The past and future of sustainable concrete:
A critical review and new strategies on cement-based materials

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Abstract

The negative impacts of cement-based material (CBM) production are way bigger than ever expected. To illustrate the scale of this phenomenon, all the forests in the world, regardless of the fact that they are disappearing at an alarming rate, are not enough to offset even half the environmental impact (EI) of global aggregates and cement production. Thus, it is necessary to promote scientific research and guide more researchers and professionals in the construction industry to investigate the undiscovered sustainability paths, namely for concrete before and after end-of-life. For that purpose, a global and extensive review is made here to provide an overall view of concrete sustainability in all possible paths. Then, each path is organized as follows: (i) brief introduction, (ii) presentation of non-traditional materials and techniques that can be used for the selected strategy, (iii) their limitations and (iv) future trends. The study also identifies what is already known to avoid putting valuable research resources into redundant scientific studies. The following paths of concrete production sustainability were identified: mix composition (e.g. reduce the EI and resources use of binders, aggregates, water and reinforcement), materials manufacturing (e.g. new production techniques of cement, aggregates and steel bars), concrete mixing (e.g. mixer type and mixing method), on-site application (e.g. regular casting and digital concrete/3D printing), and in-service performance (e.g. increase the durability of reinforced concrete and carbon capture and thermal conductivity). On most of these paths, many studies have been made on the same non-traditional materials and techniques and similar outputs were obtained. Yet, many other non-traditional materials and techniques have not been explored before, or are incomplete in terms of the characteristics analysed. More than providing definite solutions, this contribution intends to open the minds of the readers to the vastly unexplored world of "green concrete".

Main Keywords

Concrete sustainability; Life-cycle assessment; Cementitious materials; Recycled materials; Sustainable development; Integrated sustainability trends.

Acronyms list:

AAM - Alkali-activated material	MIBA - municipal solid waste incinerator bottom ash
ACR - alkali-carbonate reaction	MIFA - municipal solid waste incinerator fly ash
ADP - abiotic depletion potential	MRA - mixed recycled aggregate
AP - acidification potential	MSA - mussel shell ash
ASR - alkali-silica reaction	NF - natural fibres
AWA - agricultural waste ash	ODP - ozone depletion potential
AWAF - agricultural wastes and aquaculture farming	OPC - Ordinary Portland cement
AWAFA - agricultural wastes and aquaculture farming ashes	OWA - olive waste ash
BLA - bamboo leaf ash	PCM - Phase change materials
BTQ - binary, ternary and quaternary	PE-NRe - non-renewable primary energy resources
CBA - coal bottom ash	PE-Re - renewable primary energy resources
CBM - cement-based materials	POCP - photochemical ozone creation potential
CCA - corn cob ash	POFA - palm oil fuel ash
CDRA - mixed construction and demolition recycled aggregate	RCA - recycled concrete aggregate
CDW - construction and demolition waste	RH - rise husk; RHA - rise husk ash
CNT - carbon nanotubes	RMA - recycled masonry aggregate
ECR - epoxy-coated rebar	SAP - Super absorbent polymer
EC - expanded clay	SA - silica aerogel
ECG - expanded cork granules	SBA - sugarcane bagasse ash
EGA - elephant grass ash	SCC - self-compacting concrete
EI - environmental impacts	SCM - supplementary cementitious material
EP - Eutrophication potential	SF - silica fume
FA - coal fly ash	SMM - Shape memory material
FBBA - forest biomass bottom ash	SP - Superplasticizer
FRP - fibre reinforced-polymer	SSA - sewage sludge ash
GGBS - ground granulated blast furnace slag	SSD - saturated surface-dry
GR - galvanized rebars	SSR - stainless steel rebar
GWP - Global warming potential	TWA - tire waste aggregate
L - lime	TWA - tobacco waste ash
LCA - Life Cycle Assessment	WA - wood ashes
LOI - loss on ignition	w/b - water to binder ratio
LWA - light-weight aggregate	WFA - wood fly ash
M - methylcellulose	WSA- wheat straw ash

1 Introduction

Many studies have alerted us to the negative impacts of cement-based materials (CBM) production within the construction industry. These impacts may be way bigger than ever anticipated. Illustrating the concept, the total world production of aggregates and cement can be around 48.3 billion tonnes (IEA, 2019; USGS, 2019) and 4.1 billion tonnes (average - (Freedonia, 2016; PMR, 2017)) in 2018, respectively. Additionally, the average global warming potential (GWP) of 1 kg aggregate and cement is 0.0123 kg $CO_{2\ eq}$ (Braga, 2015; Korre and Durucan, 2009; Marinkovic´ et al., 2010; Tošić et al., 2015) and 981 kg $CO_{2\ eq}$ (Blengini, 2006; Braga, 2015; Chen et al., 2010; de Schepper, M. et al., 2014; ECRA, 2015; Marinkovic´ et al., 2010; Teixeira et al., 2016), respectively. Thus, the total GWP of aggregates and cement will be around 5.9409E+11 kg $CO_{2\ eq}$ and 4.0221E+15 kg $CO_{2\ eq}$, respectively. Contrary to a common statement, instead of concrete, aggregates are the most consumed material after water. Previous values shown in the previous sentences indicate that, although aggregates consumption is almost 12 times bigger than that of cement, their environmental impact (EI) is insignificant relatively to cement. If one considers only half of the produced aggregates and cement used for paste, mortar and concrete without considering the mixing procedure and transportation, the total GWP will be around 2.0113E+15 kg $CO_{2\ eq}$. Thus, the EI of the main raw materials to produce paste, mortar and concrete is at least 710 and 31 times higher than the total emitted CO_2 by "human exhalation" and "all human activities including exhalation" per year, respectively (source of the secondary data: human population ≈ 7.7576E+09 (WPC, 2019), global normalisation factors for the environmental footprint and Life Cycle Assessment - LCA of all activities of human (Sala et al., 2017) per year ≈ 8.40E+03 kg $CO_{2\ eq}$, Human CO_2 exhalation (USGCRP, 2019) per year ≈ 365 kg $CO_{2\ eq}$). If it were not for some tiny ocean plants, namely phytoplankton, the three trillion trees on the surface of Earth would not be enough to offset half the EI of aggregate and cement production (source of the secondary data: number of trees ≈ three trillion (Ehrenburg, 2015) and CO_2 consumption of a mature tree ≈ 22 kg/year (EVA, 2012)).

Most of the materials used in concrete production are, in *sensu stricto*, non-sustainable because they are coming from non-renewable sources. In addition, concrete may contribute to 4-8% of the world's CO_2 and consume a significant amount of natural resources, besides other negative impacts during concrete mixing and on-site application. Nevertheless, the term sustainability mentioned in this work, can still be used to characterize the concrete production, since concrete is one of the most competitive construction materials and it can last for centuries. In fact, concrete is arguably the main driver of modern development, protecting humans from natural disasters and providing a structure for transportation, education, healthcare, energy, among many other industries.

After an extensive review, the lessons learned show that many case studies and review studies have been made to overcome the mentioned issue regarding the high negative impact of the construction industry, namely that of concrete. For example, similarly to this study, there are other attempts focused the gate-to-cradle boundaries of CBM (Morbi et al., 2010) and concrete pavements (FHWA-HIF-16-013, 2016) in the construction industry, including the relationship between the main sustainability parameters (e.g. cost and performance, including rehabilitation cost, *versus* service life for high- and low- performance concrete). Nevertheless, to the best of the authors' knowledge, there is no single study collecting all the strategies (given example for each) and providing a global overview of the mix design and whole life cycle of concrete (Figure 1), namely mix composition (sections 3-7), materials manufacturing (section 8), concrete mixing (section 9), on-site application (section 10) and in-service performance (sections 11-13). Thus, this study organized and discussed most of the potential strategies to guide and introduce scientists and the general public in and outside the construction industry to the available sustainability options. Apart from introducing the most sustainable options for CBM, this study also shows the limitations (critical issues) and future needed investigation for these strategies to be a baseline and foundation for coming studies.

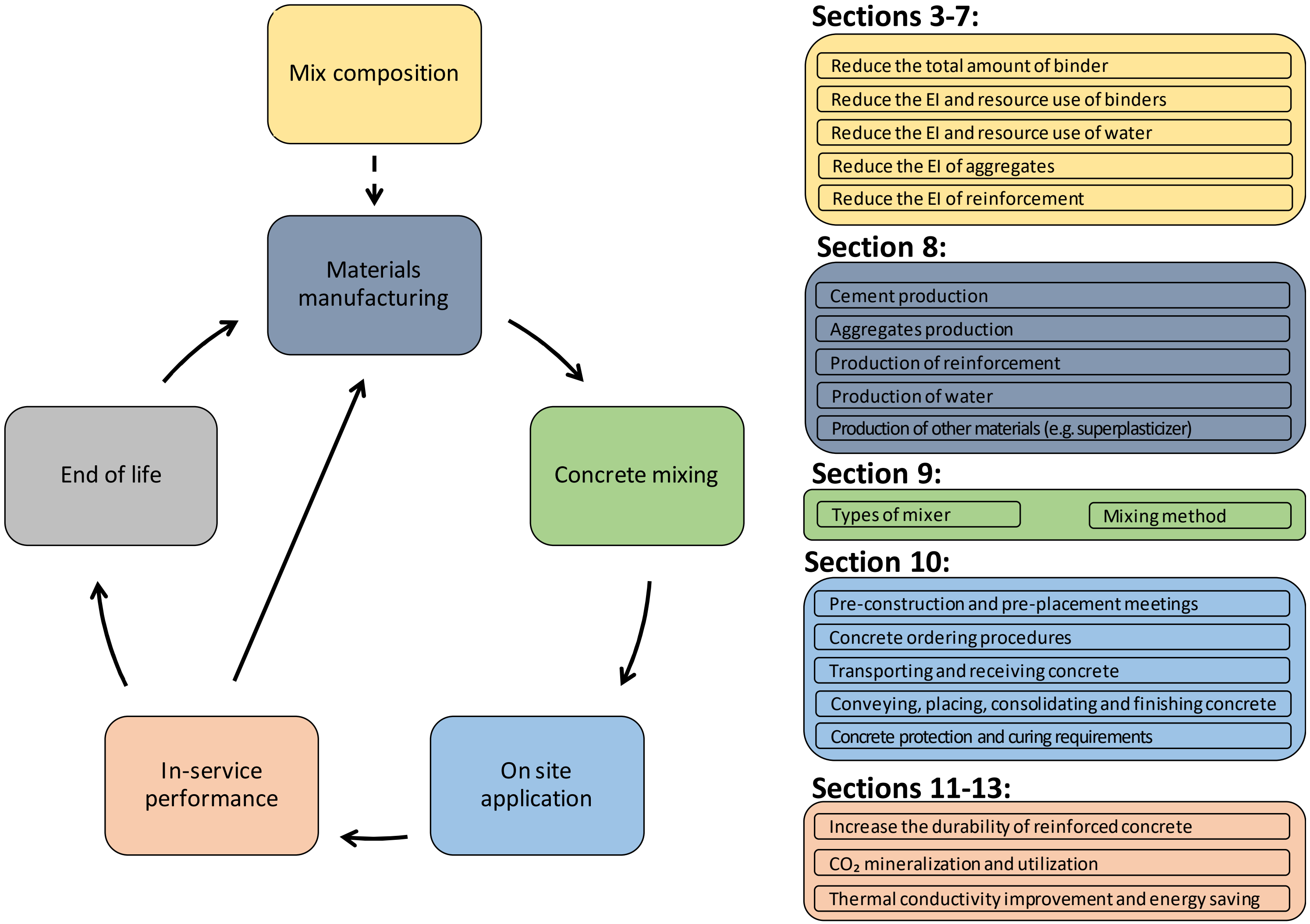


Figure 1 - Strategies for sustainable concrete

2 Methodology

This work is a systematic and extensive analysis that intends to synthesize, identify, and evaluate the literature regarding the sustainability paths concerning mix design and whole life cycle of CBM (Figure 1), with special emphasis on concrete. Thereafter, this work is followed by an exhaustive analysis of the literature to identify topics for further study. The study is mainly focused on the various options to move towards CBM's sustainability. Thus, a literature research was made using the search engines of several databases (Figure 2). For each database, the same search options were repeated using combinations of different keywords based on the strategy. Furthermore, for each selected study, the reference list and the studies cited in the selected study were checked to find further relevant studies.

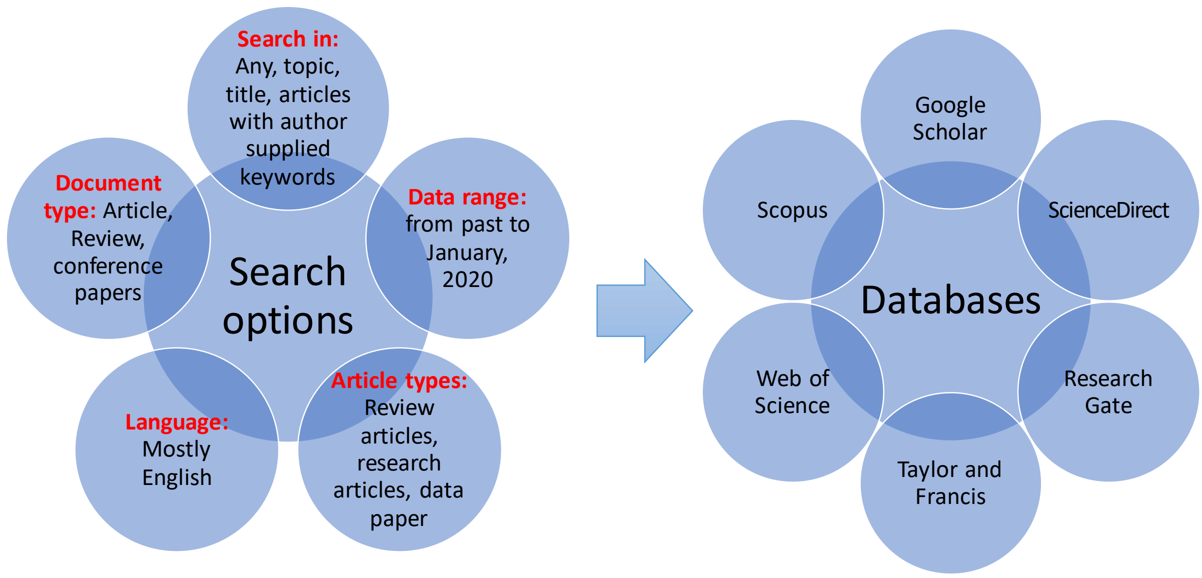


Figure 2 - Databases and search options (besides the main databases, other databases such as ICE, Wiley Online Library, RILEM, Web of Knowledge are also considered)

Since the range of the study is very wide and the number of cited references is unusual, various strict boundaries were defined to maintain the reliability of the cited references (e.g. rank of the journal, number of citations and number of the studied parameters and samples). The validity of the selected papers was specified by analysing the title, abstract, materials and methodology of the research studies. Thereafter, the non-relevant studies were removed. For that purpose, several main criteria were defined in order to demonstrate whether a material is relevant to this research work. The chosen studies met the following criteria:

- For the scientific publications, the number of citations must be at least four except if it is published in an ISI (Web of Science) journal or in a recent year;
- If there are many studies on the same strategy/subject, priority was given to those with more

complete parameters (e.g. considering EI, technical performance and cost);

- Review studies were prioritized relative to case studies;
- Finally, more recent studies were preferred to older publications;
- The focus is mostly on the studies that relate to concrete, followed by mortar and paste.

In some cases, the authors have use more than 3-4 references for a single path in order to stress that path has been studied by multiple scholars, and researchers must avoid duplicating paths. In other cases, only a few studies (e.g. 1-2 studies) have been used because the number of studies for that path is limited. The basic body of the literature comprised 2,044 studies. The journal papers have the lion share of the total number of cited studies (87%) and are distantly followed by conference papers (3%), book/book chapter (3%), scientific reports (2%), standards (2%), theses (2%) and others (1%) such as patents, software, international symposiums/seminars and web-sites (Figure 3a). The ''publication and accessed year'' of the references range from 1956 to 2020 and 91% of the studies were made in the 2000-2020 period (Figure 3b). Figure 4 shows the citations and publication year of the journal papers. Since there was a big gap between the citation of the studies (e.g. 16, 64, 256, 1024 and 4096 citations), the scale was depicted in a different manner (logarithmic scale). The results show that about 90% of the papers have at least four citations.

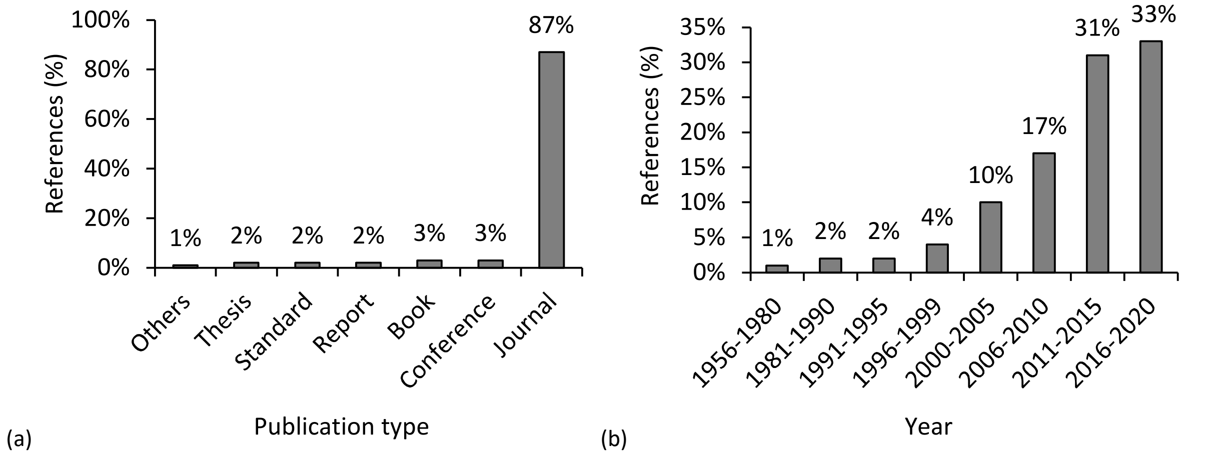


Figure 3 - Breakdown of cited references per publication (a) type and (b) year

Based on the citation number, the sections can be ordered as the following: sections 13, 12, 11, (6-10), 5, 4 and 3 (Figure 4). In general, section 13 (thermal conductivity improvement and energy saving) has received the most citations, followed by section 12 (CO_2 mineralization and utilization) and then section 11 (increase the durability of reinforced concrete) with a big scatter due to the wide scope of this section and many studies on this path (Figure 5). After that, sections 6, 7, 8, 9 and 10 followed and they have similar citation levels. Then came sections 5 (reduce the environmental impacts and resources use of aggregates) and 4 (reduce the environmental impacts and resources use of binders). Similarly to section 11, section 4 has a big scatter due to its wide scope many studies on this path (Figure 5). Finally, studies relating to section 3 (reduce the total amount of binder) had the least citations compared to other sections, probably due to the fact that studies on this path are not majorly promoted by the scientific community and concrete industry. According to Figure 5, about 73% of the studies relate to only sections 4-5 and 11. This means that most of the efforts have been made on only a few sustainability paths and the others have been disregarded and insufficiently developed.

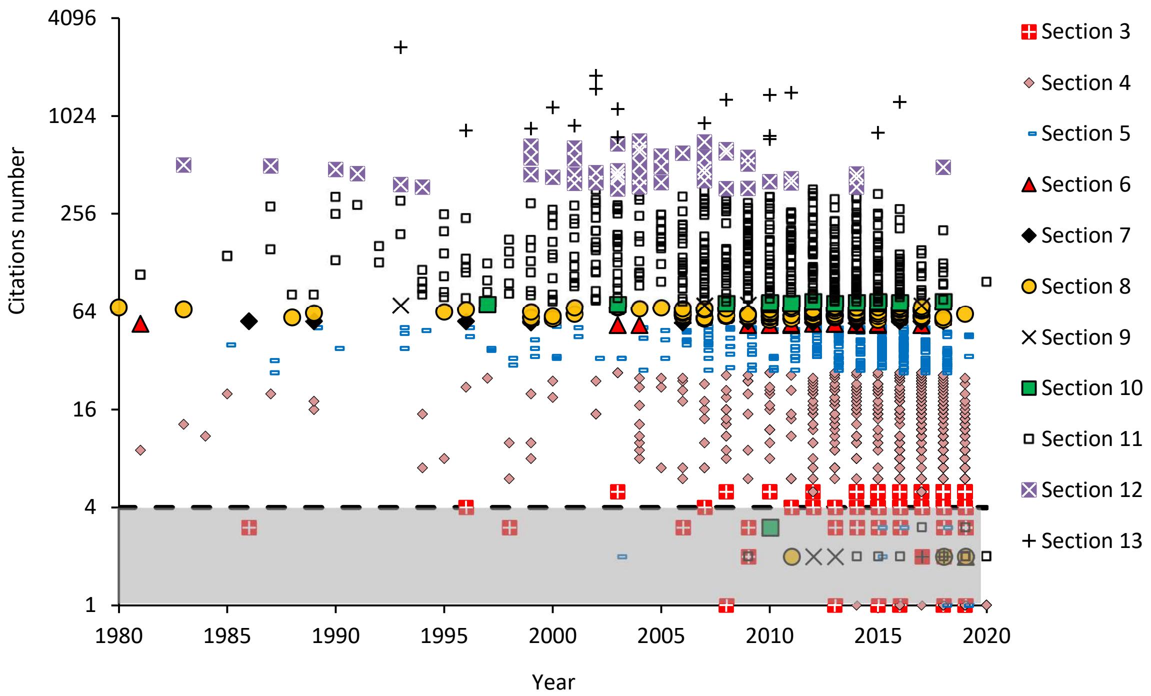


Figure 4 - Publication year *versus* citations

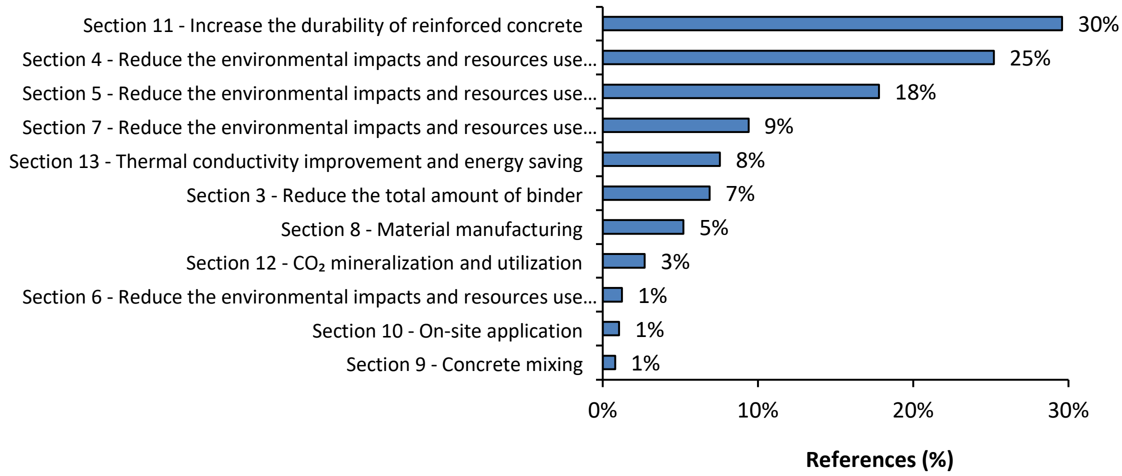


Figure 5 - Percentage of total cited papers per section

3 Reduce the total amount of binder

The essential goal of this strategy is to obtain environmental-friendly, durable and economically feasible concrete mixes using an unconventionally low binder content. According to EN 206-1 (EN 206-1, 2000), the minimum cement content in concrete must be equal to or higher than 260 kg/m^3 to achieve an adequate durability performance, depending on the exposure class. Another study (Damineli et al., 2010) collected the results of 1585 concrete mixes from different countries and concluded that it is possible to obtain a 20 MPa compressive strength concrete with the minimum cement content (260 kg/m^3). However, the literature shows no consensus on minimum binder content requirements relative to the durability performance of concrete (Bentur et al., 1997; Damineli et al., 2010). For example, a study (Dhir et al., 2004) concluded that, apart from the strength class and water/cement ratio, it may be unnecessary to impose a minimum cement content to reliably obtain an adequate durability performance, as specified by standards (EN 206-1, 2000). Other studies (Buenfeld and Okundi, 1998; Loo et al., 1994; Monteiro and Helene; Wasserman and Bentur, 2006) show that cement content can be reduced without jeopardizing the durability performance. To date, the literature on this strategy is very scarce (Carvalho, 2017; Damineli et al., 2010; Damineli et al., 2013; Dhir et al., 2004; Dinakar et al., 2007; Ergün, 2011; F. J. Wombacher and Sommer; Fennis-Huijben et al., 2012; Kapelko, 2006; Kato et al., 2019; Liu et al., 2012; López-Uceda et al., 2016; Mohamadreza et al.; Naik and Ramme, 1987; Park et al., 2012; Penttala and Komonen, 1996; Proske et al., 2013; Pusch et al., 2014; Su and Miao, 2003; T. de Grazia et al., 2019; Tagliaferri de Grazia et al., 2018; Tikkanen et al., 2014; Tikkanen et al., 2011; Topçu et al., 2009; Urban, 2018; Wassermann et al., 2009; Yousuf, 2018; Yousuf et al., 2019).

The following sub-strategies are suggested to reduce the amount of binder in concrete.

3.1 Pozzolanic or hydraulic powders

Generally, most supplementary cementitious materials (SCMs) (§4) can be used in concrete to reduce the binder content (by replacing a given amount of cement with SCMs) because they may significantly improve some durability properties, except for carbonation in most cases. By lowering carbonation resistance, the use of SCM is only recommended in concrete structures when not directly exposed to high CO_2 contents (e.g. foundation and underwater structures near chloride-enriched environments or watertight concrete - §11.2.3), with unconventional reinforcement rebars (§11.1), or when involving great masses to reduce the heat of hydration. Additionally, some attempts were made on low binder mortar. For example, Li et al. (Li, L.G. et al., 2019) showed that the cement content of mortar can be reduced by 33% with an increase in strength of 33% by using superplasticizer (SP) and ceramic polishing waste as addition (Li, L.G. et al., 2019). This path can also be followed in concrete (Cheng et al., 2014). Nonetheless, some studies (Ferrer et al., 2016; Kurda et al., 2019c; Kurda et al., 2019b; Vares and Penttala, 2007) show that, even when carbonation resistance is involved for XC3 and XC4 exposure classes, concrete with common cover depth can protect rebars for more than 50 years by using low or even high volume of SCMs.

