-cracking strength and toughness.

(7) Alternative option to improve sustainability in mass concrete, beside reuse of wastes or natural fibers, would be to design mass concretes with smaller volumes, i.e. concretes with lower cross sections and/or for much longer service time, i.e. more durable.

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