3.2 Filler powders

The workability, stiffness and cohesiveness of concrete are significantly influenced by the volume of paste (Dhir et al., 2004; Ferraris and Gaidis; Wassermann et al., 2009). Thus, low binder may negatively affect the mentioned properties of concrete and indirectly influence other properties due to less-than-optimal compaction (e.g. in terms of strength and porosity). One way to overcome this issue is by using (chemically non-active) fillers, namely marble waste (Aliabdo et al., 2014; Ashish, 2019; Ergün, 2011; Khodabakhshian et al., 2018; Singh, M. et al., 2019; Topçu et al., 2009), limestone powder (Carvalho, 2017; John et al., 2018; Li, W. et al., 2015; Ling and Kwan, 2018; Urban, 2018), quartz (Damineli, 2013; Moosberg-Bustnes et al., 2004; Tikkanen, 2013; Vogt, 2010), dolomite (Barbhuiya, 2011; Mikhailova et al., 2013; Nguyen et al., 2018), granite (Ghannam et al., 2016; Ghorbani et al., 2019b; Ghorbani et al., 2018; Mashaly et al., 2018), cristobalite (Damineli, 2013; Vogt, 2010), nepheline syenite (Damineli, 2013; Lagerblad and Vogt, 2004; Vogt, 2010), wollastonite (Jahim, 2010; Kalla et al., 2015; Mathur et al., 2007; Vogt, 2010), iron (Ghannam et al., 2016), soil (Cong and Bing, 2015), and talc - hydrated magnesium silicate (Pusch et al., 2014; Woo and Ryu, 2006). However, studies on the effect of fillers in low binder concrete are very limited (Ergün, 2011; Pusch et al., 2014; Topçu et al., 2009) and mostly related to normal concrete with limestone filler (Carvalho, 2017; Scrivener et al., 2018; Urban, 2018) or self-compacting concrete (Topçu et al., 2009; Urban, 2018).

Filler powders will also work as nucleation site-acting (Moosberg-Bustnes et al., 2004) (Gutteridge and Dalziel, 1990; Lawrence et al., 2003; Soroka and Stern, 1976; Stumm, 1992). For example, Penttala and Komonen (Penttala and Komonen, 1996) obtained high mechanical (compressive and tensile) strength and durability performance (carbonation and capillary water absorption) concrete with a low binder amount (180 kg/m^3 cement and 13 kg/m^3 condensed silica fume -SF) and micro-filler (ground quartz). Another study of Tikkanen et al. (Tikkanen et al., 2014) showed that the strength of low binder concrete (cement type: CEM II/A-M(S-L)) can be increased by adding mineral powder (limestone and quartz). This study did not focus on durability. However, they showed that the $Ca(OH)_2$ (the main contributor to carbonation resistance) content of concrete mixes slightly decreases when mineral powder increases. This may happen because the filler, despite its crystallinity and considerably smaller resulting porosity, reacted in the alkaline medium and consumed $Ca(OH)_2$ to create C-S-H. The same author (Tikkanen et al., 2011) used the same type of cement and showed that, by using mineral powders (limestone and quartz), 75 kg/m^3 of cement can be removed without jeopardizing the compressive strength. However, according to this study, the fine powder content should not be higher than 550 kg/m^3 because of pumpability requirements. Other fillers, e.g. quartz (Moosberg-Bustnes et al., 2004), granite (Ghorbani et al., 2019b; Ghorbani et al., 2018; Mashaly et al., 2018) and earth concrete (Van Damme and Houben, 2018), can be also used to promote nucleation sites.

3.3 Water to binder ratio (w/b) and dispersants

Generally, lowering the binder content of concrete by using this sub-strategy can be considered the most promising solution in terms of sustainability, quality, and economy. Using the knowledge collected from different studies (Aïtcin, 2019; Aïtcin et al., 2016; Bache, 1981; Jensen and Hansen, 2001; Lura et al., 2003; Mehta and Monteiro, 2006; Wilson et al., 2017), Figure 6 was drawn, and the results show that the quality of cement paste essentially depends on the closeness of cement particles, rather than the binder content or volume, and rate of hydration. Figure 6 shows that the porosity (linked to free water) of cement paste with water to binder ratio (w/b) of 0.36 or lower is insignificant (almost non-porous materials) because all the water content will be consumed by the cement particles. Nevertheless, more studies must be made to confirm the previous assumption.

This can be concluded for concrete as well. Derived from the results of 140 concrete mixes, made with 140-260 kg/m^3 of cement, SCMs and different types of aggregates, sourced from 29 publications (Abbas et al., 2009; Barra and Vázquez, 1998; Berndt, 2009; Brand et al., 2015; Butler et al., 2011; Cong, 2006; Costabile, 2001; Dhir and Paine, 2007; Gonçalves et al., 2004; Gurdián et al., 2014; Huda, 2014; Jau et al., 2004; Khodair and Bommareddy, 2017; Kim et al., 2013; Kou et al., 2011; Kou and Poon, 2013; Kou et al., 2007; Kurad et al., 2017; Li, Y. et al., 2018; Lima, Carmine et al., 2013; Limbachiya et al., 2012; Marinković et al., 2017; Marinković et al., 2016; Otsuki et al., 2003; Poon and Kou, 2010; Radonjanin et al., 2013; Sadati et al., 2016; Somna et al., 2012; Tangchirapat et al., 2013; Zega and Maio, 2006), Figure 7 shows that concrete with acceptable compressive strength can be produced with unconventionally low binder content (grey background - Figure 7) when the w/b ratio is equal to or less than 0.40. This can also be seen for low and high binder content (white background - Figure 7) that complies with EN 206-1 (EN 206-1, 2000) standard (these are out of the scope of this section). Regarding the durability performance, by comparing the results of previous studies (Cartuxo, F., 2013; Fattuhi, 1986; Geng and Sun, 2013; Kurda et al., 2019b; Kurda et al., 2018c; Limbachiya et al., 2012; Lo et al., 2009; Pedro et al., 2018; Sim and Park, 2011; Singh, S. and Singh, N., 2016; Wassermann et al., 2009), it can be said that CO_2 and chloride diffusion of concrete exponentially decrease by lowering w/b to ≈ 0.36 (0.35-0.40) due to the smaller diameter of pores that may not be easily penetrated by CO_2 or any other agents. In other words, carbonation and chloride ion penetration resistances are likely to be excellent in concrete with the mentioned w/b value. However, further study needs to be performed to confirm this trend, especially when low binder content is used.

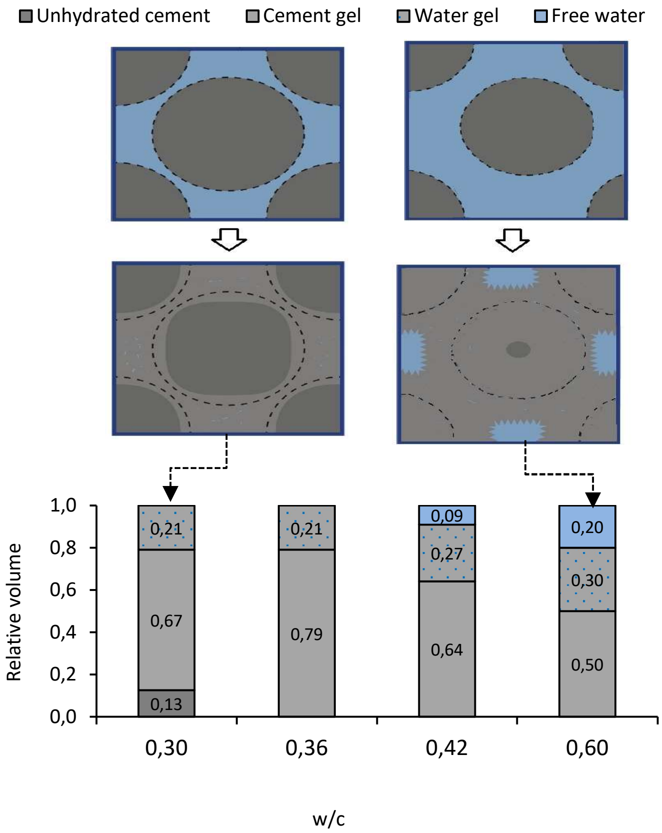


Figure 6 - Hydration of cement paste with different w/b (Cement gel - water chemically reacted with cement particles; Water gel - water physically linked with hydrated cement particles in a closed system although they have not reacted chemically yet and it significantly affects the rate of strength development; Free water - open porosity filled with water; further details on the mentioned expressions are shown in (Jensen and Hansen, 2001; Powers, 1968; Richardson, 2004))

However, the workability of these mixes needs to be such that the mixes are applicable on site. For that purpose, water-reducing admixtures, fillers (to maintain volume ratio of aggregate to fine powder - §3.2) and SCMs with spherical particles (e.g. FA) can be used. For example, some studies (Kapelko, 2006; López-Uceda et al., 2016) obtained a reliable mechanical strength of low binder concrete by using SP. With the chemical admixtures available on the market, it is possible to produce a workable concrete with w/b lower than 0.20 (Aïtcin, 2019). Additionally, the EI of most chemical admixtures used in concrete is very small (Braga et al., 2017; Kurda et al., 2018e), because of the small amounts used relative to the bulk of concrete mix. Although chemical admixtures increase the total cost of concrete, their cost can be offset by decreasing the cement content (Kurda, 2017). However, further study is needed to find the optimum cement content by using chemical admixtures without affecting the total cost and performance of concrete. Furthermore, for most concrete characteristics, the performance of SP in concrete with blended cement is higher than that of the concrete with Portland cement (Kurda et al., 2018a; Kurda et al., 2018c).

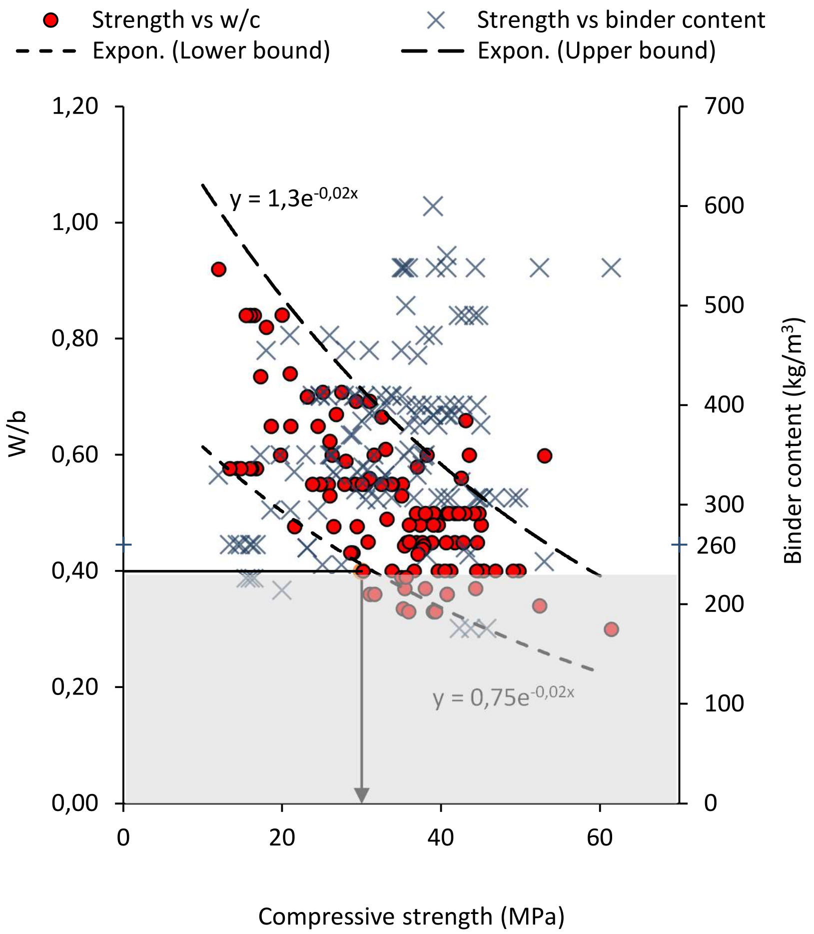


Figure 7 - Effect of w/b and binder content on compressive strength of concrete regardless of the type of aggregates and binder (cement content = 140-260 kg/m^3; No. of studies = 29; Workability S2-S3; Confidence interval of boundary lines = 95%; white background - concrete mixes that comply with the binder content suggested by standard EN 206-1; grey background - concrete mixes with less binder content than suggested by that standard)

Aïtcin et al. (Aïtcin, 2019) showed that filler (non-reactive particles) will be fully encapsulated in a low w/b mix because the distance between cement particles is small. Thus, indirectly, the filler particles will significantly contribute to the compressive strength of cement paste (Aïtcin et al., 2016), and therefore the cement content can be lowered. Thus, it can be said that, in regard to cement paste containing a filler, decreasing w/b can be more effective than modifying the physical and chemical characteristics of cement.

Finally, according to the above discussion, low binder concrete with reliable technical performance, EI and cost can be produced by lowering w/b to 0.40 (Figure 7), using SP, fillers and SCMs with spherical particles, simultaneously. However, concrete with lower w/b must be even more carefully water-cured. Otherwise, the uncontrolled development of autogenous and plastic shrinkage causes serious early cracking that may compromise the durability performance of concrete structures.

3.4 Indirect reduction of the binder amount

In this sub-strategy, the binder content is decreased but none of the concrete's technical characteristics is jeopardized. In other words, the following solutions may not have been used in low binder content so far, but they are presented in this section as a clue to produce it: nanomaterials (§11.2.2.1), binary-quaternary mixes (§4.4), stainless rebars (§11.1.1), barriers against the penetration of aggressive agents (§11.2). The reasoning is, since they can improve the concrete's characteristics, they can be also used to offset the consequences of reducing the amount of cement.

Several studies (Carvalho, 2017; Fennis-Huijben et al., 2012; Liu et al., 2012; Yousuf, 2018; Yousuf et al., 2019) show that low binder concrete with acceptable technical characteristics can be produced by considering particle packing models (e.g. Faury and Alfred mix design models). For example, Carvalho (Carvalho, 2017) concluded that the durability and strength of concrete with 175 kg/m^3 of cement designed by the particle packing models can be higher than concrete mixes designed with traditional approaches using 250 kg/m^3 cement content.

By considering all the above sub-strategies (section 3.1-3.4), low binder concrete may have low technical performance. As stated before, the best way to solve this issue is by lowering w/b (§3.2). However, this strategy may not work by itself. Thus, it is urgent to develop a new cement type for normal-strength concrete that in general has better compatibility with most chemical admixtures, lower water-demands, early strength-gain, lower heat-evolution compared with Ordinary Portland cement (OPC), thus allowing a reduction of the binder content for the same final characteristics of concrete. As suggested by other studies (Aïtcin, 2019; Chitvoranund et al., 2016; Gartner and Sui, 2018; Hanein et al., 2017; Londono-Zuluaga et al., 2017; Montes et al., 2018; Naqi and Jang, 2019; Shi, C. et al., 2019; Sui et al., 2015; Sui et al., 2006; Sui et al., 1999; Zea-Garcia et al., 2019), the ye'elimite-rich cement techniques (§4.5) can be considered a preliminary solution for the mentioned issues because the rheological problem (major issue (Aïtcin, 2019)) of low binder concrete can be controlled.

4 Reduce the environmental impacts and resources use of binders

Cement is the main contributor to energy consumption and greenhouse gas emissions in concrete (Kurda et al., 2018b; Marinković et al., 2008). One strategy to decrease concrete's EI is by replacing its cement with co-products and by-products (without reducing the overall binder content). In this strategy, most of the researchers are focused on the effect of SCMs on the technical performance of concrete. Apart from industrial waste ashes (§4.2), LCA studies on other sub-strategies (§4.1 and §4.3-4.6) are very few. Most studies presume that the EI of concrete decreases by decreasing its cement content, by incorporating SCMs. However, this assumption may not be correct when the service life of concrete is considered (examples regarding this matter are shown in the first paragraph of section 11). Therefore, it is preferable to study simultaneously the technical performance (e.g. mechanical and durability characteristics), EI/resources use (GWP, energy consumption, abiotic depletion potential (ADP), eutrophication potential (EP), acidification potential (AP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), renewable primary energy resources (PE-Re), etc.), economy and toxicity of concrete. Then, it is possible to classify each product from a sustainability point of view. In addition, the production process of some non-conventional materials involves several steps, such as recovery, transportation and treatment that potentially present considerable EI. Thus, all steps involved in concrete production from cradle to grave need to be considered.

4.1 Agricultural wastes and aquaculture farming as SCM

Generally, most of the agricultural wastes and aquaculture farming (AWAF) are burned as renewable and sustainable energy resources, and they have remarkable potential as low-cost binders to be used as SCMs in concrete. Contrary to industrial wastes (§4.2), LCA studies on concrete containing AWAF ashes (AWAFA) as SCM are very limited. Regarding the technical performance, there is a consensus (most references cited in §4.1) that the workability and drying shrinkage of concrete decrease with increasing AWAFA content, and the opposite occurs for setting time. However, as shown in the following sub-sections (§4.1.1-4.1.10), other technical properties' prevailing trends depend on the incorporation ratio and type of AWAFA. In addition, studies on the effect of AWAFA on the carbonation performance of concrete are very limited.

Figure 8 presents the chemical composition of different types of AWAF such as rice husk ash (RHA - (Fuad et al., 1993; Gursel et al., 2016; Khan et al., 2012; Massazza, 1998; Moayedi et al., 2019; Nguyen, 2011; Ramezanianpour, 2014)), corn cob ash (CCA - (Adesanya, 1996; Adesanya and Raheem, 2009b; Suwanmaneechot et al., 2015)), sugarcane bagasse ash (SBA - (Chusilp et al., 2009; Frias et al., 2007; Frías et al., 2011; Payá et al., 2002; Rukzon and Chindaprasirt, 2012; Somna et al., 2012)), wheat straw ash (WSA - (Biricik et al., 1999; Khushnood et al., 2014; Memon et al., 2018; Zhang, Q. et al., 2019)), leaf ash (Ademola and Buari, 2014; Dhinakaran and Gangava, 2016; Dwivedi et al., 2006; Frías et al., 2012; Singh et al., 2007; Umoh and Odesola, 2015), palm oil fuel ash (POFA - (Al-mulali et al., 2015; Aprianti S, 2017; Awang et al., 2014; Tangchirapat et al., 2009; Tangchirapat et al., 2007)), forest biomass bottom ash (FBBA - (Garcia and Sousa-Coutinho, 2013; Rajamma et al., 2009)), wood fly ash (WFA - (Berra et al., 2015; Miles et al., 1995;

Rajamma et al., 2012; Saraber and Haasnoot, 2012)), olive waste ash (OWA - (Al-Akhras and Abdulwahid, 2010; Al-Akhras et al., 2009; Cuenca et al., 2013; Vassilev et al., 2010)), tobacco waste ash (TWA - (Celikten and Canbaz, 2017; Moreno et al., 2018)), elephant grass ash (EGA - (Cordeiro and Sales, 2015; Roselló et al., 2015)) and mussel shell ash (MSA - (Lertwattanaruk et al., 2012; Olutoge et al., 2012; Zhong et al., 2012)), sourced from 48 publications. The results show that there is a wide range in terms of the chemical composition of most AWAF ashes. Thus, the performance of concrete containing the same type of AWAF ashes may differ because their characteristics dramatically change according to the combustion technique and genetic types (e.g. white and black rise husks) of the AWAF (Fuad et al., 1993; Garcia and Sousa-Coutinho, 2013). In other words, each region has different species of animals (e.g. oyster shell) and plants that have unique chemical compositions. According to the literature, AWAF ashes can be used as an active binder when they are incinerated at about 1000 °C, because at this temperature the quantity of amorphous particles increases (Etiegni and Campbell, 1991; Garcia and Sousa-Coutinho, 2013). However, further studies need to be done to confirm the quality of the AWAF ashes in terms of the burning technique.

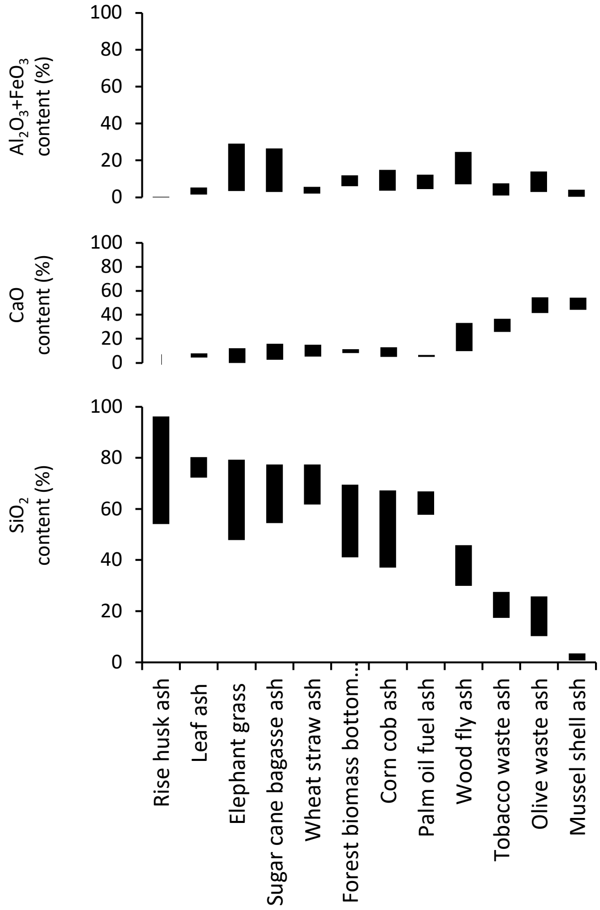


Figure 8 - Chemical characteristics of rise husk ash, corn cob ash, sugar cane bagasse ash, wheat straw ash, leaf ash, palm oil fuel ash, forest biomass bottom ash, wood fly ash, olive waste ash, tobacco waste ash, elephant grass and mussel shell ash (Ademola and Buari, 2014; Adesanya, 1996; Adesanya and Raheem, 2009b; Al-Akhras and Abdulwahid, 2010; Al-Akhras et al., 2009; Al-mulali et al.,

2015; Aprianti S, 2017; Awang et al., 2014; Berra et al., 2015; Biricik et al., 1999; Celikten and Canbaz, 2017; Chusilp et al., 2009; Cordeiro and Sales, 2015; Cuenca et al., 2013; Dhinakaran and Gangava, 2016; Dwivedi et al., 2006; Frías et al., 2012; Frias et al., 2007; Frías et al., 2011; Fuad et al., 1993; Garcia and Sousa-Coutinho, 2013; Gursel et al., 2016; Khan et al., 2012; Khushnood et al., 2014; Massazza, 1998; Memon et al., 2018; Miles et al., 1995; Moayedi et al., 2019; Moreno et al., 2018; Nguyen, 2011; Payá et al., 2002; Rajamma et al., 2009; Rajamma et al., 2012; Ramezanianpour, 2014; Roselló et al., 2015; Rukzon and Chindaprasirt, 2012; Saraber and Haasnoot, 2012; Singh et al., 2007; Somna et al., 2012; Suwanmaneechot et al., 2015; Tangchirapat et al., 2009; Tangchirapat et al., 2007; Umoh and Odesola, 2015; Vassilev et al., 2010; Zhang, Q. et al., 2019)

4.1.1 Rice husk ash

Relatively to other AWAFA, RHA is the most common material studied in the literature. Well burned rice husk (RH) may contain a high amount of amorphous silica. However, its quantity significantly depends on the type of RH, i.e. black or white (Fuad et al., 1993). Apart from workability (Khan et al., 2012), most of the concrete technical performances, i.e. strength (Fuad et al., 1993; Gursel et al., 2016; Nguyen, 2011), carbonation (Gastaldini et al., 2007), shrinkage (Nguyen, 2011), porosity (Nguyen, 2011; Saraswathy and Song, 2007a), water absorption (Saraswathy and Song, 2007a) and chloride ion penetration (Gursel et al., 2016), improve or remain similar to those of conventional concrete when cement is replaced with up to 20% of RHA (Fuad et al., 1993; Gursel et al., 2016; Khan et al., 2012; Massazza, 1998; Moayedi et al., 2019; Nguyen, 2011; Ramezanianpour, 2014).

4.1.2 Palm oil fuel ash

After RHA, POFA is the second most studied AWAF. The literature suggests that POFA can be used in high-strength concrete due to its high ratio of ultrafine particles (Alani et al., 2019; Aldahdooh et al., 2013; Awal and Shehu, 2013; Bamaga et al., 2013; Javed et al., 2018; Tangchirapat et al., 2009). Generally, it is suggested that POFA can be effectively used as SCM to replace up to 20% of cement in concrete (Al-mulali et al., 2015; Bamaga et al., 2013; Sata et al., 2007; Tangchirapat et al., 2009).

4.1.3 Corn cob ash

According to the literature, the optimum incorporation ratio of CCA depends on the type of CBM (e.g. paste and concrete). Although some studies (Adesanya and Raheem, 2009a, 2010; Suwanmaneechot et al., 2015) have been concluded that the paste containing up to 15% of CCA complies with NIS 439:2000, ASTM C 150:1994 and BS 12:1991 requirements (Adesanya and Raheem, 2009a, 2010; Suwanmaneechot et al., 2015), there is a consensus in the literature that cement of concrete should not be replaced with more than 10% of CCA (Adesanya, 1996; Adesanya and Raheem, 2009b; Mujedu et al., 2014; Olafusi and Olutoge, 2012).

4.1.4 Sugarcane bagasse ash

Different replacement levels (5-25%) are given by the literature as optimum values to substitute cement with SBA in concrete (Ganesan et al., 2007; Hailu and Dinku, 2012; Katare and Madurwar, 2017; Lin et al., 2012; Mangi, S.A. et al., 2017; Montakarntiwong et al., 2013). Cordeiro et al. (Cordeiro et al., 2009) concluded that SBA must be burned at least at 600 ^{o}C for 3 hours to obtain amorphous and low carbon content precursor. Nevertheless, this temperature may not be enough to degrade the entire carbon-containing phases. The optimum incorporation ratio of SBA depends on the target properties of concrete, i.e. 10% (Rukzon and Chindaprasirt, 2012), 15% (Ganesan et al., 2007), 20% (Singh et al., 2000), 5-20% (Hailu and Dinku, 2012; Lin et al., 2012; Srinivasan and Sathiya, 2010), 25-30% (Ganesan et al., 2007; Rukzon and Chindaprasirt, 2012) and 25% (Ganesan et al., 2007) to obtain improvements in water absorption, sorptivity, strength, chloride penetration, chloride penetration and soundness, respectively.

4.1.5 Straw ash

Studies on the effect of straw ash as a partial substitute for cement in concrete are very limited and mostly related to WSA. This is maybe related to the fact that the results are not promising relatively to other AWAF (Aksoğan et al., 2016; Al-Akhras, 2011; Zhang, Q. et al., 2019). However, it is mostly used for other applications (Al-Akhras, N. M. et al., 2008; Ataie and Riding, 2013; Biricik et al., 1999; Khushnood et al., 2014; Memon et al., 2018). There are also a few studies on the effect of the use of rice straw ash (El-sayed et al., 2017) and rape-plant straw ash (Zhang et al., 2014) on the technical performance of concrete and mortars (Munshi and Sharma, 2016). Other straw ashes, made with barley (Risnes et al., 2003), corn (Masiá et al., 2007), and rape (Masiá et al., 2007) straws, have similar chemical compositions to WSA.

4.1.6 Leaf ashes

Amorphous and pozzolanic ash can be obtained by incinerating banana (Kanning, Rodrigo C. et al., 2014; Kanning et al., 2011) and bamboo (Dwivedi et al., 2006; Singh et al., 2007; Villar-Cociña et al., 2011) leaves. It was concluded that the activity of bamboo leaf ash (BLA) is greater than that of RHA and SBA (Frías et al., 2012). The results show that cement can be replaced with up to 15% (Dhinakaran and Gangava, 2016) and 20% (Goyal and Tiwari, 2016; Kanning, Rodrigo C. et al., 2014) of each BLA and banana leaf ash, respectively, for a compromise between the durability and strength performances. Nevertheless, a study produced low binder content concrete with a high w/b ratio and showed that the strength decreases with increasing BLA content (Asha et al., 2014). Apart from the mentioned ashes, there are other leaf ashes, used only in pastes and mortars (Ademola and Buari, 2014; Umoh and

Odesola, 2015).

4.1.7 Forest biomass bottom ashes

Forests must be isolated and divided in several zones to prevent uncontrollable fires. Normally, the isolated zones must be cleaned of all the grass, wood, straw, leaves, etc. For sustainability reasons, these forest residues can be used to obtain renewable energy and use their ash for construction purposes. Accordingly, these ashes may have significant ranges in terms of chemical and physical properties, depending on the source of biomass. Previous studies (Farinha et al., 2019; Garcia and Sousa-Coutinho, 2013) showed that strength may slightly improve with the incorporation of 10-15% FBBA as cement substitution, especially after 90 days. Several studies on the effect of forest residues ashes on mortar have been made (Coelho, 2010; Farinha et al., 2019; Garcia and Sousa-Coutinho, 2013; Rajamma et al., 2009). However, this path has not been followed for concrete.

4.1.8 Wood ashes

Although wastes from forests (section 4.1.7) contain a variety (contaminated) of materials, quite often their characteristics may not be that different from those of wood ashes. A couple of studies (Sigvardsen, Nina M. et al., 2019; Teixeira et al., 2019) showed that the majority of wood ashes (WA) have lower SIO_2+Al_2O+Fe_2O_3 and higher CaO content than those of coal ashes. This helps concrete to develop more C-S-H. However, the amount of loss on ignition (LOI) in WA is significantly higher than that of the coal ashes, which negatively affects the performance of concrete. Most of the studies show that the mechanical performance of concrete decreased with increasing incorporation ratio of WA (Abdullahi, 2006; Chowdhury et al., 2015; Kara et al., 2012; Udoeyo et al., 2006). In terms of durability, namely chloride ion penetration, there is no consensus in the literature, but some studies showed that it may increase durability by being incorporated with other SCM (Teixeira et al., 2019). WA is also harmful in terms of carbonation (Teixeira et al., 2019) and water absorption (Udoeyo et al., 2006), but it may decrease the carbonation rate with FA because of the synergetic behaviour of the two materials (Teixeira, 2019). In addition, despite several attempts (Abdullahi, 2006; Chowdhury et al., 2015; Kara et al., 2012; Mangi, S. et al., 2017; Siddique, 2012b; Teixeira et al., 2019; Udoeyo and Dashibil, 2002; Udoeyo et al., 2006) to understand the effect of WA on concrete, Magi et al. (Mangi, S. et al., 2017) stated that there is no detailed study on the effect of WA on high-strength concrete. Furthermore, attempts to treat WA before using it as SBM are very limited (Sigvardsen, Nina Marie et al., 2019).

The bark ashes of most trees (balsam (Bryers, 1996), beech (Bryers, 1996), pine (Theis et al., 2006), birch (Bryers, 1996), elm (Bryers, 1996), eucalyptus (Theis et al., 2006), hemlock (Bryers, 1996), maple

(Bryers, 1996), poplar (Bryers, 1996), spruce (Bryers, 1996), and tamarack (Bryers, 1996)) contain a significant amount of CaO (43-68%) that is very close to that of ordinary Portland cement. However, studies on their effect on concrete have not been made. For example, although the amount of CaO in cement and the mentioned materials may be the same, it does not necessarily have the same potential in terms of reactivity. In fact, their potential depends on the ratio of amorphous particles.

4.1.9 Other agriculture-farming wastes

There are also few attempts to use other farming wastes ashes such as those from the olive (Al-Akhras et al., 2009; Cuenca et al., 2013; Eisa, 2014), tobacco (Moreno et al., 2018), elephant grass (Cordeiro and Sales, 2015), banana (Kanning, Rodrigo C et al., 2014), sisal (Wei and Meyer, 2014) and ripe plantain peels (Ahmad and Ma'aruf, 2016) sectors as SCMs in concrete. According to the mentioned studies, the performance of farming waste ashes depends on their exposure to heat that directly affects the amount of amorphous particles.

4.1.10 Shell wastes

Most of the shells are used as partial replacement of natural aggregates in concrete (§5.2). However, some attempts have been made to show the effect of oyster shell ash as partial replacement of cement on the technical performance of mortar (Lertwattanaruk et al., 2012; Zhong et al., 2012), as well as that of mussel shell ash (Lertwattanaruk et al., 2012; Zhong et al., 2012), periwinkle shell ash (Dahunsi and Bamisaye, 2002; Umoh and Olusola, 2013), cockle shell ash (Othman et al., 2013) and eggshell (Tan et al., 2018) on cement pastes, mortars and concrete. According to the mentioned studies, the shell ashes generally decrease strength, drying shrinkage and thermal conductivity, increase setting time, and improve resistance to magnesium-sulphate attack.

4.2 Industrial wastes as SCM

Contrary to AWAF, there are many studies on the effect of industrial waste ashes as substitutes of cement on the cost, EI and quality of concrete. However, further study on the majority of these materials is still needed due to their discrepant chemical composition. Using the ternary phase diagram, Figure 9 is drawn, presenting the chemical composition of different types of binders, sourced from 81 publications (Ademola and Buari, 2014; Adesanya, 1996; Adesanya and Raheem, 2009b; Aïtcin, 2016; Al-Akhras and Abdulwahid, 2010; Al-Akhras et al., 2009; Al-mulali et al., 2015; Alemayehu and Lennartz, 2009; Andrade, L. et al., 2009; Aprianti S, 2017; Awang et al., 2014; Ayano and Sakata, 2000; Berra et al., 2015; Biricik et al., 1999; Brännvall and Kumpiene, 2016; Burduhos Nergis et al., 2018;

Celik et al., 2014; Chen et al., 2013; Chusilp et al., 2009; Cordeiro and Sales, 2015; Cuenca et al., 2013; Dai et al., 2014; De Belie et al., 2018; Dhinakaran and Gangava, 2016; Dhir et al., 2017; Djon Li Ndjock et al., 2017; Du and Pang, 2018; Dwivedi et al., 2006; Frías et al., 2012; Frias et al., 2007; Frías et al., 2011; Fuad et al., 1993; Garcia-Lodeiro et al., 2011; Garcia and Sousa-Coutinho, 2013; Gursel et al., 2016; Hwang and Laiw, 1989; Imris et al., 2000; Jamaluddin et al., 2016; Kaid et al., 2009; Kasemchaisiri and Tangtermsirikul, 2008; Khan et al., 2012; Khushnood et al., 2014; Kıyak et al., 1999; Lemougna et al., 2014; Marghussian and Maghsoodipoor, 1999; Massazza, 1998; Memon et al., 2018; Milagre Martins et al., 2010; Miles et al., 1995; Mineral and Technology, 1989; Moayedi et al., 2019; Mobasher et al., 1996; Moura et al., 1999; Newlands and Macphee, 2017; Nguyen, 2011; Park et al., 2009; Payá et al., 2002; Rafieizonooz et al., 2016; Rajamma et al., 2009; Rajamma et al., 2012; Ramezanianpour, 2014; Romano et al., 2018; Roper et al., 1983; Roselló et al., 2015; Rossen, 2014; Rukzon and Chindaprasirt, 2012; Sanchez de Rojas et al., 2004; Sanjith et al., 2015; Saraber and Haasnoot, 2012; Siddique, 2013; Singh et al., 2007; Snellings et al., 2012; Somna et al., 2012; Suwanmaneechot et al., 2015; Tangchirapat et al., 2009; Tangchirapat et al., 2007; Umoh and Odesola, 2015; Vassilev et al., 2010; Zain et al., 2004; Zhang, Q. et al., 2019; Zheng et al., 2009). The results show that the chemical composition of industrials wastes relatively to AWA (§4.1) are more discrepant and significantly depends on the type and source of the materials. It is important to mention that the data given in Figure 9, namely the amount of CaO, Al_2O_3 and SiO_2 given for each material (e.g. CFA and GGBS), cannot be directly compared with the same amount in cement because the amount of amorphous particles in these materials is different from that in cement.

4.2.1 Coal fly ash

According to the American (ASTM C618-02, 2005) and Canadian (CSA-A23, 1982) standards, which are comparable to European standard (EN 450-1, 2012), FA is classified as high (type C) and low (type F) CaO content. Relatively to other industrials wastes, type F coal FA is the most common material used in the literature regarding technical performance (Gonzalez-Corominas et al., 2016; Gopalan, 1996; Güneyisi et al., 2015; Huang et al., 2013a; Jalal et al., 2015; Jiang and Malhotra, 2000; Karaşin and Doğruyol, 2014; Khatib, 2008; Khunthongkeaw et al., 2006; Kim et al., 2013; Kou and Poon, 2013; Kou et al., 2007; Kumar et al., 2007; Kurda et al., 2017a; Kurda et al., 2019b; Lammertijn and Belie, 2008; Leung et al., 2016; Lima, Carmine et al., 2013; Limbachiya et al., 2012; M., 2002; Malhotra, 1993; Mardani-Aghabaglou et al., 2013; Marinković et al., 2016; Marthong and Agrawal, 2012; Michael, 2007; Misra et al., 2007a; Misra et al., 2007b; Mittal et al., 2004; Naik et al., 2002; Nath and Sarker, 2011; O'Brien et al., 2009; Pacheco Torgal et al., 2011; Poon and Kou, 2010; Rashad, 2015a, 2015b; Ruixia, 2010; Şahmaran et al., 2008; Saravanakumar and Dhinakaran, 2013; Shaikh and Supit, 2015; Siddique, 2004a; Simčič et al., 2015; Singh,

N. et al., 2019; Somna et al., 2012; Surya et al., 2015; Tangchirapat et al., 2013; Thomas and Bamforth, 1999; Tian et al., 2011; Wang et al., 2017b; Wu and Xu, 2011; Xie et al., 2019; Yoo et al., 2015; Yoon et al., 2014; Yoshitake et al., 2014; Younsi et al., 2011; Zhao et al., 2015a), LCA (DTI, 2013; Göswein et al., 2018; Kurda et al., 2020; Kurda et al., 2018e; Kurda et al., 2018c; O'Brien et al., 2009; Page et al., 1979; Tait and Cheung, 2016; Teixeira et al., 2016; Wu and Xu, 2011), cost (Braga et al., 2017; Camões et al., 2003; Kurda et al., 2018b), and toxicity (Egemen and Yurteri, 1996; Kadir et al., 2015; Kurda et al., 2018b; Palumbo et al., 2005; Regennitter, 2007; Sočo and Kalembkiewicz, 2007; Tripathi et al., 2004; Tsiridis et al., 2006; Ye et al., 2007; Zhu, 2011). Nevertheless, studies on the service life and toxicity of concrete containing a high volume of FA are still very limited. According to most of the previous studies (Gonzalez-Corominas et al., 2016; Gopalan, 1996; Güneyisi et al., 2015; Huang et al., 2013a; Jalal et al., 2015; Jiang and Malhotra, 2000; Karaşin and Doğruyol, 2014; Khatib, 2008; Khunthongkeaw et al., 2006; Kim et al., 2013; Kou and Poon, 2013; Kou et al., 2007; Kumar et al., 2007; Kurda et al., 2019b; Lammertijn and Belie, 2008; Leung et al., 2016; Lima, Carmine et al., 2013; Limbachiya et al., 2012; M., 2002; Malhotra, 1993; Mardani-Aghabaglou et al., 2013; Marinković et al., 2016; Marthong and Agrawal, 2012; Michael, 2007; Misra et al., 2007a; Misra et al., 2007b; Mittal et al., 2004; Naik et al., 2002; Nath and Sarker, 2011; O'Brien et al., 2009; Pacheco Torgal et al., 2011; Poon and Kou, 2010; Rashad, 2015a, 2015b; Ruixia, 2010; Şahmaran et al., 2008; Saravanakumar and Dhinakaran, 2013; Shaikh and Supit, 2015; Siddique, 2004a; Simčič et al., 2015; Singh, N. et al., 2019; Somna et al., 2012; Surya et al., 2015; Tangchirapat et al., 2013; Thomas and Bamforth, 1999; Tian et al., 2011; Wang et al., 2017b; Wu and Xu, 2011; Xie et al., 2019; Yoo et al., 2015; Yoon et al., 2014; Yoshitake et al., 2014; Younsi et al., 2011; Zhao et al., 2015a), the technical properties of concrete may worsen when a high volume of cement is replaced with FA type F. Some researchers overcame this issue by replacing a given amount of cement with FA and adding extra FA as an addition (Lima, Carmine et al., 2013; Naik and Ramme, 1987; Pepe, 2015).

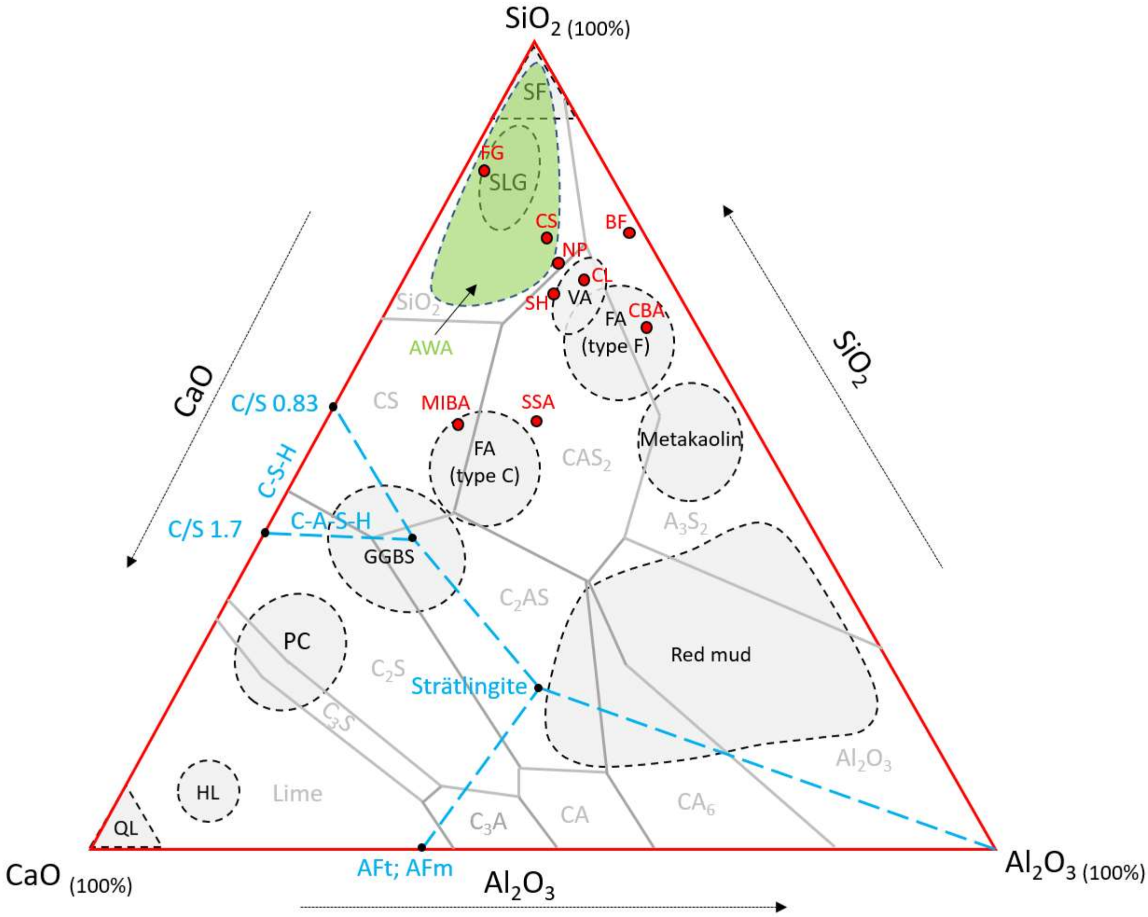


Figure 9 - CaO-SiO_2-Al_2O_3 ternary phase diagram of different binders. AWA = agricultural wastes (rise husk ash, corn cob ash, sugarcane bagasse ash, straw ash, palm oil fuel ash, forest biomass bottom ash, wood ash), BF = Brick feedstock, BF = brick feedstock, CBA = coal bottom ash, CL = clay, CS = copper slag, FA = coal fly ash, FG = flat glass, GGBS = ground granulated blast furnace slag, HL = hydraulic lime, MIBA = municipal solid waste incinerator bottom ash, NP = natural pozzolan, PC = Portland cement, QL = quick lime, SF = silica fume, SH = shale, SLG = soda lime glass. Texts with red and black colours are average value and range values, respectively. C = CaO, S = SiO_2, A = Al_2O_3 (grey texts). AFt = ettringite, AFm = monosulphate, C-S-H = Calcium-Silicate-Hydrate (blue texts). CS, C2S, C3S, and lime are reactive to CO_2. Data obtained from (Ademola and Buari, 2014; Adesanya, 1996; Adesanya and Raheem, 2009b; Aïtcin, 2016; Al-Akhras and Abdulwahid, 2010; Al-Akhras et al., 2009; Al-mulali et al., 2015; Alemayehu and Lennartz, 2009; Andrade, L. et al., 2009; Aprianti S, 2017; Awang et al., 2014; Ayano and Sakata, 2000; Berra et al., 2015; Biricik et al., 1999; Brännvall and Kumpiene, 2016; Burduhos Nergis et al., 2018; Celik et al., 2014; Chen et al., 2013; Chusilp et al., 2009; Cordeiro and Sales, 2015; Cuenca et al., 2013; Dai et al., 2014; De Belie et al., 2018; Dhinakaran and Gangava, 2016; Dhir et al., 2017; Djon Li Ndjock et al., 2017; Du and Pang, 2018; Dwivedi et al., 2006; Frías et al., 2012; Frias et al., 2007; Frías et al., 2011; Fuad et al., 1993; Garcia-Lodeiro et al., 2011; Garcia and Sousa-Coutinho, 2013; Gursel et al., 2016; Hwang and Laiw, 1989; Imris et al., 2000; Jamaluddin et al., 2016; Kaid et al., 2009; Kasemchaisiri and Tangtermsirikul, 2008; Khan et al., 2012; Khushnood et al., 2014; Kıyak et al., 1999; Lemougna et al., 2014; Marghussian and Maghsoodipoor, 1999; Massazza, 1998; Memon et al., 2018; Milagre Martins et al., 2010; Miles et al., 1995; Mineral and Technology, 1989; Moayedi et al., 2019; Mobasher et al., 1996; Moura et al., 1999; Newlands and Macphee, 2017; Nguyen, 2011; Park et al., 2009; Payá et al., 2002; Rafieizonooz et al., 2016; Rajamma et al., 2009; Rajamma et al., 2012; Ramezanianpour, 2014; Romano et al., 2018; Roper et al., 1983; Roselló et al., 2015; Rossen, 2014; Rukzon and Chindaprasirt, 2012; Sanchez de Rojas et al., 2004; Sanjith et al., 2015;

Saraber and Haasnoot, 2012; Siddique, 2013; Singh et al., 2007; Snellings et al., 2012; Somna et al., 2012; Suwanmaneechot et al., 2015; Tangchirapat et al., 2009; Tangchirapat et al., 2007; Umoh and Odesola, 2015; Vassilev et al., 2010; Zain et al., 2004; Zhang, Q. et al., 2019; Zheng et al., 2009)

4.2.2 Coal bottom ash

CBA is mainly recommended to be used in concrete as a partial replacement of sand because it has less active SiO_2 content compared to FA and its particles are porous, irregular and angular, and have a rough surface texture (Andrade, L.B. et al., 2009; Rafieizonooz et al., 2016; Ramzi et al., 2016; Singh and Siddique, 2013; Singh, Navdeep et al., 2018). However, some studies show that it can also work as a potential SCM after proper grinding (Mangi et al., 2019). Most of the previous studies are focused on the effect of CBA, as cement replacement, on concrete strength (Argiz et al., 2018; Chaipanich et al., 2014; Jaturapitakkul and Cheerarot, 2003; Khan and Ganesh, 2016; Kurama and Kaya, 2008; Marto et al., 2010; Pyo and Kim, 2017; Rafieizonooz et al., 2016; Wongkeo et al., 2012), and a few studies focused on durability (Argiz et al., 2018; Khongpermgoson et al., 2019; Singh, 2018), toxicity (Kadir et al., 2015), EI (Bumanis et al., 2013; Hafez et al., 2019b; Hafez et al., 2019a; Rathnayake et al., 2018) and cost (Bumanis et al., 2013). Based on the mechanical strength, CBA is recommended to be used at up to 10% of cement's weight (Argiz et al., 2018; Khan and Ganesh, 2016; Kurama and Kaya, 2008).

4.2.3 Industrial slags

Industrial slags are another by-product remaining after an intended metal smelts from its raw ore. To produce more sustainable concrete, cement has been substituted with ground granulated blast furnace slag, i.e. lead slag (Penpolcharoen, 2005), copper slag (Gursel and Ostertag, 2019; Prem et al., 2018; Shi et al., 2008), nickel slag (Papadakis et al., 2002), and iron slags (Jiang et al., 2018; Yi et al., 2012). Due to their high density, reactivity and/or pozzolanicity, most of the mentioned slags were recommended to be used as aggregates for radiation shielding concrete (Hafez et al., 2019; Ismail et al., 2008; Lee, H.-S. et al., 2016; Picha et al., 2015). However, due to their chemical composition (Figure 9), ground granulated blast furnace slag (a by-product of iron and steel-making) is also studied as SCM in terms of quality (Özbay et al., 2016; Saleh Ahari et al., 2015; Song and Saraswathy, 2006b) and EI (Heard et al., 2012; Jamshidi et al., 2015; Tait and Cheung, 2016). However, this solution significantly increases the dead loads of the concrete structure.

4.2.4 Silica fume (SF)

SF has been successfully used for many applications (Çakır and Sofyanlı, 2015; Choi et al., 2016; Cwirzen et al., 2008a; Jalal et al., 2015; Mastali and Dalvand, 2016; Papa et al., 2016; Sadrmomtazi et al., 2012; Saleh Ahari et al., 2015; Saraya, 2014; Tamimi et al., 2016), and it may act as a healing agent, filler and SCM in concrete (Abd Elhakam et al., 2012; Dilbas et al., 2014; Gesoğlu et al., 2009; González-Fonteboa et al., 2009; Jalal et al., 2015; Leung et al., 2016; Malhotra, 1993; Pedro et al., 2017a, 2017b; Pedro et al., 2018; Rashad, 2015b). SF significantly increases strength, pozzolanic activity (Papa et al., 2016; Saraya, 2014; Tamimi et al., 2016), durability and impact resistance (Çakır and Sofyanlı, 2015; Choi et al., 2016; Jalal et al., 2015; Mastali and Dalvand, 2016; Zhang, Zengqi et al., 2016) of concrete due to its multi-range macro-particles and chemical composition. Existing standards such as European standard (EN 197-1, 2000) already have the recommended amount of silica fume that cement may have when using conventional materials (e.g. natural aggregate). Regarding non-conventional materials such as recycled aggregate and steel fibres, 10%-14% of SF considered as an optimum (Çakır and Sofyanlı, 2015; Jalal et al., 2015; Mastali and Dalvand, 2016). Nevertheless, SF may decrease workability (Khatri et al., 1995) and long-term compressive strength (De Larrard and Bostvironnois, 1991) and it is not easily dispersed in concrete. In addition, SF may not be effective in terms of creep (Buil and Acker, 1985) and corrosion resistance in marine environment (Sandberg, 1998).

4.2.5 Other artificial pozzolans

Artificial pozzolans can be classified as industrial by-products (most of SCM in §4.1-4.3) and burned materials, namely (i) calcined clays (Al-Rezaiqi et al., 2018; Asadollahfardi et al., 2019; Saboo et al., 2019; Saleh Ahari et al., 2015; Schulze and Rickert, 2019; Shafiq et al., 2015; Shi, Z. et al., 2019; Sujjavanich et al., 2017; Vu et al., 2001), (ii) ceramic residues (Andreola et al., 2010; Cheng et al., 2014; El-Dieb and Kanaan, 2018; Kannan et al., 2017; Li, L.G. et al., 2019; Pacheco-Torgal and Jalali, 2010), (iii) sedimentary rocks containing clay minerals (Seraj et al., 2015; Vejmelková et al., 2018; Yılmaz and Ediz, 2008) and (iv) burned bauxites (Liu and Poon, 2016; Rathod et al., 2013).

Natural calcined clay such as kaolinite (Fernandez et al., 2011; Schulze and Rickert, 2019; Simone and Jorg), montmorillonite (Fernandez et al., 2011; Simone and Jorg), and muscovite/illite (Fernandez et al., 2011; Simone and Jorg) can be used as SCM (Schulze and Rickert, 2019). However, the most common one is metakaolin (Asadollahfardi et al., 2019; Saboo et al., 2019; Saleh Ahari et al., 2015; Shafiq et al., 2015; Sujjavanich et al., 2017; Vu et al., 2001), which is derived from calcined kaolin clay. Their performance significantly depends on the calcined temperature (600-850 °C for 1-12 h) (Rashad, 2013b). The use of metakaolin in the construction sector is still far behind that of the other SCMs because of its price (3-4 times higher price than that of cement (Vejmelková et al., 2018)).

Ceramic residues (Andreola et al., 2010; Li, L.G. et al., 2019; Pacheco-Torgal and Jalali, 2010) or ceramic polishing waste (Cheng et al., 2014; El-Dieb and Kanaan, 2018; Kannan et al., 2017) are other active pozzolans and they are considered as the illite group (Vejmelková et al., 2018), used for the production of red-ceramics. After milling, they can be used as a partial replacement of cement (Andreola et al., 2010; Cheng et al., 2014; El-Dieb and Kanaan, 2018; Kannan et al., 2017; Li, L.G. et al., 2019; Pacheco-Torgal and Jalali, 2010). However, studies in this path are still very limited and the ceramic residues powder is not widely available (Vejmelková et al., 2018).

Sedimentary rocks contain clay minerals, also termed calcined shale (Seddik Meddah, 2015; Seraj et al., 2015; Taylor-Lange et al., 2014) and claystone (Vejmelková et al., 2018). Although they may be an alternative solution to the other two artificial pozzolans (Vejmelková et al., 2018), due to their lower price and availability, studies on these materials are still very scarce.

In the aluminium industry, sedimentary rock (bauxite) with a relatively high Al content is burned. As a result, a significant amount of hazardous waste (red mud) is generated (this can also be included in §4.2.3). This bauxite residue is considered as an effective SCM to be used as partial replacement of cement in concrete (Liu and Poon, 2016; Rathod et al., 2013).

4.2.6 Natural pozzolans

Natural pozzolans are sourced from (i) volcanic tuffs/zeolites (Raggiotti et al., 2018; Ramezanianpour et al., 2013), (ii) siliceous such as opal and diatomaceous earth (Abrão et al., 2019; Li, J. et al., 2019; Tagnit-Hamou et al., 2003; Vejmelková et al., 2018; Yılmaz and Ediz, 2008), and (iii) volcanic glasses such as volcanic ashes (Hossain and Lachemi, 2007; Lemougna et al., 2018; Siddique, 2012a), pumice and pumicite (Nozahic et al., 2012; Ulusu et al., 2016). Most of the conclusions drawn for artificial pozzolans can be apply to concrete containing natural pozzolans, except the fact that it costs less (Lemougna et al., 2018; Raggiotti et al., 2018). In other words, the cost of concrete can significantly decrease by increasing the incorporation ratio of natural pozzolans because they do not need to be burnt.

4.3 Municipal wastes as SCM

4.3.1 Glass powder

Glass is an amorphous and non-crystalline material. It has been used as partial replacement of aggregate in concrete (Hama et al., 2019; Karim, F. et al., 2016; Korjakins et al., 2009; Korjakins et al., 2012; Matos et al., 2016; Park et al., 2004; Rossomagina and Puzanov, 2004; Yang, S. et al., 2019) and in other products such as fired-clay bricks (Muñoz et al., 2016), alkali-activated materials (Benmokrane et al., 2002; Liu, Y. et al., 2019), glass-reinforced panels (Pastor et al., 2014), structural repair mortar (Calmon et al., 2014), ultra-lightweight fibre-reinforced concrete (Yu et al., 2016), micro filler for concrete (Korjakins et al., 2009;

Korjakins et al., 2012), lightweight aggregates (Nemes and Józsa, 2006) and concrete blocks (Yang, S. et al., 2019). However, sometimes the results are not satisfactory when waste glass is used as aggregates in concrete due to a destructive reaction between silica in waste glass aggregate and alkalis in Portland cement that form silica gel (the main contributor to expansion) and micro-cracks generate around the reactive aggregates (Rossomagina and Puzanov, 2004). Nevertheless, several studies concluded that very fine glass powder as a partial replacement of cement in concrete may have sufficient pozzolanic properties and no detectable deleterious action from alkali-silica reaction and they reported several replacement ratios (40% (Vijayakumar et al., 2013), 20% (Hama, 2017), 15% (Kamali and Ghahremaninezhad, 2015), 10% (Aliabdo et al., 2016)) as an optimum. Additionally, glass can be considered as industrial (e.g. from car manufacturers) and municipal (flat glass sourced from households) waste.

4.3.2 Sludge ashes

Sludges are semi-solid slurries mostly produced from drinking water and wastewater treatment plants. Since dried sludge has similar heat value (calorific) to that of brown coal (Abd Ar Rafie et al., 2016; Fytili and Zabaniotou, 2008; Oladejo et al., 2018), its incineration has become more attractive lately. For sustainability reasons, the ashes resulting from burning these sludges, such as sewage sludge ash (SSA) (Baeza-Brotons et al., 2014; Horiguchi et al., 2010; Lynn et al., 2015; Monzó et al., 1999; Nakic, 2018; Smol et al., 2015) and sludge wastewater sludge ash (Sogancioglu et al., 2013), can be used as a partial replacement of cement in concrete. Generally, only low contents of SSA can be used (MIM and OBE, 2012). For higher quantities, treatment is required to extract phosphorus (Dhir et al., 2017b; MIM and OBE, 2012). Generally, they can be used as aggregates (Jamshidi et al., 2012; Kosior-Kazberuk, 2011), as binder (Chang et al., 2010; Monzó et al., 1999), in blocks (Baeza-Brotons et al., 2014; Pérez Carrión et al., 2014), in lightweight aggregate concrete (Bhatty and Reid, 1989; Yip and Tay, 1990), and in aerated/foamed concrete (Wang and Chiou, 2004).

Apart from the above sludges, paper sludge (Banfill and Frias, 2007; Bui et al., 2019; Ferrándiz-Mas et al., 2014; Santa et al., 2013), granite waste sludge (Al-Hamaiedeh and Khushefati, 2013; Mármol et al., 2010), galvanic sludge (Luz et al., 2009), glass waste sludge (Kim, J. et al., 2014; You et al., 2016), paint sludge (Avci et al., 2017), and contaminated arsenic sludge (Roy et al., 2018) are also used, after burning or drying, in pastes, mortars and concrete.

4.3.3 Municipal solid waste incineration ashes (MIBA)

In terms of chemical composition, MIBA can be divided in “pozzolanic regions” and “latent hydraulic” (Dhir et al., 2017), depending on the combustion temperature and the source of the solid waste. Most studies are focused on the effect of MIBA on the compressive strength (Fatihhi et al., 2019; Jurič et al., 2006; Li, X.-G. et al., 2012; MANGA, 2016; Silva et al., 2019b) and leachability (Jurič et al., 2006; Shao et al., 2014; Shirazi and Marandi, 2012; Silva et al., 2019b) of concrete. Generally, MIBA are detrimental to the strength of concrete due to the reaction between cement and aluminium of MIBA (Dhir et al., 2017; Silva et al., 2019b). Regarding municipal solid waste incineration fly ash, high chloride ions content is the main detrimental aspect to its potential use (Aubert et al., 2004; Haiying et al., 2010; Hartmann et al., 2015; Keppert et al., 2013; Shao et al., 2014; Ye et al., 2007).

4.4 Binary, ternary and quaternary SCM mixes

So far, there is no systematic review on the effect of binary, ternary and quaternary SCMs (BTQ-SCM) on the performance of concrete, specifically for incorporation ratios of SCM higher than the standard limit (EN 197-1, 2000). Additionally, consensus on the negative and positive effect of this path cannot be reached (Celik et al., 2015; Gursel et al., 2016; Jones et al., 1997; Patel et al., 2016; Rahla et al., 2019; Saleh Ahari et al., 2015; Tang et al., 2019c). Nevertheless, according to the results of most studies (Celik et al., 2015; Gursel et al., 2016; Rahla et al., 2019; Saleh Ahari et al., 2015; Tang et al., 2019c), the synergetic behaviour of BTQ-SCM with normal particle size (> 100 nm) and specific surface area (< 10,000 m^2/kg) (Shi et al., 2015) may not be significant. However, promising results are shown by using one or two SCMs with normal particle size and a small quantity of nano SCM particles, such as nano SiO_2 (Jalal et al., 2015; Li, 2004; Qing et al., 2007; Tavakoli et al., 2020), nano $CaCO_3$ (Antoni et al., 2012; Khongpermgoson et al., 2019; Shaikh and Supit, 2014), nano TiO_2 (Khushwaha et al., 2015; Li, Z. et al., 2017; Maravelaki-Kalaitzaki et al., 2013; Norhasri, M.S.M. et al., 2017), nano Fe_2O_3 (Khoshakhlagh et al., 2012; Nazari et al., 2010; Rashad, 2013c), nano Al_2O_3 (Rashad, 2013c; Wu et al., 2016a), nano ZnO (Arefi and Rezaei-Zarchi, 2012; Duraipandian, 2016), and nano clay (Allalou et al., 2019; Morsy et al., 2010).

4.5 Alternatives to Portland cement clinker

Another solution to promote sustainability, instead of replacing cement with SCMs, is by producing alternative cement clinker such as ye'elimite-rich cements - binders based on phosphates (Abyzov, 2017; Lieberman et al., 2018; Yang, Q. et al., 2002), , magnesium-based cements (Gartner and Macphee, 2011; Liska et al., 2008), thermal activated low-carbon recycled cement (Bogas, J.A. et al., 2019), binders by activating of liberated concrete fines (recycled concrete fines are activated through a thermal treatment method) (Florea et al., 2014), and binders based on reactive calcium silicates produced by hydrothermal processing techniques (Link et al., 2015; Stemmermann et al., 2010).

Generally, Ye'elimite-rich cements can be divided in two main groups (i) low belite (calcium sulphoaluminate cements - CSA) such as reactive belite-rich Portland cement clinkers (Gartner and Sui, 2018; Naqi and Jang, 2019; Sui et al., 2015; Sui et al., 2006; Sui et al., 1999), and (ii) high belite such as belite-ye'elimite-ferrite binders (Gartner and Sui, 2018; Naqi and Jang, 2019; Shi, C. et al., 2019), belite-alite-ye'elimite binder (Chitvoranund et al., 2016; Londono-Zuluaga et al., 2017; Shi, C. et al., 2019; Zea-Garcia et al., 2019), and belite-ye'elimite-ternesite binder (Hanein et al., 2017; Montes et al., 2018; Shi, C. et al., 2019). Generally, these cements require a lower temperature, but their performance is worse than that of OPC.

However, studies regarding these new cement clinkers are very scarce due to the cost barriers (Gartner and Sui, 2018) and the fact that it is complicated to simulate it in laboratory conditions such needed operations as filling a “rotary clinker kiln” with the raw materials used to make these cements.

4.6 Activation techniques and geopolymer

One way to promote sustainability is by utilizing co-products or by-products as partial replacements of cement. However, their incorporation ratios are limited because, after a given ratio (high volume), further hydration products in the paste may not be produced. To overcome this issue, alkaline activator (e.g. NaOH, KOH, and Na_2SiO_3) can be used. Thus, alkali activation techniques can be considered an alternative process to partial replacement of cement with SCMs. Materials that are rich in amorphous Al_2O_3 and SiO_2 can be used as a precursor, such as:

i. AWAF: RHA (Bernal et al., 2012; Detphan and Chindaprasirt, 2009), POFA (Islam et al., 2014; Ranjbar et al., 2014; Salih et al., 2014b; Zarina et al., 2013), CCA (Matalkah et al., 2017; Oyebisi et al., 2018), SBA (Castaldelli et al., 2013), straw ash (Al-Akhras, 2013; Matalkah et al., 2017), FBBA (Girón et al., 2015), WA (Cheah et al., 2017; Matalkah et al., 2016), other agriculture-farming wastes (e.g. alfalfa steam ash, cotton gin ash, com stalk ash and switch grass ash - (Alonso et al., 2019; Bernal et al., 2016; Matalkah et al., 2017)), and shell wastes (Djobo et al., 2016; Monneron-Gyurits et al., 2018);

ii. Industrial waste ashes: FA (Choo et al., 2016; Hajimohammadi and van Deventer, 2017; Nematollahi et al., 2014; Palomo and Fernández-Jiménez, 2011; Payá et al., 2019; Singh and Middendorf, 2020; Zhang, Zuhua et al., 2016; Zhou et al., 2016), CBA (Donatello et al., 2014), industrials slags (Aydın and Baradan, 2012; Font et al., 2020; Huseien et al., 2018; Islam et al., 2014; Li and Liu, 2007; Mehta and Siddique, 2018; Payá et al., 2019; Sun et al., 2018), SF (Assi, L. et al., 2018; Assi, L.N. et al., 2018; Çevik et al., 2018; Daniel et al., 2017; Duan et al., 2017; Kovtun et al., 2015; Okoye et al., 2016; Okoye et al., 2017), artificial pozzolans (calcined clays (Duxson et al., 2007; Granizo et al., 2000; Longhi et al., 2016; Sun et al., 2018), ceramic residues (Reig et al., 2013; Shoaei et al., 2019), sedimentary rocks containing clay minerals and burned bauxites (Dimas et al., 2009; Gong and Yang, 2000; Kumar and Kumar, 2013)), natural pozzolans (volcanic tuffs/zeolites (Raggiotti et al., 2018; Ramezanianpour et al., 2013), siliceous such as opal and diatomaceous earth (Abrão et al., 2019; Li, J. et al., 2019; Tagnit-Hamou et al., 2003; Vejmelková et al., 2018; Yılmaz and Ediz, 2008), and volcanic glasses such as volcanic ashes (Hossain and Lachemi, 2007; Kani and Allahverdi, 2009; Kani et al., 2012; Lemougna et al., 2018; Siddique, 2012a), pumice and pumicite (Almalkawi et al., 2017; Yadollahi et al., 2015), mine mud waste (Manso and Castro-Gomes, 2015, 2019; Manso et al., 2018; Manso and Castro-Gomes, 2016));

iii. Municipal waste ashes: glass powder (Kourti et al., 2011; Liu, Y. et al., 2019; Martinez-Lopez and Ivan Escalante-Garcia, 2016; Pascual et al., 2014; Puertas and Torres-Carrasco, 2014; Tashima et al., 2012; Torres-Carrasco and Puertas, 2015), sludge ashes (Banfill and Frias, 2007; Cherian and Siddiqua, 2019; Guo et al., 2010; Santa et al., 2013; Yang et al., 2013), MIBA (Aliabdo et al., 2019; Chen, Z. et al., 2016; Galiano et al., 2011; Garcia-Lodeiro et al., 2016; Giro-Paloma et al., 2017; Huang, G. et al., 2019; Huang et al., 2018; Jing et al., 2007; Kim and Kang, 2014; Krausova et al., 2012; Lancellotti et al., 2013; Liu, Y. et al., 2018; Onori et al., 2011; Penilla et al., 2003; Qiao et al., 2008a, 2008b; Rożek et al., 2019; Song et al., 2015; Wongsa et al., 2017; Xuan et al., 2019; Zhu et al., 2016, 2018; Zhu et al., 2019), and municipal solid waste incinerator fly ash (MIFA) (Ferone et al., 2013; Jin, M. et al., 2016; Lach et al., 2018; Li, R. et al., 2019; Ryu et al., 2013; Shao et al., 2014; Shiota et al., 2017; Sofi et al., 2007; Yakubu et al., 2018).

Alkali-activated materials (AAM's) can be also produced with blended SCMs. For example, GGBS-SBA (Castaldelli et al., 2013), biomass FA-metakaolin (Rajamma et al., 2012), RHA-GGBS (Mehta and Siddique, 2018), FA-metakaolin (Duan et al., 2015; Fernández-Jiménez et al., 2008), POFA-FA (Islam et al., 2014), FA-RHA (Chindaprasirt and Rukzon, 2008), FA- SF (Assi, L. et al., 2018; Assi, L.N. et al., 2018; Duan et al., 2017; Okoye et al., 2016; Okoye et al., 2017), and FA-slag (Al-Majidi et al., 2016; Fang et al., 2018; Nath and Sarker, 2014; Rao and Rao, 2015; Rashad, 2013a) blends have been used. FA with spherical particles to control the fresh properties is used as SCM to produce AAM (Al-Majidi et al., 2016; Chindaprasirt and Rukzon, 2008; Deb et al., 2014; Duan et al., 2015; Fernández-Jiménez et al., 2008; Islam et al., 2014; Ismail et al., 2013; Nath and Sarker, 2014; Rao and Rao, 2015; Rashad, 2013a). In other words, most AAM studies are related with industrials wastes because concrete with different mechanical performance (e.g. 55-60 MPa (Chindaprasirt and Rukzon, 2008), 20-60 MPa (Nath and Sarker, 2014), 30-62 MPa (Rashad, 2013a), 20-60 MPa (Fang et al., 2018), 20-50 MPa (Al-Majidi et al., 2016), 20-70 MPa (Deb et al., 2014)) can be obtained from their use for a regular curing temperature (20-23 °C). Relatively to industrial waste ashes, studies on AAM containing agricultural and municipal waste ashes are still very few. Perhaps this happens because the results are not promising when agricultural and municipal waste ashes are used in AAM alone (Chen, Z. et al., 2016; Detphan and Chindaprasirt, 2009; Galiano et al., 2011; Garcia-Lodeiro et al., 2016; Giro-Paloma et al., 2017; He et al., 2013; Huang, G. et al., 2019; Huang et al., 2018; Jing et al., 2007; Kim and Kang, 2014; Krausova et al., 2012; Lancellotti et al., 2013; Liu, Y. et al., 2018; Nazari et al., 2011; Onori et al., 2011; Penilla et al., 2003; Qiao et al., 2008a, 2008b; Rożek et al., 2019; Salih et al., 2014a; Song et al., 2015; Songpiriyakij et al., 2010; Wongsa et al., 2017; Xuan et al., 2019; Yusuf et al., 2014; Zhu et al., 2016, 2018; Zhu et al., 2019). One way to boost the performance of AAM is by blending one SCM with nanoparticles, especially nanosilica (Adak et al., 2014; Adak et al., 2017; Behfarnia and Salemi, 2013; Bittnar et al., 2009; Çevik et al., 2018; Deb et al., 2015; Ehsani et al., 2017; Naskar and Chakraborty, 2016; Qing et al., 2007; Singh, NB et al., 2018) or ultrafine slag (alccofine - (Jindal, B. et al., 2017; Jindal et al., 2017b; Jindal, B.B. et al., 2017a; Jindal, B.B. et al., 2017b)), or low quantity of cement (Alonso and Palomo, 2001; Chindaprasirt and Rukzon, 2008; Jiang, 1997; Nath and Sarker, 2014; Palomo et al., 2007; SHI et al., 2012; Shi et al., 2003; Shi et al., 1993).

5 Reduce the environmental impacts and resources use of aggregates

Replacing virgin aggregates (de Brito et al., 2018) with non-conventional aggregates is another strategy that can be used to promote sustainability. However, relatively to other strategies (e.g. reduce the EI of binder, §4), the EI of concrete can only slightly decrease (up to 10% (Braga et al., 2017; Kurad et al., 2017; Turk et al., 2015; Wu and Xu, 2011), mostly depending on transportation scenario (Blengini and Garbarino, 2010; Coelho and de Brito, 2013; Göswein et al., 2018)) or slightly increase (Marinković et al., 2010; Tošić et al., 2015). For that purpose, many specifications, e.g. from Portugal (LNEC E471, 2006), UK (BRE Digest 433, 1998; BS 6543, 1985; BS 8500-2, 2002), Austria (BRV, 2007), Japan (JSA - JIS A 5021, 2016; JSA - JIS A 5022, 2016; JSA - JIS A 5023, 2016), Denmark (DCA-N.34, 1995), Brazil (NBR 15.116, 2005), Holland (CUR-VB 4, 1984; CUR-VB 5, 1994; CUR 125, 1986), Switzerland (TV 70085, 2006), USA (ACI 555R-01, 2001), Germany (DIN 4226-100, 2002), France (DREIF, 2003), Spain (Vázquez et al., 2004), China (WBTC-N.12, 2002), Australia (EEPL, 2012), and others (RILEM TC 121-DRG N. 27, 1994) have been developed based on the technical properties of recycled aggregates, i.e. components, water absorption, density and maximum incorporation level in concrete and other construction materials. However, the specifications have not defined any limitations in terms of LCA. This gap is directly associated with the lack of joint investigation/data in terms of LCA and technical properties of recycled aggregates concrete.

5.1 Construction and demolition waste

5.1.1 Recycled concrete aggregate

Concrete can be found in most recycled aggregates due to fact that it is the most consumed material in structural applications. It can be separated from other construction and demolition waste (CDW) materials and re-used in concrete. Generally, the effect of recycled concrete aggregate (RCA) on the technical properties of concrete depends on its replacement level (Ferreira et al., 2011; Lavado et al., 2020; Silva, R. V. et al., 2015b; Yang, K. et al., 2008), water absorption (Akib and Sayyad, 2015; Amorim et al., 2012; Arezoumandi et al., 2015; Arora and Singh, 2016; Brand et al., 2015; Carro-López et al., 2015; Cartuxo et al., 2015; Chan, 1998; Cong, 2006; Corinaldesi, 2011; Evangelista et al., 2015; Fumoto and Yamada, 2003; González-Fonteboa et al., 2012; Hasaba et al., 1981; Katz, 2003; Kebaïli et al., 2015; Kikushi et al., 1998; Kim et al., 2013; Kim et al., 2015; Kim and Yun, 2014; Kou and Poon, 2009b; Kou and Poon, 2013; Leite, 2001; Levy and Helene, 2007; Lima, C. et al., 2013; Müeller and Winkler, 1998; Nuaklong et al., 2016; Pedro et al., 2015b; Qasrawi and Marie, 2013; Ravindrarajah et al., 1987; Reddy et al., 2014; Reis et al., 2015; Schoon et al., 2015; Sérifou et al., 2013; Silva, R. V. et al., 2015b; Sim and Park, 2011; Soares et al., 2014a; Solyman, 2005; Tam et al., 2015; Wang et al., 2013; Wang, 2012; Yang et al., 2016; Yaprak et al., 2011; Zega and Di Maio, 2011), moisture content (Silva et al., 2014; Silva, R. V. et al., 2015b), size (de Juan and Gutiérrez, 2009; Evangelista and de Brito, 2007; Ferreira et al., 2011; Fonseca, 2009; Gokce et al., 2011; Kurad et al., 2017; Kurda et al., 2019a; Kurda et al., 2019a; Kurda et al., 2018a; Silva et al., 2014), shape (Ferreira et al., 2011; Fonseca, 2009; Silva et al., 2014), density (Akib and Sayyad, 2015; Amorim et al., 2012; Arezoumandi et al., 2015; Arora and Singh, 2016; Brand et al., 2015; Carro-López et al., 2015; Cartuxo et al., 2015; Chan, 1998; Cong, 2006; Corinaldesi, 2011; Evangelista et al., 2015; Fumoto and Yamada, 2003; González-Fonteboa et al., 2012; Hasaba et al., 1981; Katz, 2003; Kebaïli et al., 2015; Kikushi et al., 1998; Kim et al., 2013; Kim et al., 2015; Kim and Yun, 2014; Kou and Poon, 2009b; Kou and Poon, 2013; Leite, 2001; Levy and Helene, 2007; Lima, C. et al., 2013; Müeller and Winkler, 1998; Nuaklong et al., 2016; Pedro et al., 2015b; Qasrawi and Marie, 2013; Ravindrarajah et al., 1987; Reddy et al., 2014; Reis et al., 2015; Schoon et al., 2015; Sérifou et al., 2013; Silva et al., 2014; Silva, R. V. et al., 2015b; Sim and Park, 2011; Soares et al., 2014a; Solyman, 2005; Tam et al., 2015; Wang et al., 2013; Wang, 2012; Yang et al., 2016; Yaprak et al., 2011; Zega and Di Maio, 2011), recycling procedure (Chisholm, 2011; de Juan and Gutiérrez, 2009; Nagataki et al., 2004; Silva et al., 2014; Wegen and Haverkort, 1998), and quality of the original material (Barreto Santos et al., 2020; Chandra, 2004; Dhir et al., 1999; Hansen and Narud, 1983; Hasaba et al., 1981; Nagataki et al., 2004; Silva et al., 2014), and on the composition of the resulting concrete, i.e. water to cement ratio (Correia et al., 2006; Evangelista and de Brito, 2010;

Kurda et al., 2019a; Pedro et al., 2015a; Pedro et al., 2015b; Pedro et al., 2017a; Silva et al., 2014; Soares et al., 2014b), chemical admixtures (Gutiérrez, 2004; Otsuki et al., 2003; Prakash and Krishnaswamy, 1998; Salem et al., 2003; Silva et al., 2014), type of binders (Ahmed, 2011; Arifi et al., 2014; Berndt, 2009; Bhikshma and Divya, 2012; Costabile, 2001; de Juan and Gutiérrez, 2009; Gonzalez-Corominas et al., 2016; Gurdián et al., 2014; Kim et al., 2013; Kou et al., 2007; Kurad et al., 2017; Kurda et al., 2019b; Kurda et al., 2018a; Kurda et al., 2018e; Limbachiya et al., 2012; Marinković et al., 2016; Nuaklong et al., 2016, 2018; Ping and Yidong, 2011; Poon and Kou, 2010; Sadati et al., 2016; Silva et al., 2014; Singh, N. and Singh, S., 2016; Somna et al., 2012; Surya et al., 2015; Tangchirapat et al., 2013; Tian et al., 2011; Wu and Xu, 2011), and environmental conditions (Buyle-Bodin and Hadjieva-Zaharieva, 2002; Fonseca et al., 2011; Silva et al., 2014).

There is a wide range in the characteristics of RCA due to the quality of the original material (Pedro et al., 2014) and the size of the aggregates (Hafez et al., 2020; Kurad et al., 2017). For example, the water absorption, saturated surface-dry (SSD), particle oven-dried, apparent, and loose bulk density of fine RCA are 3.5-13%, 2161-2929 kg/m^3, 1913-2620 kg/m^3, 2410-2600 kg/m^3 and 1344 kg/m^3, respectively (Carro-López et al., 2015; Cartuxo et al., 2015; Chan, 1998; Evangelista et al., 2015; Fumoto and Yamada, 2003; Hasaba et al., 1981; Katz, 2003; Kikushi et al., 1998; Kim and Yun, 2014; Kou and Poon, 2009b; Leite, 2001; Levy and Helene, 2007; Lima, C. et al., 2013; Müeller and Winkler, 1998; Schoon et al., 2015; Sérifou et al., 2013; Sim and Park, 2011; Solyman, 2005; Wang, 2012; Yaprak et al., 2011; Zega and Di Maio, 2011). In addition, the water absorption, loose bulk density and particle oven-dried density of coarse RCA are 2.8-6.8%, 1230-1600 kg/m^3 and 2140-2760 kg/m^3, respectively (Akib and Sayyad, 2015; Amorim et al., 2012; Arezoumandi et al., 2015; Arora and Singh, 2016; Brand et al., 2015; Cong, 2006; Corinaldesi, 2011; González-Fonteboa et al., 2012; Kebaïli et al., 2015; Kim et al., 2013; Kim et al., 2015; Kou and Poon, 2013; Nuaklong et al., 2016; Pedro et al., 2015b; Qasrawi and Marie, 2013; Ravindrarajah et al., 1987; Reddy et al., 2014; Reis et al., 2015; Sérifou et al., 2013; Soares et al., 2014a; Tam et al., 2015; Wang et al., 2013; Yang et al., 2016).

In general, fine RCA is more detrimental to concrete than coarse RCA due to its high mortar content that increases its water absorption. In terms of strength, some studies mentioned that 20-30% incorporation of RCA may have a minor impact on concrete (Dhir and Paine, 2004; Evangelista and de Brito, 2007). Nevertheless, the effect of RCA depends on the target strength of concrete. For example, by sorting the results of the following studies based on their target strength: 20-30 MPa (Larrañaga, 2004; Sagoe-Crentsil et al., 2001; Sérifou et al., 2013; Yang, K. et al., 2008), 30-40 MPa (Amorim et al., 2012; Arezoumandi et al., 2015; Guo et al., 2013; Kathirvel and Kaliyaperumal, 2016; Kim and Yun, 2014; Larbi et al., 2015; Maleševet al., 2010; Movassaghi, 2006; Pacheco et al., 2015; Soares et al., 2014b), 40-50 MPa (Akib and Sayyad, 2015;

Corinaldesi, 2011; Geng and Sun, 2013; González-Fonteboa et al., 2012; Kathirvel and Kaliyaperumal, 2016; Khatib, 2005; Pereira, 2010; Yaprak et al., 2011; Zega and Di Maio, 2011), 50-60 MPa (Bogas et al., 2016; Corinaldesi, 2011; Evangelista and de Brito, 2007; González-Fonteboa et al., 2012; Ramos, 2014), 60-70 MPa (Bogas et al., 2016; Cartuxo et al., 2015; Evangelista and de Brito, 2007; Pereira et al., 2012; Ramos, 2014; Tam et al., 2015), and 70-80 MPa (Bogas et al., 2016; Cartuxo et al., 2015; Ramos, 2014), it can be said that the strength of high-strength concrete sharply reduced with increasing RCA replacement (failure will occur in the weaker old adhered mortar of RCA relative to the cement paste of conventional concrete). This may not occur for low strength concrete (at least up to 30% incorporation) because the ultimate strength of low-strength concrete depends mostly on its cement paste characteristics. In addition, most properties of concrete containing RCA have been studied, i.e. fresh properties (Geng and Sun, 2013; Kurda et al., 2017b; Lavado et al., 2020; Zega and Maio, 2006), tensile strength (Evangelista and de Brito, 2007; Pereira, 2010; Santos et al., 2020), modulus of elasticity (Khatib, 2005; Leite, 2001; Solyman, 2005), carbonation (Basheer et al., 2001; Levy and Helene, 2004; Prameetthaa et al., 2015), chloride penetration resistance (Cartuxo, F, 2013; Evangelista and de Brito, 2010), water absorption (Cartuxo et al., 2016; Evangelista and de Brito, 2010; Ghorbani et al., 2019a; Masood et al., 2020; Nobre et al., 2020; Zega and Maio, 2006), shrinkage (Domingo-Cabo et al., 2009; Khatib, 2005; Solyman, 2005; Zega and Maio, 2006), UPV (Khatib, 2005; Pereira, 2010), creep (Domingo-Cabo et al., 2009; ZOU et al., 2009), LCA (Braunschweig et al., 2011; de Schepper, M. et al., 2014; De Schepper, Mieke et al., 2014; Evangelista and de Brito, 2007; Göswein et al., 2018; Knoeri et al., 2013; Kurda et al., 2018c; Marinkovic´ et al., 2010; Quattrone et al., 2014; Tošić et al., 2015; Weil et al., 2006), cost (Braga et al., 2017; Golgota et al., 2014; Kurda, 2017; Kurda et al., 2018d), and toxicity (Rodrigues et al., 2020; Rodrigues et al., 2017a). However, studies on the combined effects on technical performance, LCA and cost are very few.

5.1.2 Recycled Masonry Aggregate (RMA)

The composition of recycled masonry aggregates (RMA) is identified to be a minimum of 90%, by mass, of mortar and burnt clay materials such as ceramic roofing tiles and shingles, ceramic bricks, light-weight concrete blocks, sand-lime bricks, and blast-furnace slag bricks and blocks (Hansen, 1992; Silva et al., 2014). According to the results of 787 concrete mixes collected in (Silva, R. V. et al., 2015b), after RCA, RMA is the second most suitable type of CDW aggregates to be used in concrete. In other words, for a given incorporation ratio, RMA is more detrimental than RCA in concrete because of the former's lower density, higher water absorption, and higher Los Angeles abrasion loss (Gomes and de Brito, 2009; Silva et al., 2014). Based on the results of these studies, the 95% quantile highest strength loss of concrete mixes made with 100% of coarse RMA is 50%. The suitability of RMA in concrete can be also confirmed by other technical performances such as tensile strength (Bommisetty et al., 2019;

Debieb and Kenai, 2008; Medina et al., 2012; Pacheco-Torgal and Jalali, 2011; Senthamarai and Devadas Manoharan, 2005; Silva, R. V. et al., 2015c), modulus of elasticity (Senthamarai and Devadas Manoharan, 2005; Silva et al., 2016), carbonation (Gomes and de Brito, 2009; Silva, R. V. et al., 2015d), chloride penetration (Gomes and de Brito, 2009; Pacheco-Torgal and Jalali, 2011; Paine and Dhir, 2010; Silva, Rui Vasco et al., 2015), water absorption (Gomes and de Brito, 2009; Pacheco-Torgal and Jalali, 2011; Paine and Dhir, 2010), shrinkage (Silva et al., 2015a) and creep (Silva, R. V. et al., 2015a). However, there are no detailed studies on life-cycle environmental and economic assessment.

5.1.3 Contaminated construction and demolition waste

CDW that contains high amount of different contaminations (e.g. wood, glass, asphalt and plastics) can be used as aggregates in concrete (Silva et al., 2019a; Sormunen and Kärki, 2019). However, the literature has limited detail on the composition and origin of this type of aggregates (Mália et al., 2013; Silva et al., 2014). A revision of Silva et al. (Silva et al., 2014) considered results of 116 studies and showed that, for a 95% confidence interval, the average (lower and higher bounds) oven-dried density, saturated surface-dry density, and water absorption are 2280 kg/m^3 (2241-2318 kg/m^3), 2399 kg/m^3 (2366-2431 kg/m^3), 5% (2-32%) for coarse mixed construction and demolition recycled aggregates (CDRA), and 2207 kg/m^3 (2161-2253 kg/m^3), 2399 kg/m^3 (2364-2433 kg/m^3), 8% (4-50 %) for fine CDRA, respectively.

Similar factors mentioned in section 3.2 may affect the influence of mixed CDRA on the technical performance of concrete. Apart from these factors, the chemical composition of CDRA, namely sulphate (Barbudo et al., 2012; de Juan and Gutiérrez, 2009; Dhir et al., 2001), chloride (Dhir and Paine, 2003), and alkali contents (Dhir and Paine, 2003; Dhir and Paine, 2004; Dhir and Paine, 2007), may significantly compromise the performance of concrete. For example, most specifications are limited and concerned about the maximum sulphate content (0.8% (DIN 4226-100, 2002; LNEC E471, 2006; Prescriptions Techniques, 2003) or 1.0% (NBR 15.116, 2005; RILEM TC 121-DRG N. 27, 1994; TV 70085, 2006; Vázquez et al., 2004; WBTC-N.12, 2002)). Furthermore, for similar mix compositions, relatively to uncontaminated CDW aggregates, there is a big scatter between the performance of concrete mixes made with mixed CDRA (Akhtar and Sarmah, 2018a; Bravo et al., 2017; Bravo et al., 2018; Bravo, Miguel et al., 2015; Bravo, M. et al., 2015; Cantero et al., 2019; Ma et al., 2019). This can be mainly explained by the percentage of contaminated materials (Ambrós et al., 2017; Di Maria et al., 2016; Ulsen et al., 2013; Vegas et al., 2015), such as gypsum (main responsible for sulphate expansion (EN 12620, 2008; Hansen, 1992)) and reactive silica (Dhir and Paine, 2003; Dhir and Paine, 2004; Dhir and Paine, 2007). The review conducted by Silva et al. (Silva, R. V. et al., 2015b) based on the results of 787 concrete mixes containing different types of CDW aggregates did not recommend using mixed CDRA in concrete unless they are adequately tested for their composition and properties before use.

5.1.4 Mixed Recycled Aggregate (MRA)

In spite of the conclusions of the previous section (§5.1.3), mixed CDRA can still have benefits by separating concrete and masonry particles and using this mixture as mixed recycled aggregates (MRA). Thus, this type of aggregate can be considered as intermediate between RCA (§5.1.1) and RMA (§5.1.2). Recently, a jigging technique was suggested to separate brick/concrete particles in mixed CDRA (Ambrós et al., 2017; Hu, K. et al., 2019; Sampaio et al., 2016) but studies on this separation technique are very limited. Some specifications [78, 86] identified the composition of this type of aggregates (less than 90% of natural aggregates and Portland cement-based fragments). Thus, it may include other CDW common materials such as light-weight concrete and ceramic (Awoyera et al., 2016; Awoyera et al., 2018; Etxeberria Larrañaga and Vegas, 2015; Gonzalez-Corominas and Etxeberria, 2014; Silva et al., 2014). According to the statistical analysis made in the study of Silva et al. (Silva, R. V. et al., 2015b), the 95% quantile maximum strength loss of concrete mixes made with 100% of coarse MRA is 60%. Other technical performances decay with the use of MRA (Corinaldesi and Moriconi, 2009; Dhir and Paine, 2007; Gomes and de Brito, 2009; Juan-Valdés et al., 2018; Mas et al., 2012; Silva, R. V. et al., 2015c; Yang, J. et al., 2011; Zheng, C. et al., 2018). However, MRA still can be recommended for construction materials, especially for low-strength concrete.

5.2 Agricultural wastes and aquaculture farming as aggregates

As shown in §4.1, cement in concrete can be replaced with many types of AWAF ashes. Due to dumping problem of agricultural wastes and global demand to aggregates (due to rapid urbanization), many agro wastes can also be used in concrete as a partial replacement of aggregates, especially as a fine aggregate. Apart from sustainability reasons, the purpose of this strategy is to produce lightweight and low thermal conductivity concrete (Aslam et al., 2016; Prusty et al., 2016; Rashad, A., 2016; Shafigh et al., 2014a). On this path, most of the studies are focused on the technical properties of concrete containing bottom AWAF (as raw material and ash) as a partial replacement of sand such as SBA (Modani and Vyawahare, 2013; Sales and Lima, 2010), groundnut shell (Gunasekaran and Kumar, 2008; Sada et al., 2013), sawdust (Ganiron, 2014; Mageswari and Vidivelli, 2009), wild giant reed ash (Ismail and Jaeel, 2014), wheat straw (Al-Akhras, Nabil M et al., 2008; Binici et al., 2008), WA (Ottosen et al., 2016), rice husk/ash (Chabannes et al., 2014; Kunchariyakun et al., 2015; Sua-Iam and Makul, 2013), cork (Nóvoa et al., 2004; Panesar and Shindman, 2012), tobacco waste (Ozturk and Bayrakl, 2005), CCA (Binici et al., 2008; Memon et al., 2019), leather (Baffa and Akasaki, 2005), palm tree shell (Alengaram et al., 2010; Aslam et al., 2016; Gunasekaran et al., 2011; Kaur and Kaur, 2012; Mahmud et al., 2009; Mannan and Ganapathy, 2001; Muthusamy et al., 2013; Ndoke, 2006; Okpala, 1990; Shafigh et al., 2014b; Yap et al., 2015), plane leaf ashes (Binici et al., 2008) and olive husk (Odi, 2007), sunflower (Chabannes et al., 2015), seashell (e.g. oyster (Eo and Yi, 2015; Kuo et al., 2013; Mo et al., 2018; Yang et al., 2010; Yang et al., 2005), mussel (Martínez-García et al., 2017; Mo et al., 2018), cockle (Mo et al., 2018; Ponnada et al., 2016), scallop (Mo et al., 2018; Varhen et al., 2017), and periwinkle (Adewuyi and Adegoke, 2008; Falade, 1995; Mo et al., 2018)). Most of the studies on this path are related to palm tree shells (Alengaram et al., 2010; Aslam et al., 2016; Gunasekaran et al., 2011; Kaur and Kaur, 2012; Mahmud et al., 2009; Mannan and Ganapathy, 2001; Muthusamy et al., 2013; Ndoke, 2006; Okpala, 1990; Shafigh et al., 2014b; Yap et al., 2015). Additionally, only compressive strength has been studied in detail.

5.3 Industrial wastes as aggregates

Similarly to AWAF, industrial wastes can also be used as fine natural aggregate replacement in concrete. De Brito and Saikia (de Brito and Saikia, 2013) and Rashad (Rashad, A., 2016) made extensive literature reviews about this strategy. The results show that most of the studies are focused on the effect of artificial pozzolan wastes (§5.1.2-5.1.4) as sand replacement in concrete, followed by natural pozzolans (e.g. volcanic tuffs/zeolites (Bogas and Cunha, 2017; Juimo Tchamdjou et al., 2018; Maia and Neves, 2017; Marra et al., 2016), siliceous (Kotwa, 2017; Posi et al., 2013), and volcanic glasses (Öz, 2018; Sallı Bideci, 2016; Top et al., 2019; Wongsa et al., 2018)), FA (Dhir et al., 2000; Joseph and Ramamurthy, 2009; Maslehuddin et al., 1989; Parvati and Prakash, 2013; Pofale and Deo, 2010; Roy, 2011; Seo et al., 2010; Siddique, 2003a, b), CBA (Aggarwal et al., 2007; Bai and Basheer, 2003; Bai et al., 2005; Basheer and Bai, 2005; Kasemchaisiri and Tangtermsirikul, 2008; Singh and Siddique, 2014, 2016; Yuksel and Genç, 2007), iron and steel slags such as blast furnace slag (e.g. ground blast furnace slag (Binici et al., 2012; Miyamoto et al., 2015; Senani et al., 2018; Singh et al., 2015) and air-cooled blast furnace slag (Gesoğlu et al., 2012; Ozbakkaloglu et al., 2016)) and steelmaking slag (e.g. converter slag (Wang et al., 2009) and electric arc furnace slag (Alizadeh et al., 2003; González-Ortega et al., 2014; Maharaj and Mwasha, 2016; Manso et al., 2004; Pellegrino et al., 2013; Qasrawi et al., 2009; Vijayaraghavan et al., 2017)), SF (Ghafoori and Diawara, 1999, 2007; Ismeik, 2010), plastic waste (§5.5), rubber waste (§5.5), and then distantly followed by non-ferrous slags (e.g. copper slag (Gupta and Siddique, 2019; Lori et al., 2019; Mahesh Babu and Ravitheja, 2019; Rajasekar et al., 2019; Sharma and Khan, 2017; Vijayaraghavan et al., 2017), lead and zinc slag (Alwaeli, 2013, 2017)). These types of aggregates can reduce the cost and EI and enhance several durability properties of concrete. However, widespread reliable data are missing for the use of these aggregates in concrete.

5.4 Municipal wastes as aggregates

Similarly to industrial wastes, municipal wastes as a raw material and ashes are used in concrete as a partial replacement of natural aggregates, in the shape of glass (§5.5), MIBA (Dhir et al., 2017; Dhir et al., 2002; Ginés et al., 2009; Roethel and Breslin, 1995; Saikia et al., 2008; Sorlini et al., 2011; Van den Heede et al., 2016; Zhang and Zhao, 2014), SSA (Baeza-Brotons et al., 2014; de Lima et al., 2015; Dhir et al., 2017b; Jamshidi et al., 2012; Khanbilvardi and Afshari, 1995; Kosior-Kazberuk, 2011), wastewater sludge ash (de Almeida Lima and Zulanas, 2016; Khanbilvardi and Afshari, 1995; Rabie et al., 2019), paper sludge (Bui et al., 2019), and granite waste sludge (Shermale and Varma, 2015; Vashistha et al., 2019a; Vashistha et al., 2019b). Most of the studies related to concrete containing municipal waste aggregates are focused on compressive strength.

5.5 Insulating aggregates

Normally, non-conventional aggregates are used to consume less virgin aggregates. However, some of them (e.g. plastic, rubber and lightweight aggregates) can be used for other sustainability purposes, namely to decrease the thermal conductivity of concrete (see section 13.2). They can be used in different applications of concrete. This strategy can also be identified as industrial waste (§5.3).

The fast growth of the global tires market and their short service life are another serious environmental issue (3 billion units in 2019 with forecast 7% growth rate (Freedonia-WT, 2019)). One way to promote sustainability is by using tire waste aggregate in concrete (rubberized concrete). Most of the technical properties of rubberized concrete have been studied, such as fresh properties (Corinaldesi and Donnini, 2019; Gesoğlu and Güneyisi, 2007; Su et al., 2015), shrinkage (Bravo and de Brito, 2012; Corinaldesi and Donnini, 2019; Kang and Jiang, 2008; Yung et al., 2013), mechanical strength (Aslani et al., 2018; Corinaldesi and Donnini, 2019; Rashid et al., 2019; Su et al., 2015; Yung et al., 2013), chloride ion penetration (Bravo and de Brito, 2012; Gesoğlu and Güneyisi, 2007; Sofi, 2018), freeze/thaw resistance (Corinaldesi and Donnini, 2019), fire resistance (Corinaldesi and Donnini, 2019; Guo et al., 2014), thermal insulation (Corinaldesi and Donnini, 2019) corrosion resistance (Corinaldesi and Donnini, 2019), resistance to aggressive environmental (Corinaldesi and Donnini, 2019; Topçu and Demir, 2007), carbonation (Bravo and de Brito, 2012; Rashad, A.M., 2016), sound absorption (Corinaldesi and Donnini, 2019; Thomas and Chandra Gupta, 2016), water permeability (Bravo and de Brito, 2012; Sofi, 2018; Su et al., 2015; Thomas and Chandra Gupta, 2016), and density (Aslani et al., 2018; Su et al., 2015). According to the cited studies, rubber content in concrete must be limited to up to 30% in order to guarantee an acceptable level of mechanical performance. The results show that tire waste aggregate enhances the energy absorption ability, ductility, and electrical resistivity of concrete (Corinaldesi and Donnini, 2019; Rashad, A.M., 2016; Siddika et al., 2019; Strukar et al., 2019; Yung et al., 2013). Contrary to other types of recycled aggregates, fine tire waste aggregate is less detrimental than coarse particles (Siddika et al., 2019; Strukar et al., 2019).

According to the first review study made in (Siddique et al., 2008), the concept of using plastic waste as a partial replacement of natural aggregates in concrete is relatively new. Nowadays, many studies are made on this path (Akçaözoğlu et al., 2010; Albano et al., 2009; Babafemi et al., 2018; Choi et al., 2005; De la Colina Martínez et al., 2019; Ferreira et al., 2012; Frigione, 2010; Poliotti and Bairán, 2019; Silva et al., 2013) especially because of the amount of plastic wastes in the industry (e.g. electronic plastics waste). Most of the studies suggested using plastic waste aggregate in the production of non-structural concrete or temporary structures. Nevertheless, by using different forms of waste plastic (e.g. waste plastic flakes (Rai et al., 2012; Sharma and Bansal, 2016), polyvinyl chloride pipe (Kou et al., 2009), polyethylene terephthalate particles (Córdoba et al., 2013; Janfeshan Araghi et al., 2015; Rahmani et al., 2013), high-density polyethylene waste (Naik et al., 1996), shredded fibres of polythene bags (Bhogayata et al., 2013), PET bottle fibres (Foti, 2013), and PET waste (Fraternali et al., 2011)), the performance of concrete increased, especially when used as a fibre (Sharma and Bansal, 2016).

Similarly to other insulating aggregates, researchers also focused on the effect of glass aggregates in concrete blocks (Lam et al., 2007; Turgut, 2008; Turgut and Yahlizade, 2009; Yang, S. et al., 2019) and structural concrete (Abdallah and Fan, 2014; Adaway and Wang, 2015; Ali and Al-Tersawy, 2012; Arabi et al., 2019; Batayneh et al., 2007; Borhan, 2012; de Castro and de Brito, 2013; Ismail and Al-Hashmi, 2009; Lu et al., 2019; Tan and Du, 2013; Topçu and Canbaz, 2004; Wang, H.-Y. et al., 2014). According to the systematic review study made by Mohajerani et al. (Mohajerani et al., 2017), concrete with foamed glass aggregates or expanded glass aggregates has not been studied in detail. In addition, most of the studies are related to concrete containing soda-lime glass or they did not mention the type of used glass. Moreover, the weakening of the bond between cement paste and the glass aggregates (Ali and Al-Tersawy, 2012; de Castro and de Brito, 2013; Ismail and Al-Hashmi, 2009; Tan and Du, 2013; Topçu and Canbaz, 2004; Wang, H.-Y. et al., 2014), and expansion due to alkali-silica reaction (Meyer and Xi, 1999; Mirzahosseini and Riding, 2015), are two of the significant issues of this path. Nevertheless, according to the data (experimental and literature) collected by Penacho et al. (Penacho et al., 2014), concrete and mortars with satisfactory performance can be produced with glass sand. Nevertheless, they only did short-term testing without performing the full alkali-silica reaction test.

Lightweight aggregates (LWA) can be manufactured (e.g. lightweight expanded clay, EC (Ayati et al., 2018; Rashad, 2018)), or sourced from nature (e.g. pumice (Rashad, 2019)), and waste products (e.g. (e.g. sludge ash (Tay and Yip, 1989)., oil-palm (Aslam et al., 2016) and MIBA (Caprai et al., 2020) as lightweight aggregate). The manufactured-lightweight aggregates increase the total EI of $1m^3$ of concrete (Lukic et al., 2012). However, this path can still be considered sustainable because it helps to build a safe structure with less weight (Braga et al., 2014) and avoids thermal bridges in buildings (Real et al., 2016). Further details on this path are given in §13.2. In addition, lightweight concrete may also be produced with a lightweight steel system. However, studies on this path are very limited (Ahmed and Tsavdaridis, 2018; Dai and Richard Liew, 2010; Iuorio et al., 2019; Othuman Mydin and Wang, 2011), and mostly focused on sandwich systems.

5.6 Other types of aggregates

Concrete can also be produced with other non-conventional aggregates such as alkali-activated aggregates (§4.6), magnetite/hematite/ferrock (D et al., 2017; Gencel et al., 2010; Kubissa et al., 2018; Lanuza et al., 2017), pumice stones (Badogiannis et al., 2019; Wang, Xiaoxiao et al., 2018), stone slurry (Almeida et al., 2007), ethylene-vinyl acetate (Martins et al., 2004; Santiago et al., 2009), lead-zinc tailings (Wang, Xinpeng et al., 2018), mine tailings (Jensen et al., 2018), and biochar aggregates (Akhtar and Sarmah, 2018b).

6 Reduce the environmental impacts and resources use of water

The concrete industry can be considered one of the largest water-consuming sectors. As reported in (Silva and Naik, 2010a), about 150 litres of water are needed per m^3 of concrete. This value can be increased to 500 litres per m^3 of concrete by considering washing out and losses during the production and transportation stages of concrete. The wastewater generated by this activity can be considered as a hazardous substance due to the presence of heavy metals and its high pH (Rodrigues et al., 2017a). Furthermore, mandatory chemical boundaries, other limits and general guidance on the type and amount of impurities of concrete mixing water are collected in (CCAA, 2007). According to the literature, apart from potable water, the following main water types can be used in CBM.

6.1 Seawater

Seawater has been used in concrete in previous studies (More and Dubey, 2014; Wegian, 2010; Younis et al., 2018). Romans made concrete that remains intact for centuries by using lime, volcanic ash, aggregate and seawater (Jackson et al., 2017). The mechanical strength generally increases by incorporating seawater (as a raw material instead of potable water) in concrete, especially at early ages (up to 7 days), and the opposite occurs at longer ages (More and Dubey, 2014; Wegian, 2010; Younis et al., 2018). Besides some attempts (CCAA, 2007; Duarte et al., 2019; Nishida et al., 2013; Saxena and Tembhurkar, 2019; Silva and

Naik, 2010a), it is urgent to contemplate the possibility of applying seawater in mixes, especially in unreinforced concrete, where its consequences on reinforcement corrosion are not felt. Relatively to freshwater, curing concrete with untreated seawater does not significantly affect its strength (Akinkurolere et al., 2007; Wegian, 2010). Thus, it is foreseen as a promising path to consume less freshwater.

6.2 Recycling water recovered from discarded ready-mix concrete

Similarly to seawater, water recovered from discarded ready-mix concrete has been used (i) for further washing purposes (Xuan et al., 2018) and in concrete as a raw material (Arunvivek et al., 2015; Asadollahfardi et al., 2015; Borger et al., 1994; Chini and Mbwambo, 1996; Ekolu and Dawneerangen, 2010; Fang et al., 2020; Papí, 2014; Ružinski et al., 2011; Tsimas and Zervaki, 2011) (mixing water) when it meets the regulatory requirements for fresh concrete. A study (Sealey et al., 2001) collected the traditional and non-traditional methods of cleaning mixer trucks. In addition, by recycling water recovered from a ready-mix concrete plant (Ekolu and Dawneerangen, 2010), concrete slurry waste can be also separated from water and used as recycled materials in concrete (Audo et al., 2016; Silva et al., 2020; Xuan et al., 2018). Some treatment techniques seem to be promising (Magro et al., 2019). However, studies on the durability performance of concrete with recycled water are very few.

6.3 Treated and untreated wastewater

The use of wastewater in concrete mixing is another strategy to decrease the impact of water (Hassani et al., 2020). Wastewater such as sewage (Cebeci and Saatci; Saxena and Tembhurkar, 2018; Silva and Naik, 2010b), industry (Ismail and Al-Hashmi, 2011; Nirmalkumar and Sivakumar, 2008; Vourch et al., 2008) and greywater (Al-Jabri et al., 2011; Ghrair et al., 2018) (greywater can be defined as any wastewater consumed by human activities in showers, bathtubs, laundry machines, hand basins, and kitchen sinks, in schools, office buildings, households, etc. without any inputs from toilets - (Al-Jayyousi, 2003)) are the main types used in CBM. Several studies reported that the setting time (Cebeci and Saatci), strength (Al-Jabri et al., 2011; Cebeci and Saatci; Ghrair et al., 2018; Nirmalkumar and Sivakumar, 2008), entrained air (Cebeci and Saatci) and water absorption (Al-Jabri et al., 2011) of CBM may be unaffected by the use of treated wastewater. However, the use of untreated sewage water is not recommended as mixing water in CBM composites (Cebeci and Saatci).

Apart from seawater, there are no studies on the effect of wastewater as curing water on the technical properties of CBM. Besides a few case studies, there is no systematic review to show the effect of different types of water (e.g. well water, tap water, mineral water, bore well water, seawater, agricultural wastewater, rainwater and treated and untreated wastewater) on the technical properties of CBM.

7 Reduce the environmental impacts and resources use of reinforcement

Similarly to cement, aggregates and water, regular carbon steel rebars can be replaced with non-conventional rebars such as bamboo (Agarwal et al., 2014; Atoyebi et al., 2018; Dey and Chetia, 2018; Ghavami, 1995; Ghavami, 2005; Ikponmwosa et al., 2017; Javadian et al., 2016; Jayachandran et al., 2019; Karthik et al., 2017; Li, W.-T. et al., 2017; Mali and Datta, 2018; Mali and Datta, 2020; Muhtar, 2019; Rahman et al., 2017; Terai and Minami, 2011; Wang, C.-L. et al., 2019), basalt rebars (§11.1.5), glass fibre reinforced-polymer (FRP) rebars (§11.1.6) and carbon FRP rebars (§11.1.7). Other strategies such as stainless-steel rebars (§11.1.1), low-carbon chromium reinforcing steel rebars (§11.1.2), epoxy-coated rebars (§11.1.3), and galvanized rebars (§11.1.4) may not directly reduce the EI of concrete reinforcement. However, they can be still considered as a sustainable solution due to the reasons mentioned in the first paragraph of section 11, namely increasing the durability of reinforced concrete and consequently decreasing yearly EI over the structure's life cycle.

8 Material manufacturing

Most of the other strategies (§3-7) are related to the EI and energy consumption of concrete (e.g. mix composition and technical properties of concrete) to lower its negative effects. Contrary to the mentioned sections, this chapter relates to the raw materials that have high EI and energy consumption. In other words, the strategies that decrease the EI and energy consumption of manufacturing the main raw materials used in concrete (e.g. cement - §8.1, aggregates - §8.2 and reinforcement - §8.4) are discussed. Relative to the mentioned raw materials, the EI and energy consumption of water (e.g. potable water) and admixtures (e.g. SP) are insignificant (Kurda et al., 2018b). Thus, alternative pathways in the manufacturing of these two materials are very scarce.

8.1 Cement production

As shown in Figure 10, production of cement can be classified in five stages, namely (i) raw materials extraction, (ii) transport, (iii) fuel and energy consumption, (iv) calcination and (v) grinding. To achieve lower EI and energy consumption in cement production, all the mentioned processes must be considered. As reported in (Gartner and Hirao, 2015; Ghoshal and Zeman, 2010; Hasanbeigi et al., 2012; Lippiatt et al., 2020), the CO_2 emissions of cement production can be decreased through each mentioned process:

(i) Extraction and crushing operations by considering best-practice mining (e.g. minimize essential equipment use, conveyor belts and alternative fuels (Jeswiet et al., 2015; Levesque et al., 2014; Norgate and

Haque, 2010; Parameswaran, 2016)), increasing machinery efficiency (Napier-Munn, 2015), using recycled aggregates (Bogas, J.A. et al., 2019), reducing wear and using advanced lubricants in machinery (Holmberg et al., 2017), and considering renewable energy-powered mills (Piemonte et al., 2011);

(ii) Transportation from one site to another by underground conveyor belts (Jeswiet et al., 2015) and with increased efficiency (Hanle et al., 2004; Hossain et al., 2017; Yang et al., 2017). This can be considered as a future plan because many quarries are usually nowhere near cement manufacturing plants;

(iii) Combustion by using alternative fuels (Rahman et al., 2013) such as oxy-fuel kiln (Hasanbeigi et al., 2012; Luis Míguez et al., 2018)) and belite cement (§4.5);

(iv) Decarbonation by using alternatives to decarbonation of limestone (reduce the total amount of binder - §3, blended cement - §4.1-4.4, alkali-activated concrete - §4.6, Mg cement - §12);

(v) Comminution (e.g. milling, grinding, and chipping) using renewable energy (Lamnatou and Chemisana, 2017);

(vi) Substitute technology by prefabricating carbonate parts (Rao and Rubin, 2002; Unluer and Al-Tabbaa, 2013) and green cement plant (Miller et al., 2018). In addition, some studies have developed an electrochemical process that can produce cement with almost zero carbon-footprint (Bertolini et al., 1996; Gilliam et al., 2012; Licht et al., 2012).

Finally, it can be said that the assumption of concrete with near-zero-carbon cements can be made by considering the strategy described in this section and CO_2 sequestration by mineral carbonation.

8.2 Aggregates production

To decrease the EI and energy consumption of aggregates, the whole process of quarrying/mining industry, shown in Figure 11, must be considered. In fact, each production process can be divided in several sub-processes (e.g. resources extraction includes drilling and blasting, secondary breaking, loading and hauling) and each of them needs to be studied to find a better solution in terms of sustainability. However, apart from few attempts or some general recommendations made by these studies (Asr et al., 2019; Awuah-Offei and Adekpedjou, 2011; Blengini et al., 2012; Bloodworth et al., 2009; Bringezu, 2002; Chen et al., 2008; Fourie and Brent, 2006; Hilson and Murck, 2000; Langer, 2016; Laurence, 2011; Poulin et al., 1994; Tiruta-Barna et al., 2007; Yellishetty et al., 2009), there are very few studies on the optimization tools, source of the raw materials and alternative production process, namely explosives, fuel, oils, electricity, equipment, vehicles, water, rock type, management and transportation scenario. Thus, it is urgent to focus on this path.

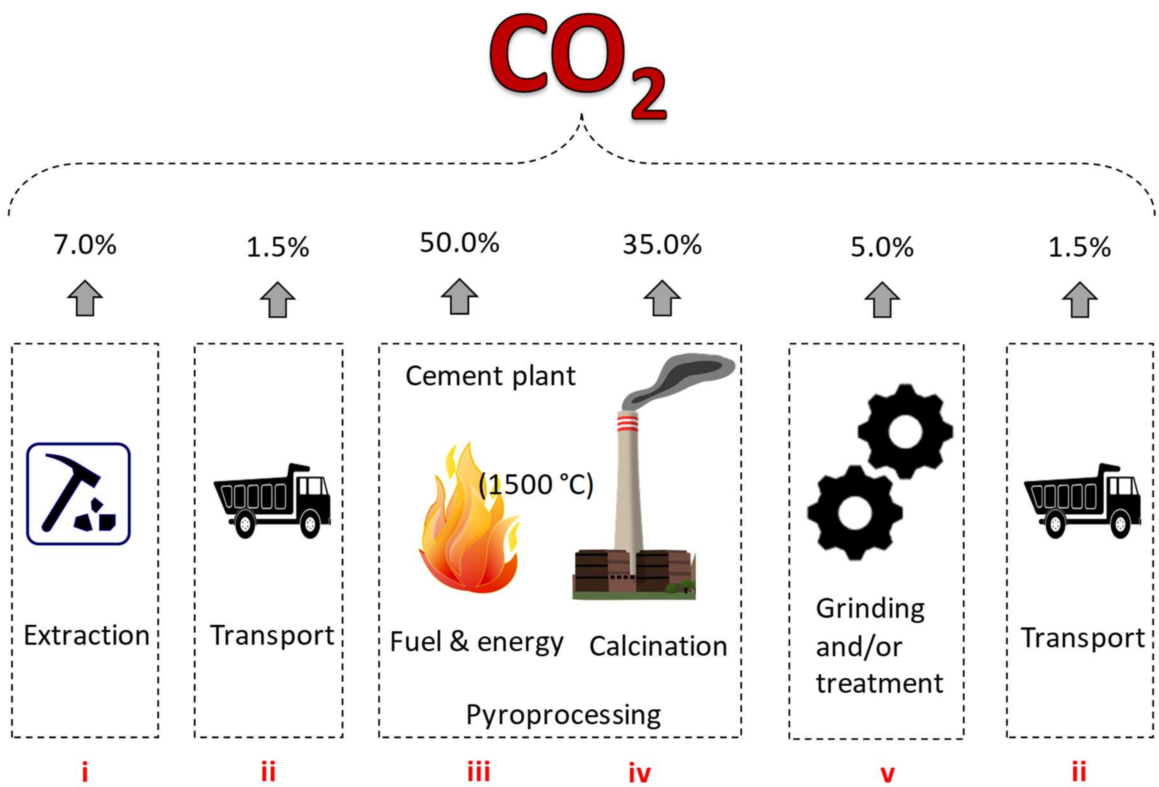


Figure 10 - Activities affecting CO_2 emission resulting from concrete production (adapted from (Gartner and Hirao, 2015; Ghoshal and Zeman, 2010; Hasanbeigi et al., 2012; Lippiatt et al., 2020))

As shown in Figure 11, for sustainability reasons, waste management can be made through recovering or recycling CDW as aggregates. Despite the many gaps previously mentioned, most of the studies have been focused only on this path, namely comparing the EI of natural and recycled aggregates (Kurda et al., 2018b, 2018e; Maduabuchukwu Nwakaire et al., 2020). Bearing these results in mind, regardless of the transportation scenario, the difference between the EI of natural aggregates and recycled aggregates may not be significant. In addition, some studies showed that the EI of aggregates from mobile plants is less than that of fixed plants (Estanqueiro et al., 2014).

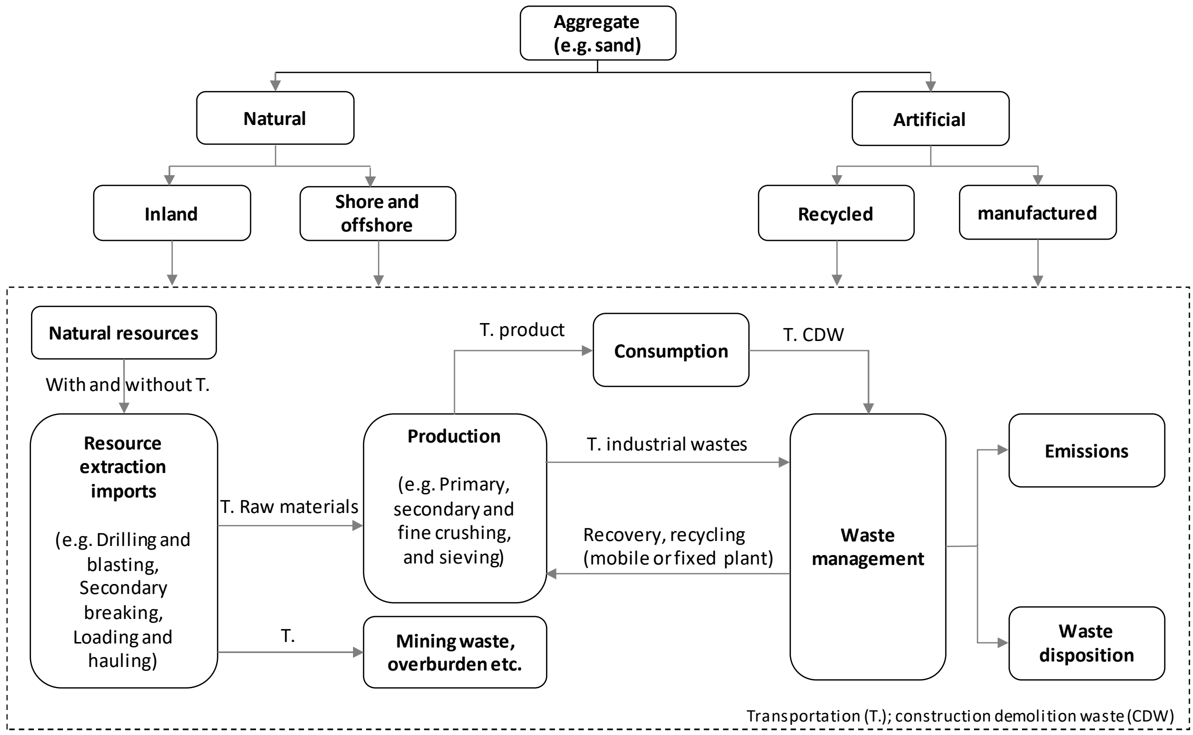
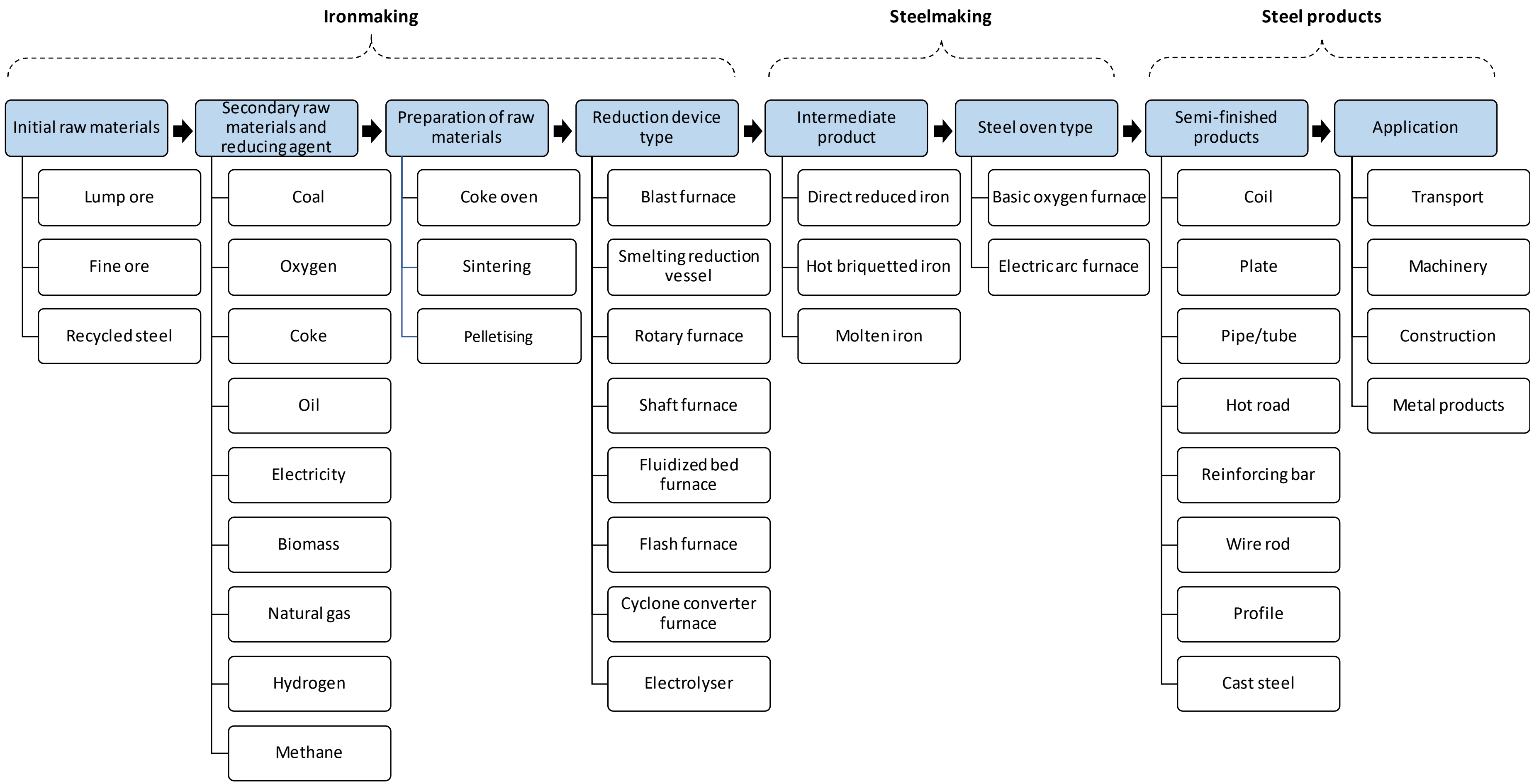


Figure 11 - Different source of aggregates with their production stage (adapted from (Bringezu, 2002; Langer, 2016))

8.3 Production of reinforcement

As schematically represented in Figure 12, the literature shows that iron and steel production (ironmaking, steelmaking and steel products) are divided in 2-3 main steps, and each one can be made with different procedures, machine and materials. Therefore, the number of routes to produce iron and steel is very high. In other words, for each production step, companies have developed many pathways for iron and steel production to decrease CO_2 emissions and energy consumption of each process. As stated in various studies (Conejo et al., 2019; Moya and Pardo, 2013; Pardo and Moya, 2013), the routes of iron and steel production can be identified in two main implementations:



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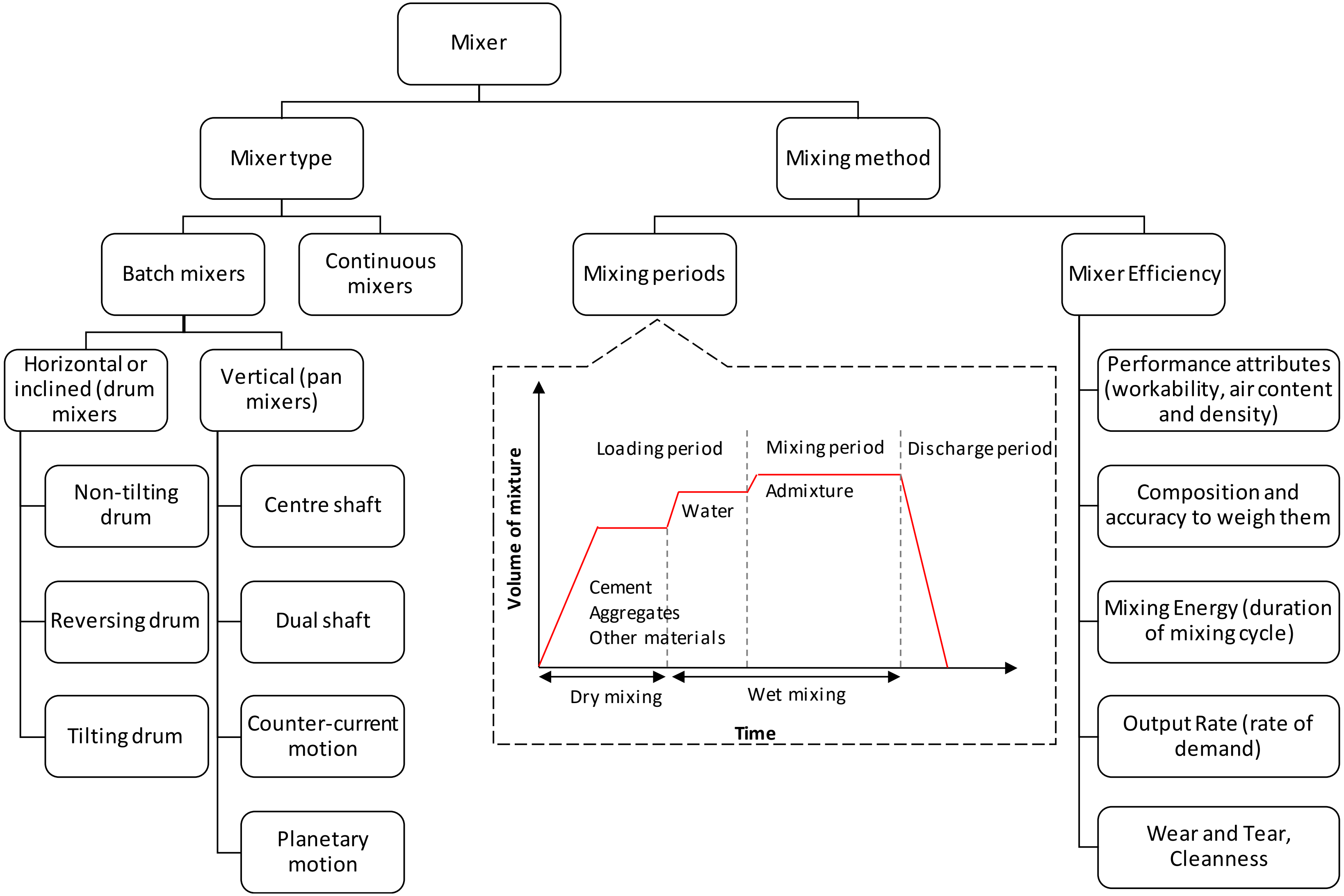
1197 Figure 12 - Simplified iron and steel production routes (adapted from (Conejo et al., 2019; Fischedick et al., 2014; Moya and Pardo, 2013; Pardo and Moya, 2013))

(i) “Best available technologies” that can highly decrease EI and energy consumption such as blast oxygen furnace waste heat and gas recovery (Jouhara et al., 2018; McBrien et al., 2016; Vance et al., 2019; Zhang, Q. et al., 2017), coke dry quenching (Lin et al., 2009; Sun et al., 2015; Wang, J.-G. et al., 2019a; Wang, J.-G. et al., 2019b; Yang et al., 2009; Zhang, M. et al., 2018), continuous casting (Chu et al., 2019; Huang et al., 2017; Hulkó et al., 2016; Pineda Huitron et al., 2020; Sousa Rocha et al., 2019; Tian, C. et al., 2019; Vynnycky and Zambrano, 2018; Wang, L.-t. et al., 2012; Yang, W. et al., 2019; Zappulla et al., 2020), optimized sinter pellet ratio (Cheng et al., 2016; Huang, X. et al., 2019; Liu et al., 2015; Zhou et al., 2015), oxy-fuel burners (Hernandez et al., 2019; Hu, Y. et al., 2019; Ilbas et al., 2018, 2019; Li, B. et al., 2018; Mayr et al., 2017; Wall et al., 2011), pulverized coal injection (Practice 99/00696, 1999; Practice 99/01486, 1999; Tiwari et al., 2018; Wu et al., 2019), scrap preheating (Arink and Hassan, 2017; Oh et al., 2015; Selvaraj et al., 2014), sinter plant waste heat recovery (Guoqun, 2009; Jouhara et al., 2018; SHIBUYA et al., 1981; TANAKA, 1980), stove waste gas heat recovery (Moya and Pardo, 2013; Pardo and Moya, 2013) and top gas recovery turbine (Cai et al., 2017; Liu, M. et al., 2019; Wu and Yang, 2012);

(ii) “Most innovative technologies”, whose use is not universal or at the moment are under development and intended to be ready for commercialization such as carbon capture and storage - blast furnace/power plant (Arasto et al., 2014; De Ras et al., 2019; Deng and Adams Ii, 2020; Goto et al., 2011; Yasipourtehrani et al., 2020), COREX (Han et al., 2013; Hu et al., 2009; Li, H.-f. et al., 2012; Practise 98/02347, 1998; Ziebik et al., 2008), direct sheet plant, FINEX (Thaler et al., 2012; Xiaoguang et al., 2008), HISARNA (Meijer et al., 2011; Qu, 2013; van der Stel et al., 2013), HYL/MIDREX/ULCORED (Atsushi et al., 2010; Cheeley, 1999; Garza, 2006; Knop et al., 2009) and top gas recycle blast furnace (Liu, L. et al., 2018; Zhang, W. et al., 2017). Nevertheless, studies show that there is still not a significant improvement in most proposed and available routes. Furthermore, future research directions can be seen in (Conejo et al., 2019; Zhang, W. et al., 2017).

9 Concrete mixing

Concrete can be made in plants (ready-mixed) or on-site (mixer). Besides its high energy consumption, concrete mixing affects the quality/homogeneity of concrete. Thus, both aspects must be considered in terms of sustainability. Generally, many different mixers and mixing methods commercially available have been used to produce concrete based on quality, cost, transportation scenario, volume of concrete and rate of demand. As shown in (Ferraris, 2001), different types of mixer and mixing methods must be considered to guarantee the quality of concrete (Figure 13). Some of the parameters shown in the figure have been considered in the construction sector without any proper study and others have been studied by researchers, e.g. operation design (Beitzel, 1984), performance attributes (Ferraris, 1999), mixing time and type of concrete mixer (Johansson, 1971), effectiveness of concrete mixers (Bartos, 1993; Valigi and Gasperini, 2007), mixing energy (Soga et al., 1986), workability and mixing (Bartos, 1993), efficiency of mixer (Charonnat and Beitzel, 1997), volumetric-measuring and continuous-mixing (Cheff et al., 1991), concrete mixers and mix systems (Dils et al., 2012; Sonnenberg, 1998), concrete mixes preparation (Sinenko et al., 2018), sensor to monitor the effect of the mixing procedure (Wang and Hu, 2005), mixing degree (Siiriä and Yliruusi, 2009) and mix design using adaptive neural fuzzy inference systems (Deligiannis and Manesis, 2008; Neshat and Adeli, 2011; Neshat et al., 2012). Additionally, most of the studies are related to the quality of concrete. Attempts to decrease the energy consumption of each process are very scarce.



1239

1240 Figure 13 - Mixer type and mixing method of concrete

10 On-site application

To build a concrete structure, most of the stages of construction, namely (i) pre-construction and pre-placement meetings (ii) concrete ordering procedures (iii) transporting and receiving concrete (iv) conveying, placing, consolidating and finishing concrete (v) concrete protection and curing requirements, must be considered to minimize potential problems, EI, energy consumption, cost and time to build a structure. Nevertheless, since this path relates to the site itself and needs a bigger scale than laboratory, individual studies with systematic data comparing the EI and energy consumption of traditional and non-traditional applications of the above mentioned stages are very rare. Among the mentioned stages, digital concrete/3D printing has been recently focused by several research groups.

Automated and additive manufacturing (AM) techniques with traditional and non-traditional cementitious materials, i.e. 3D concrete printing, shotcrete 3D printing and smart dynamic casting have been rapidly adopted in many fields. The introduction and development of this technology in construction happened in the early 21st century after Khoshnevis et al. (Khoshnevis et al., 2001) proposed the contour crafting 3D printing methodology for construction applications. They used robotic arms with a trowelled nozzle to create a better finish of the printed concrete. This path can be considered one of the sustainability strategies because it does not need manual labour and formwork. Though this path can be more economically viable due to less manual labour, it is not so socially acceptable since it will mean fewer jobs. Furthermore, these two parameters' cost may exceed 50% of the total cost of a concrete structure (Johnston, 2008). Although AM comprises many 3D printing techniques, only a few are feasible for construction purposes. Two of the most promising examples are extrusion 3D printing technique (Buswell et al., 2018; Shakor, P et al., 2019), and the binder (inkjet) 3D printing technique (Dini, 2009; Shakor, Pshtiwan et al., 2019b). These are suitable and the most applicable techniques for construction purposes (Shakor, Pshtiwan et al., 2019a). These techniques generally use mortar materials, and hence current limitation are that they cannot use coarse aggregates in the mix design due to abrasion in the pump unit, there are difficulties in feeding and the shape ability of concrete (Hosseini et al., 2019; Shakor et al., 2020a; Shakor et al., 2020b; Tay et al., 2017; Zhang, Y. et al., 2018). The other outstanding research challenges in this field are compaction (Le et al., 2012; Shanjani and Toyserkani, 2008; Wolfs et al., 2018), the gaps between layers (Kazemian et al., 2017; Panda et al., 2018; Perrot et al., 2015; Shakor et al., 2020a), the printed material's porosity (Hambach and Volkmer, 2017; Shakor et al., 2017), and the nozzle of the printhead (Bos et al., 2016; Buswell et al., 2018; Nerella et al., 2019; Shakor, P et al., 2019). In addition, studies on the durability performance of the printed CBM are very rare.

11 Increase the durability of reinforced concrete

One way to reduce EI of concrete is by increasing its durability. There are several direct (intrinsic method) and indirect (extrinsic method) ways to achieve this strategy, namely by slowing down/stopping rebars from corroding (§11.1), preventing penetration of aggressive agents to concrete (§11.2), slowing down degradation of concrete (§11.3) and durability design (§11.4). Intrinsic methods involve changing everything in the actual reinforced concrete either by changing concrete itself (e.g. additions, mix design and cover) or using more resistant steel rebars. Extrinsic methods could probably involve the use of paint or hydrophobic coatings among other methods. Generally, these strategies may increase the initial cost and EI of the structure. However, it may also considerably reduce costs or EI over the structure's life cycle (long term) because the number of rehabilitations necessary in low-performance concrete is higher than in high-performance concrete. Thus, the total cost of low-performance concrete will be closer to that of high-performance concrete with every rehabilitation (Figure 14).

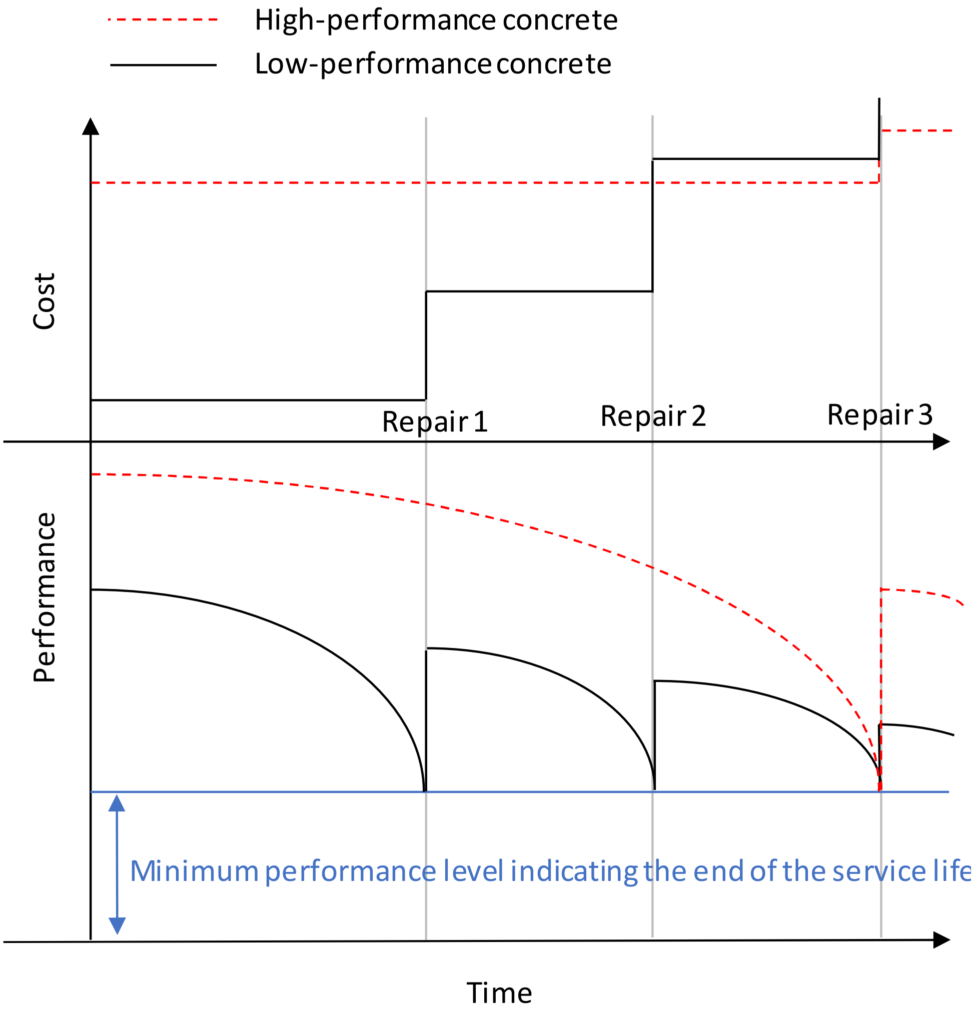


Figure 14 - Cost and performance, including rehabilitation cost, *versus* service life for high- and low- performance concrete

11.1 Slow down/stop rebar corrosion

11.1.1 Stainless-steel rebars

The corrosion resistance and chloride threshold of stainless steel rebars (SSR) are about 800-1500 and 4-24 times higher than those of the conventional bars, respectively (Lollini et al., 2019; McDonald et al., 1998; Van Niejenhuis, 2015; Vinoth Jebaraj et al., 2017). Due to its importance in the construction industry, several standards from EU (EN 10088-1, 2005), UK (BS 6744, 2016), USA (ASTM A955/A955M-19, 2019) and guideline reports (Markeset et al., 2006; Mietz, 1997; SSINA) have been developed. Generally, stainless steel can be divided in four types: (i) Austenitic (most widely used type (Mietz, 1997) with high range of corrosion resistance (Calderon-Uriszar-Aldaca et al., 2018; Markeset et al., 2006; Rabi et al., 2019; Tsouli et al., 2018; Tsouli et al., 2019)); (ii) Ferritic (relatively to other SSR types, it has lower range of corrosion resistance (Arrayago et al., 2018; Markeset et al., 2006)); (iii) Austenitic-ferritic (also called duplex stainless, is a combination between austenitic and ferritic SSR). Comparing to other SSR types, austenitic-ferritic is cheaper and rated in the very high range of corrosion resistance (Duarte et al., 2014; Li, X. et al., 2018; Markeset et al., 2006; Pachón-Montaño et al., 2018; Rabi et al., 2019)); (iv) Martensitic (it is not recommended to be used as reinforcement (Markeset et al., 2006) because it has minimal ductility (Darvell, 2018)).

Generally, SSR are rarely used in the construction field because they may increase the initial cost of the structure by as much as 6-10 times (Gu and Hong Meng, 2016). However, it may also considerably reduce costs over the structure's life cycle (long term), especially for bridges (Cope and Labi, 2009) and rehabilitation (Gu and Hong Meng, 2016; Perez-Quiroz et al., 2008). In addition, stainless-steel-clad rebar was introduced in the market in the past decade (Basham, 1999). They have a conventional carbon steel core covered with a thin outer cladding of stainless-steel. They basically perform similarly to solid stainless-steel rebars (Gu et al., 1998). However, they require following more demanding specifications for cutting and bending (CRSI, 2013).

Further studies are required to identify chloride threshold values of different types and grades of SSR, and corrosion risk when it contacts carbon steel. In addition, researchers are only focused on Austenitic SSR (Calderon-Uriszar-Aldaca et al., 2018; Tsouli et al., 2018; Tsouli et al., 2019). It is clear that a review study needs to be made to understand recent developments in stainless steel.

11.1.2 Low-carbon chromium reinforcing steel rebars

High corrosion resistant reinforcing steel can be made either by solid stainless steel (high chromium content, specified in AASHTO (AASHTO MP 18M/MP 18-15, 2015) - §11.1.1) or by low-carbon chromium (low chromium content, specified in ASTM (ASTM A1035 / A1035M-19, 2019)). Even though this type of steel is identified in standard (ASTM A1035 / A1035M-19, 2019), related studies are very limited (Callaghan, 1993; CRSI - ETN-M-11-17, 2017; CRSI, 2013; Darwin et al., 2002; EIG, 2011; Kahl, 2007; Lee, 2018; Sharp et al., 2011) and most of them are not associated with concrete reinforcement.

11.1.3 Epoxy-coated rebars

In this sub-strategy, conventional rebars are coated with epoxy to increase their corrosion resistance and act as a physical barrier, and their chloride threshold value is above or equal to that needed to initiate corrosion in regular steel rebars (Manning, 1996; McDonald, 2016; Venkatesan et al., 2006). According to previous studies, epoxy-coated rebars (ECR) with damage level of 0.004-0.50% may increase the corrosion resistance of rebars by 69-1762 times (Basham, 1999; Gustafson and Neff, 1994; Smith and Virmani, 1996), and their cost is lower than that of other rebars. However, their performance may not be guaranteed because the coating may be damaged during bending, handling, placing, transportation, and concrete casting. For example, recent studies (Sagüés et al., 2001; Smith and Virmani, 1996) show several cases where ECR-reinforced concrete (made in the past 30 years) failed due to corrosion issues. Therefore, an update of the service life of structure containing ECR needs to be done, especially for structures made 30 years ago. So far, there is no systematic review study on the performance of concrete with ECR. Even though there are some case studies on the application of ECR in bridge decks (Smith and Virmani, 1996), bridges (Sagüés, A.A. et al., 1994), marine bridges (Sagues et al., 2010), marine environment (Smith et al., 1993), marine substructures (Sagüés, A. et al., 1994), and tunnel structures (Montes et al., 2004) relative to other sub-strategies (§11.1.1, §11.1.4, §11.1.6-11.1.8), case studies on this path are very limited (Dong et al., 2012; Lee, J. et al., 2018; McDonald, 2016; Swamy and Koyama, 1989; Wang, X.-H. et al., 2018; Zhou and Qiao, 2018). Furthermore, there are some attempts to increase the bond strength between ECR and concrete (Chang et al., 2002; Yeih et al., 2004), and overcome the issue of damaging spots of the ECR by using self-healing epoxy coatings (Weishaar et al., 2018).

11.1.4 Galvanized rebars

Another sustainable way to increase the reinforcement durability is by normal hot-dip galvanizing (zinc coated/metallic coated) (Andrade and Macias, 1988; Bellezze et al., 2006; Bellezze et al., 2018; Figueira et al., 2015; Hamad and Jumaa, 2008a, b; Kayali and Yeomans, 2000; Luna Molina et al., 2017; Sayadi et al., 2016a; Sena-Cruz et al., 2009; Tittarelli and Moriconi, 2010; Wang, Y.-q. et al., 2018; Zheng, H. et al., 2018). Even though the chloride resistance of galvanized rebars (GR) is only 2-4 times higher than that of conventional rebars (Porter, 1991, 1994; Zhang, 2013), it can be considered more cost-efficient than ECR (§11.1.2) because it is more difficult to damage, even though it is 40% more expensive than ECR (Luna Molina et al., 2017; Zheng, H. et al., 2018). In low-performance concrete exposed to aggressive environments, galvanized rebar may not necessarily extend the service life of reinforced concrete (Yeomans, 2004). Similarly to ECR, galvanizing decreases the bond strength between concrete and reinforcement (Arup, 1979; Belaïd et al., 2001; Pokorný et al., 2015; Robinson, 1956). Some review studies have analysed the technical performance of GR in concrete and its application in the construction industry (Pokorný et al., 2017; Yeomans, 2004). One way to promote using GR and offset its cost is by using it in concrete (e.g. FA concrete) in which durability, namely carbonation, is an issue. However, studies on the performance of GR in fully carbonated concrete are very limited (Roventi et al., 2014).

11.1.5 Basalt rebars

Basalt rebars are made with inert volcanic rock (basalt) and have been used as a fibre (Ayub et al., 2014; Borhan, 2013; Brik, 2003; Dhand et al., 2015; Dias and Thaumaturgo, 2005; Fan and Zhang, 2016a; Inman et al., 2017; Jiang et al., 2014; Lipatov et al., 2015; Monaldo et al., 2019; Serbescu et al., 2015) for strengthening purposes (secondary reinforcement) and as main reinforcement (Adhikari, 2013; Fan and Zhang, 2016b; Kumbhar, 2014; Lapko and Urbański, 2015; Urbanski et al., 2013) in concrete. They have higher tensile strength than that of standard steel rebars (Kumbhar, 2014; Lapko and Urbański, 2015), but lower modulus of elasticity that may significantly increase the deflection of a structure (Lapko and Urbański, 2015). Also, it has higher resistance to corrosion and less weight relative to standard steel rebars (Lipatov et al., 2015; Smith, 2018). Additionally, they are non-hygroscopic, and non-conductive thermally or electrically (Santhosh et al., 2018; Zhang, Y. et al., 2012). Generally, studies on basalt rebars as main reinforcement (mini bars) are very limited (Adhikari, 2013; Fan and Zhang, 2016b; Kumbhar, 2014; Lapko and Urbański, 2015; Urbanski et al., 2013).

11.1.6 Glass fibre reinforced-polymer rebars

Similarly to basalt, glass FRP can be used in concrete as fibres (Asokan et al., 2009; Dehghan et al., 2017; Mastali et al., 2016) or main reinforcement (Dong et al., 2019a; Dong et al., 2019b; El-Hassan et al., 2018; Zhao et al., 2019). In this section, however, the focus is on their performance as the main reinforcement.

Some review articles were made to understand the performance of glass FRP on the following topics: in aggressive environments (Fang et al., 2019), structural applications (Fang et al., 2019; Mugahed Amran et al., 2018), strengthening (Aslam et al., 2015; Mugahed Amran et al., 2018), near-surface in reinforced concrete structures (Al-Saadi et al., 2019), composites materials (Bakis et al., 2002; Sathishkumar et al., 2014), and the their chemical and mechanical performance (DiBenedetto, 2001). Generally, the tensile strength of glass FRP rebars is higher than that of standard steel rebars, but their modulus of elasticity is significantly lower. Thus, they may not be advisable for structural concrete, especially when it involves significant spans. Nevertheless, these rebars do not corrode at all and, in terms of weight, glass FRP rebars are lighter than standard steel rebars. In addition, they are thermally and electrically nonconductive.

The bearing capacity of structures with glass FRP rebars significantly decreases at elevated temperatures (Zhao et al., 2019). In addition, glass FRP is immune to both chloride contamination and many forms of chemical-induced degradation (Almusallam and Al-Salloum, 2006; Kim et al., 2008; Micelli and Nanni, 2004; Mukherjee and Arwikar, 2005; Robert et al., 2009; Tannous, 1998). Several studies concluded that columns with glass FRP rebars have lower carrying capacity than those with standard steel rebars (Elchalakani and Ma, 2017; Hassan et al., 2019; Khorramian and Sadeghian, 2017). Furthermore, bond between glass FRP rebars and normal (Achillides and Pilakoutas, 2004; Baena et al., 2009; Benmokrane et al., 1995; Hao et al., 2009; Okelo and Yuan, 2005; Saleh et al., 2019; Tastani and Pantazopoulou, 2006)- and high- strength (Hossain et al., 2012; Lee et al., 2017; Lee et al., 2008; Lee et al., 2012; Tekle et al., 2016) concrete is another issue of this type of reinforcement.

Generally, most of the studies focused on the performance of glass FRP rebars in columns (Afifi et al., 2013; De Luca et al., 2010; Hadi and Youssef, 2016; Karim, H. et al., 2016; Mohamed et al., 2014; Pantelides et al., 2013; Paramanantham, 1994) and beams (Almusallam and Al-Salloum, 2006; Aslam et al., 2015; Reis and Ferreira, 2003; Said et al., 2016; Zhao et al., 2019). However, studies on their performance in slabs are very limited (Deitz et al., 1999). In addition, most of the studies only focused on the present limitations of glass FRP and not on future improvements.

The performance of concrete filled glass FRP circular tubes (Fam and Cole, 2007; Fam and Mandal, 2006; Fam and Rizkalla, 2002; Mohamed and Masmoudi, 2010; Wang and ElGawady, 2019; Xie et al., 2018) or rectangular shaped FRP cross-sections (Abouzied and Masmoudi, 2017; Aslani et al., 2019; Aydın and Sarıbıyık, 2013; Belzer et al., 2013) is another application of FRP that researchers are now working on. However, knowledge on this path is still very limited.

11.1.7 Carbon fibre reinforced-polymer rebars

Carbon FRP is a type of composite material composed of polymer and carbon fibres. The carbon fibres give the stiffness and strength, and the polymer works as a cohesive-matrix to protect and hold the fibres together. Even though carbon FRP rebars have been studied in many aspects such as durability performance in general (Ceroni et al., 2006; Karbhari et al., 2003), fire resistance (Hollaway, 2010; Uomoto and Nishimura, 1999), stiffness (Takewaka and Khin, 1996), flexural strengthening (Bogas and

Gomes, 2008; Ferrari et al., 2013; Triantafillou et al., 2001), tensile (Cao et al., 2009), pull-out capacity (Barros and Sena-Cruz, 2002; de Sena Cruz and Oliveira de Barros, 2004), bond strength (Teng et al., 2006; Yun et al., 2008), shear behaviour (Zhang, H. et al., 2019), and even GWP (Das, 2011; Song et al., 2009), relative to glass FRP rebars studies on carbon FRP rebars are more limited (Barros and Sena-Cruz, 2002; Bogas and Gomes, 2008; Cao et al., 2009; Ceroni et al., 2006; Das, 2011; de Sena Cruz and Oliveira de Barros, 2004; Ferrari et al., 2013; Hassan and Rizkalla, 2002; Hollaway, 2010; Karbhari et al., 2003; Kobayashi and Fujisaki, 1995; Rasheed, 2014; Song et al., 2009; Takewaka and Khin, 1996; Teng et al., 2006; Triantafillou et al., 2001; Uomoto and Nishimura, 1999; Yun et al., 2008; Zhang, H. et al., 2019). Their seismic performance, and long-term behaviour and durability when exposed to harsh environment have not been extensively studied yet.

In addition, there are other types of FRP rebars such as aramid (Djafar-Henni and Kassoul, 2018; Leung and Burgoyne, 2001; Noritake et al., 1993; Sonnenschein et al., 2016; Uomoto and Nishimura, 1999; Wang and Wu, 2011) and glass-carbon (Kang et al., 2014) that can be used as reinforcement in concrete structure.

11.1.8 Corrosion inhibiting admixtures

The service life of concrete significantly depends on the corrosion rate of steel bars (Hansson et al., 1998; Tuutti, 1982). Thus, several methods (§11.1.1-§11.1.7) have been proposed to prevent steel bars from corroding and to extend the service life of reinforced concrete structures as a result. Relatively to other techniques, corrosion inhibitors are one of the most efficient and appropriate methods due to their low cost, excellent corrosion resistance effect, and easy application (Christodoulou et al., 2010; El-Hacha et al., 2010; Jiang et al., 2017; Karthick et al., 2016; Królikowski and Kuziak, 2011; Saraswathy and Song, 2007b; Zheng et al., 2012). As defined in a ASTM standard (ASTM C1582 / C1582M-11(2017)e1, 2017), corrosion inhibitors can be used to inhibit chloride-induced corrosion of reinforcing steel in concrete. Generally, there are no accurate data regarding the effect of corrosion inhibitors on the carbonation resistance of concrete, which is considered one of the two most influential factors on the service life of concrete and corrosion of rebars together with chloride penetration resistance.

As shown in Figure 15, the corrosion resistance of concrete depends on the reinforcement concrete cover (time - t_o) and rebars corrosion resistance (time - t_1). Each of these periods depends on different factors. Thus, corrosion inhibiting admixtures depending on their type (organic and inorganic) can affect either the concrete cover (reducing the permeability) or the rebars (forming a protective film) by (i) increasing the chloride threshold value (by improving the resistance of the passive-film or creating a barrier-film and extending its lifetime - t_0 - as a result (Hansson et al., 1998)), (ii) decreasing chloride diffusion rate (increasing t_0 (Hansson et al., 1998; Tuutti, 1982)), (iii) increasing the degree of chloride binding of concrete (decreasing the movement of ions on the metallic surface and increasing t_1 (Hansson et al., 1998; Lee, H.-S. et al., 2018; Tuutti, 1982)), (iv) eliminating the dissolved oxygen in the pore system and preventing the ingress of oxygen (increasing t_1 (Hansson et al., 1998)), or (v) increasing the electrical resistivity of the metallic surface (increasing t_1 (Lee, H.-S. et al., 2018)).

Based on several studies (Gaidis, 2004; Ormellese et al., 2006; Song and Saraswathy, 2006a; Vyrides et al., 2013), corrosion inhibitors can be classified based on mechanism (anodic and cathodic, or both actions), type of chemical (organic and inorganic/mixed inhibitors) and application (either on the surface of hardened concrete or mixed during the production stage). Most examples of corrosion-inhibiting admixtures can be seen in the USA standard (ACI 212.3R-10, 2010; ASTM C1582 / C1582M-11(2017)e1, 2017).

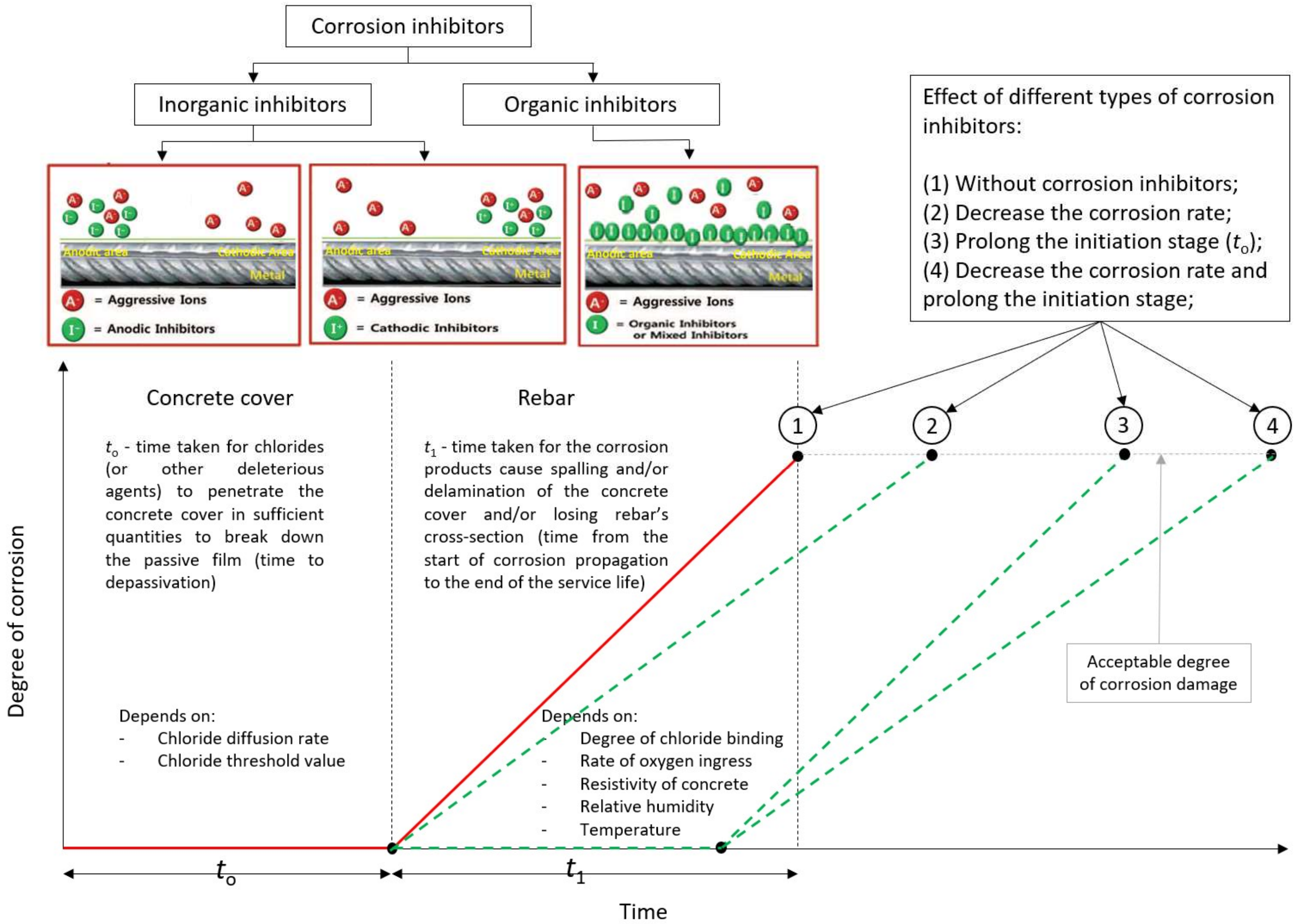


Figure 15 - Corrosion process of structural concrete as a function of lifetime with and without corrosion inhibitors (adapted from (Elsener and Angst, 2016; Hansson et al., 1998; Lee, H.-S. et al., 2018; Tuutti, 1982))

Several studies (Elsener and Angst, 2016; Hansson et al., 1998; Lee, H.-S. et al., 2018; Tuutti, 1982) simplified the electrochemical theory of corrosion, namely with and without the use of corrosion inhabiting admixtures. Under normal circumstances (non-protected metal surface), some parts of the rebars act as cathodes and others as anodes. With the presence of water and oxygen around the surface of rebar, corrosion will occur. Thus, the ultimate purpose of any corrosion inhibiting admixture or other protection systems (§11.1.1-11.1.4) is to stop fleeing/travelling electrons from the anodic area to cathodic area. This can be made by three protection mechanisms (i-iii):

(i) Anodic inhibitors can be named passivation inhibitors or sacrificial inhibitors. In electrochemical terms, the anodic reaction of the anodic inhabiting admixture must be more active than the anodic reaction of the surface of steel bars. There are two types of anodic inhibitors, non-oxidizing ions (phosphate, molybdates, and tungstate) and oxidizing anions (nitrates, chromates, and nitrites), working in the presence and absence of O_2, respectively. There are also inorganic-anodic inhibitors, such as chromates (Fernández Olmo et al., 2001), calcium nitrate (Ann et al., 2006), nitrates (Gaidis, 2004; Justnes, 2004), sodium nitrite (Song and Saraswathy, 2006a), and trisodium phosphate (Gallant and Simard, 2005; Sail et al., 2013).

(ii) Cathodic inhibitors may work similarly to anodic inhibitors by sacrificing themselves and producing a barrier film, and slowing the cathodic reaction on the surface of the metal (e.g. zinc, magnesium slats). Generally, anodic inhibitors are more effective than cathodic inhibitors because they generate less H_2. As stated in (Lee, H.-S. et al., 2018), in terms of chemical composition, corrosion inhibiting admixtures that mainly work as either anodic or cathodic mechanism can be identified as inorganic inhibitors. There are also inorganic-cathodic such as zinc oxide (Baiqing et al., 2003; Song and Saraswathy, 2006a).

(iii) Mixed inhibitors (pore blocker - hydrophobic material that has polar groups charged positively and negatively) act on the cathodic and anodic areas. There are also organic - chemisorption and - physisorption (mixed inhibitors) such as sodium ''nitrite+ zinc oxide'' (Song and Saraswathy, 2006a), triethanolamine (Song and Saraswathy, 2006a), monoethanolamin (Song and Saraswathy, 2006a), diethanolamine (Song and Saraswathy, 2006a), "disodium β-glycerol phosphate pentahydrate + sodium 3-aminobenzoate" (Criado et al., 2012), "disodium β-glycerol phosphate pentahydrate + sodium N-phenylanthranilate" (Criado et al., 2012), benzoate (Blustein et al., 2006), nitrite and ethanolamine (Asipita et al., 2014).

There are some issues that need to be answered concerning this path. For example, (i) how do the corrosion inhibitors work when concrete is fully carbonated or contaminated with salt-containing chloride ions? (ii) How long can the corrosion inhibitors protect the reinforcement of concrete structures? (iii) How to test corrosion inhibitors' reliability in laboratory to achieve practice-related results? In addition, most of the previous studies used commercially available corrosion inhibitors without providing their composition.

11.2 Slow down penetration of aggressive agents to concrete

11.2.1 Shrinkage control

Aggressive agents may penetrate concrete due to shrinkage cracks (Hewlett and Liska, 2019; Shami and Ian). To control the shrinkage of concrete, several strategies are proposed such as using shrinkage/crack-reducing admixtures (e.g. polyoxyalkylene alkyl ether and propylene glycol (ACI 212.3R-10, 2010; José Oliveira et al., 2014; Maltese et al., 2005; Meddah et al., 2008; Meddah et al., 2011; Mora-Ruacho et al., 2009; Pistolesi et al., 2009; Ribeiro et al., 2006; Schokker, 2010)), controlling the mix design (w/b and aggregate/binder ratios (Hewlett and Liska, 2019; Jensen and Hansen, 2001)), and applying a surface treatment (Xu and Chung, 2000c). In general, most of the materials used in concrete for self-healing can be included in this strategy, such as SCM (e.g. FA (Atiş, 2003; Kurda et al., 2019a), SF (Güneyisi et al., 2012) and metakaolin (Güneyisi et al., 2012)), metallic/steel fibres (Ghorbani et al., 2020; Susetyo, 2009; Yousefieh et al., 2017), polypropylene fibres (Karimipour et al., 2020; Sadiqul Islam and Gupta, 2016), cellulose fibres (Parviz and Siavosh), polystyrene aggregate (Tang et al., 2008), internal curing (e.g. light-weight aggregates (LWA) (Akcay and Tasdemir, 2010; Cusson and Hoogeveen, 2008; Kovler and Jensen, 2007), super-absorbent polymers (Jensen and Hansen, 2001; Kovler and Jensen, 2007), water-saturated recycled porous ceramic aggregate (Meddah and Sato, 2010; Suzuki et al., 2009)), and expansive agents (Collepardi et al., 2005; Hori and Morioka, 1999; Ito et al., 2004; Meddah et al., 2011; Mo et al., 2012). This strategy must be considered especially for self-compacting concrete (SCC) due to the high risk of shrinkage caused by the low volume of coarse aggregates (Barluenga and Hernández-Olivares, 2007).

11.2.2 Self-healing concrete

The self-healing (self-repairing) mechanism of concrete can be defined as the capability of concrete (or CBM) to repair its cracks by two processes, namely (a) autogenous and (b) autonomous (Figure 16). Several review studies can be seen on this path (Bekas et al., 2016; De Rooij et al., 2013; Gupta et al., 2017; He and Shi, 2017; Huseien et al., 2019; Muhammad et al., 2016; Rajczakowska et al., 2019; Sidiq et al., 2019; Souradeep and Kua, 2016; Wang, X.F. et al., 2019), but there are many contradictory statements in terms of the classification of the two mentioned process. This may have happened because some materials can be used for both purposes (autogenous - as a main healing material and as a secondary healing material to protect the main healing material).

(a) In autogenous self-healing (a natural phenomenon, spontaneous and self-created, that occurs without the presence of external/artificial phenomena), cracks may heal after some time due to (i) expansion of hydrated cementitious matrix, (ii) carbonation of calcium hydroxide, (iii) impurities present in water, and (iv) ongoing hydration of unreacted cement (Edvardsen, 1999). This healing mechanism occurs in the presence of the materials that are not specifically designed for self-healing (Van Tittelboom et al., 2013). In fact, they are added to concrete for other purposes, i.e. durability or strengthening.

(b) Contrary to autogenous self-healing, autonomous self-healing can include any technique that uses cementitious materials only for healing cracks. Bacteria-based (with and without shell) and capsule-based (polymer-based containing liquid healing agents) are the most common techniques in this path, but have not been applied in practice. Apart from the mentioned techniques, fungi, shape memory materials, and external supply of healing agent can be also classified as autogenous self-healing (Figure 16).

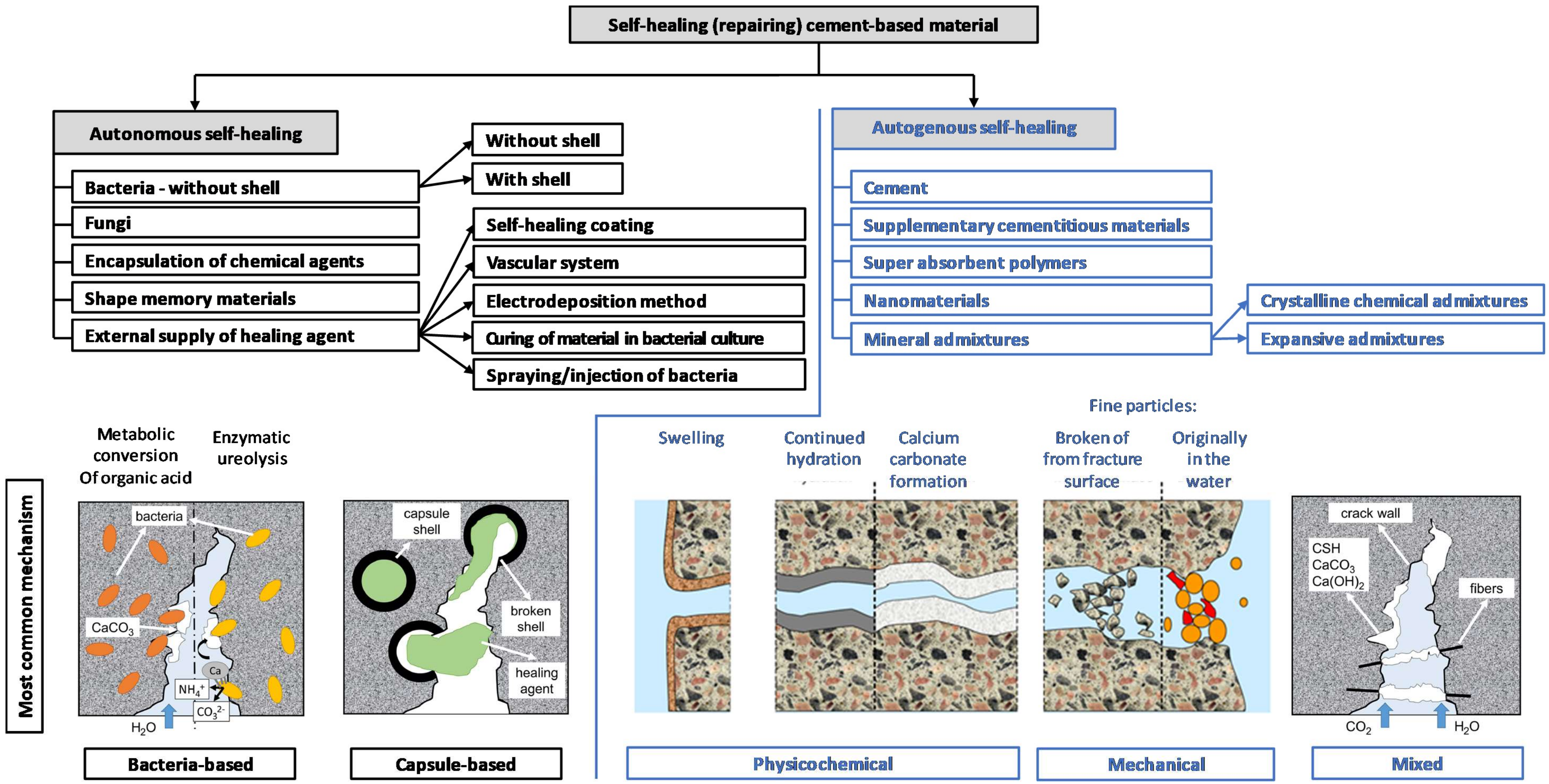


Figure 16 - Self-healing strategies in cement-based materials (adapted from (Bekas et al., 2016; De Rooij et al., 2013; Gupta et al., 2017; Huseien et al., 2019; Muhammad et al., 2016; Rajczakowska et al., 2019; Sidiq et al., 2019; Souradeep and Kua, 2016; Wang, X.F. et al., 2019))

11.2.2.1 Autonomous self-healing

11.2.2.1.1 Bacteria as self-healing agent

Bacteria are incorporated with cementitious materials as a potential self-healing agent because they motivate the precipitation of $CaCO_3$ as a crack-healing agent. Based on the metabolic processes, four types of bacteria can induce $CaCO_3$ precipitation, namely (i) aerobic respiration (Bhaskar et al., 2017a; Bundur et al., 2017c; Erşan et al., 2016a; Gupta et al., 2018; Li, W. et al., 2018; Seifan et al., 2018c; Wang, Jianyun et al., 2014; Wang, J. et al., 2012; Wang, J.Y. et al., 2014a; Wang, J.Y. et al., 2014b), (ii) nitrogen cycle (Alazhari et al., 2018; Erşan et al., 2015; Erşan et al., 2016a; Erşan et al., 2016b; Khaliq and Ehsan, 2016; Li, W. et al., 2018; Sierra-Beltran et al., 2014; Stuckrath et al., 2014; Tziviloglou et al., 2016; Wang, J.Y. et al., 2014b; Zhang, J. et al., 2017), (iii) photosynthesis (Baumgartner et al., 2006; Lee and Park, 2018; Siddique and Chahal, 2011), and sulphur cycle (Baumgartner et al., 2006; Braissant et al., 2007; Lee and Park, 2018). Further details on each of these bacteria types are shown in (Wang, X.F. et al., 2019).

In terms of application, bacteria can be directly added to the cementitious materials without shells (Bundur et al., 2017a; Bundur et al., 2017b; Jonkers et al., 2010; Luo et al., 2015a; Luo et al., 2015b; Mors and Jonkers, 2017; Qian et al., 2015; Sarkar et al., 2015; Siddique et al., 2017; Thiyagarajan et al., 2016; Williams et al., 2017; Xu and Yao, 2014) or they can be added with shells (encapsulation material) such as calcium alginate (Palin et al., 2017), ceramsite (Chen, H. et al., 2016), diatomaceous earth (Wang, J.-Y. et al., 2012), geopolymer (De Koster et al., 2015), hydrogel (Wang, JY et al., 2014a), iron oxide nanoparticle (Seifan et al., 2018a; Seifan et al., 2018b; Seifan et al., 2018c), expanded clay (EC) (Bundur et al., 2017c; Wiktor and Jonkers, 2011), melamine-based (Wang, JY et al., 2014b), polyurethane (Wang, J. et al., 2012), silica gel (Wang, J. et al., 2012), and zeolite (Bhaskar et al., 2017b). Compared to the direct addition of bacteria, the long-term viability of the bacteria with the encapsulation technique is higher because it protects bacteria from the high pH of the cementitious materials (Souradeep and Kua, 2016). Moreover, bacteria can be externally added to concrete (§11.2.2.1.4).

11.2.2.1.2 Fungi

Fungi can be multicellular or single-celled organisms such as yeasts and moulds. Some studies show that fungi can also fill the cracks in cementitious materials. However, studies on this path are very limited (Luo et al., 2018; Menon et al., 2017; Sidiq et al., 2019). Thus, as reported in (Talaiekhozan et al., 2014), the mechanism of fungi to fill cracks has not been fully understood yet.

11.2.2.1.3 Encapsulation of chemical agents

Encapsulation can be made by filling the capsule materials with a healing agent, i.e. bacteria (§11.2.2.1.1) or chemical agents (De Rooij et al., 2013; Kousourakis and Mouritz, 2010; Li, W. et al., 2017; Zhong and Post, 2015). In this section, the focus is only on the method with chemical agents. The self-healing-based encapsulation can be made with either micro- (De Rooij et al., 2013; Rajczakowska et al., 2019; Van Tittelboom et al., 2013) or tubular- (De Rooij et al., 2013; Ghosh, 2009; Joseph et al., 2010) capsules (the tube can be similar to a vascular system but it is filled with the healing agent and both ends are closed) filled with a chemical agent such as cyanoacrylate (Joseph et al., 2010; Van Tittelboom and De Belie, 2010), epoxy (Mihashi et al., 2001; Thao et al., 2009; Van Tittelboom and De Belie, 2010; Xing et al., 2008), acrylic resin (Mihashi et al., 2001), sodium silicate solution (Pelletier et al., 2011), "methyl methacrylate with triethylborane as catalyst'' (Yang, Z. et al., 2011), tung oil (Cailleux and Pollet, 2009), calcium hydroxide (Cailleux and Pollet, 2009), and polyurethane (Van Tittelboom et al., 2011). Additionally, the capsule material can be made with glass (Escobar et al., 2013; Joseph et al., 2010; Thao et al., 2009; Van Tittelboom and De Belie, 2010; Van Tittelboom et al., 2011), Perspex (Thao et al., 2009), urea formaldehyde formalin (Mihashi et al., 2001), gelatine (Cailleux and Pollet, 2009; Mihashi et al., 2001), formaldehyde (Xing et al., 2008), polyurethane (Pelletier et al., 2011), silica gel (Yang, Z. et al., 2011), ceramics (Cailleux and Pollet, 2009; Van Tittelboom et al., 2011), and others (Wang, X.F. et al., 2019).

11.2.2.1.4 External supply of healing agent

The external supply of healing agent can be related to many paths. Nevertheless, the paths mentioned in this section are related to the techniques that spontaneously work when cracks occur. This strategy can be made with hollow fibres and is called a vascular system. In this system, the healing agent is supplied to concrete by an external source through the hollow tubes previously installed in concrete at the fresh stage (Dry, 1994; Escobar et al., 2013; Huang et al., 2014b; Joseph et al., 2010; Sangadji and Schlangen, 2012). Generally, the tube can be made of glass (Al-Gemeel et al., 2018; De Rooij et al., 2013) or carbon fibre-reinforced plastic (De Rooij et al., 2013). This system can be made with single-channel when only one healing agent is used and multiple-channel when the healing agent involves the reaction of two components (Souradeep and Kua, 2016). This strategy is feasible only at laboratory scale and it may not be cost-efficient for bigger scales because it requires a long piping system to cover the entire structure (Souradeep and Kua, 2016) and it is difficult to release the agent from the pipe (De Rooij et al., 2013). Therefore, capsule-based self-healing can be considered as an alternative method.

Apart from the vascular system, this strategy can be also made by curing of material in bacterial culture (Tripathi et al., 2019), spraying of bacteria (Wiktor and Jonkers, 2015), injection of bacteria (Li and Qu, 2015; Sangadji et al., 2013), electrodeposition method (JIANG et al., 2004; Jiang et al., 2008; Modaresi et al., 2015; Nobuaki Otsuki and Eiji; Otsuki and Ryu, 2001; Ryou and Monteiro, 2004; Ryu and Otsuki, 2002), and self-healing coating (§11.2.3).

11.2.2.1.5 Shape memory materials as self-healer

Shape memory materials (SMM), i.e. alloy wire (Bonilla et al., 2018; Huseien et al., 2019; Sherif and Juan; Sun et al., 2013a; Wang, X.F. et al., 2019) or polymers (Huseien et al., 2019; Jefferson et al., 2010; Teall et al., 2018; Wang, X.F. et al., 2019) as reinforcing bar, are effective to reduce the size of cracks and increase the resistance of concrete to any damage actions due to their super-elastic behaviour (Choi, E. et al., 2014; Han et al., 2017; Kim et al., 2016; Kuang, Y. and Ou, J., 2008; Li et al., 2006; Li et al., 2007; Sakai et al., 2003; Song et al., 2006; Sun et al., 2013b). However, the cracks cannot be filled and still exist. SMM can be activated by electricity or heating to generate effective stress to facilitate energy dissipation and control cracks (Choi et al., 2017; Kim, D.J. et al., 2014; Nassiri-monfared et al., 2018). SMM fibres can be straight or dog-bone shaped, with and without paper wrapping in the middle (Choi, E. et al., 2014). A systematic review study must be done to show the types of materials that can be used for this purpose.

11.2.2.2 Autogenous self-healing

11.2.2.2.1 Supplementary cementitious materials

Apart from cement, many of the SCMs may work as autogenous self-healing materials (Rajczakowska et al., 2019). For that purpose, researchers have studied the feasibility of slag (Alyousif et al., 2015; Darquennes et al., 2016; Gruyaert et al., 2014; Huang et al., 2014a; Hung et al., 2018; Jiang, Z. et al., 2015; Kim et al., 2018; Mehdipour et al., 2018; Olivier et al., 2016; Qian et al., 2009; Qiu et al., 2016; Ryou et al., 2015; Schlangen et al., 2006; Van Tittelboom et al., 2012), FA (Alyousif et al., 2015; Gruyaert et al., 2014; Herbert and Li, 2012; Herbert and Li, 2013; Hung and Su, 2016; Hung et al., 2018; Kan and Shi, 2012; Liu, Hezhi et al., 2017; Ma et al., 2014; Mehdipour et al., 2018; Na et al., 2012; Özbay et al., 2013; Qian et al., 2009; Şahmaran et al., 2008; Sherir et al., 2016, 2017a, b; Siad et al., 2015; Siad et al., 2017; Suryanto et al., 2016; Termkhajornkit et al., 2009; Van Tittelboom et al., 2012; Yildirim et al., 2014; Zhang and Zhang, 2017), lime (Jo et al., 2015; Siad et al., 2015; Yildirim et al., 2015), silica (Jiang, Z. et al., 2015; Nishiwaki et al., 2015; Ryou et al., 2015), and metakaolin (Ryou et al., 2015) for monitoring autogenous crack healing in cementitious materials.

11.2.2.2.2 Super absorbent polymer

Super absorbent polymer (SAP) can absorb a great quantity of liquid and swell significantly to form an insoluble and soft gel (De Rooij et al., 2013; Van Tittelboom et al., 2013). It may work as a direct physical blocking effect after exposure to water and swelled, or it may work as an internal curing system and motivate autogenous healing (De Rooij et al., 2013; Pelto et al., 2017). Although this strategy causes autogenous healing, it can be also considered as autogenous because these materials are also added to concrete and do not belong to a typical mix design. For that purpose, it has been used in CBM (Didier, 2018; Hong and Choi, 2017, 2018; Lee, H.X.D. et al., 2016, 2018; Mechtcherine et al., 2013; Mechtcherine et al., 2017; Mignon et al., 2017; Snoeck and Belie, 2016; Snoeck et al., 2016; Snoeck et al., 2014). Nevertheless, uncoated SAP may absorb a part of concrete mixing water during the fresh state and generate a considerable amount of porosity in hardened concrete. To overcome this issue, the SAP particles are encapsulated with a shell to resist the mechanical stresses of mixing procedure and become fragile enough to be broken when a propagating crack passes through them (Pelto et al., 2017).

11.2.2.2.3 Expansive and crystalline admixtures

Another way to achieve autogenous self-healing can be through (i) expansive admixtures such as calcium sulpho aluminate (Wang, Xianfeng et al., 2018), MgO (Qureshi et al., 2016; Sherir et al., 2017a), CaO (De Nardi, Cristina et al., 2017; De Nardi, C. et al., 2017; Qureshi et al., 2016), anhydrite(Wang, Xianfeng et al., 2018), bentonite (Qureshi et al., 2016; Rehman et al., 2019); generally, they react with calcium hydroxide to procedure expansive products (e.g. calcium hydroxide, ettringite, magnesium carbonate and magnesium hydrate) and consequently fill the cracks; (ii) crystalline chemical admixtures that consist of hydrophilic active chemicals particles (ACI 212.3R-10, 2010) such as crystalline catalysts (De Nardi, Cristina et al., 2017; Ferrara et al., 2014; Roig-Flores et al., 2016; Wang, Xianfeng et al., 2018), sodium silicate (Alghamri et al., 2016; Beglarigale et al., 2018; Kanellopoulos et al., 2015), colloidal/active silica, sodium carbonate (Sisomphon et al., 2011; Wang, Xianfeng et al., 2018), sodium monofluorophosphate (Sisomphon et al., 2011). According to a previous study (Wang, X.F. et al., 2019), crystalline admixtures such as ethyl silicates sodium bicarbonate and lithium carbonate can be used for the same goal. In terms of application, the mineral admixture can be added to concrete by encapsulation (Alghamri et al., 2016; Beglarigale et al., 2018; Kanellopoulos et al., 2015; Qureshi et al., 2016) or direct (Ferrara et al., 2014) use or only by dipping the sample in a solution (Jacobsen and J. Sellevold, 1996). Studies on this path, namely using crystalline chemical admixtures in concrete, are very limited and, as presented by (Wang, X.F. et al., 2019), there might be other materials (e.g. ethyl silicates sodium bicarbonate and lithium carbonate) to be used for the same purpose.

11.2.2.2.4 Nanomaterials-based self-healing concrete

As any other autogenous self-healing strategies, the main purpose of using nanomaterials is to act as a crack bridging agent and in concrete as filler and enhance concrete's performance (Norhasri, M.S.M. et al., 2017; Reches, 2018). According to a review study (Huseien et al., 2019) on nanomaterials-based self-healing concrete, nanomaterials in self-healing concrete are added to control the corrosion of steel bar. Generally, several types of nanomaterials have been used in concrete such as carbon nanotube (CNT) (Ahmed et al., 2018a; Ahmed et al., 2018b; Bogas and Hawreen, 2019; Bogas, J. et al., 2019; Carriço et al., 2018; Cwirzen et al., 2009; Guedes et al., 2016; Hawreen, 2017; Hawreen and Bogas, 2018; Hawreen et al., 2018a; Hawreen et al., 2017; Hawreen and Bogas, 2019; Hawreen et al., 2018b; Hawreen et al., 2019), polycarboxylates (Norhasri, M.M. et al., 2017), titanium oxide (Sobolev et al., 2006), nanokaolin (Morsy et al., 2010), nanoclay (Morsy et al., 2010), nanoiron (Olar, 2011), nanosilver (Olar, 2011), and graphene (Chuah et al., 2014; Dimov et al., 2018).

11.2.2.2.5 Other techniques

The expression "smart concrete" can include most of the autogenous and autogenous self-healing strategies. Several studies on so-called smart concrete use carbon fibre (Chen and Chung, 1993; Chen and Chung, 2011; Pu-Woei and Chung; Sun et al., 2000; Van Mullem et al., 2019; Zhou et al., 2009), shape memory alloy (Kuang, Y.-c. and Ou, J.-p., 2008; Li et al., 2007), phase change materials (D'Alessandro et al., 2018) and sensors fabricated using nanotubes or others hybrid fillers (D'Alessandro et al., 2015; Han, B. et al., 2014; Loh et al., 2015).

11.2.3 Surface protection

According to review studies (Pan et al., 2017a, b), in terms of chemical composition, surface protection agents can be classified as: (i) organic, which is the most commonly used and effective technique to protect concrete (Delucchi et al., 1997); however, its service life is short, and it may not easy to remove (Delucchi et al., 1997; Pan et al., 2017a, b); (ii) inorganic, such as sodium silicate solution (most common), lithium silicate, fluosilicates and potassium silicates, which have been also used to protect the surface of concrete (Franzoni et al., 2013; Pacheco-Torgal and Jalali, 2009; Pan et al., 2017a, b).

In terms of mechanism, based on the strategies given in various studies (Esteves et al., 2019) (Dai et al., 2010; Duarte et al., 2020; Flores-Colen et al., 2020; Galvão et al., 2020; Medeiros and Helene, 2009; Pan et al., 2017a) and a standard (BS EN 1504-2), surface protection can be divided in four main groups (i) surface coating, (ii) multifunctional surface treatment, (iii) pore blocking surface treatment, and (iv) hydrophobic impregnation.

11.2.3.1 Surface coating

Surface coating creates a continuous polymer film that works as a physical barrier to stop aggressive agents penetrating into CBM (Almusallam et al., 2003; Diamanti et al., 2013; Pan et al., 2017a). As reported by (Pan et al., 2017a), in terms of composition, surface coating can be divided in three groups: (i) traditional polymer coatings such as epoxy resins (Ahmad et al., 2005; Chruściel and Leśniak, 2015; Moloney et al., 1987; Reddy and Sykes, 2005; Sangermano et al., 2013; Topçuoğlu et al., 2006; Velan and Bilal, 2000; Wetzel et al., 2003; Yamini and Young, 1977; Yarovsky and Evans, 2002; Zerda and Lesser, 2001), acrylic (Carretti and Dei, 2004; Chattopadhyay et al., 2004; Kozak, 2015; Lewis et al., 2012) and polyurethane/asphaltic (Awad and Wilkie, 2010; Elnaggar et al., 2019; Sørensen et al., 2009; Toutanji et al., 2013; Yang, X.F. et al., 2002a; Yang, X.F. et al., 2002b; Yang et al., 2001; Zur, 2010); (ii) polymer nanocomposite coatings such as polymer-clay (Hackman and Hollaway, 2006; Kojima et al., 1993; Scarfato et al., 2012; Woo et al., 2008b), silane-clay (Woo et al., 2008a), polymer-silica (Carmona-Quiroga et al., 2010; Manoudis et al., 2007; Woo et al., 2007); as confirmed in (Pan et al., 2017a), polymer-Al_2O_3 as coating has potential for this path but it has not been investigated yet; (iii) mixed coatings, such as polymer modified cementitious coating (Diamanti et al., 2013), acrylic rubber surface coating (Swamy and Tanikawa, 1993), and alkali-activated materials coating (Aguirre-Guerrero et al., 2017; Balaguru, 1998; Salwa et al., 2013; Zhang, Z. et al., 2012; Zhang et al., 2010).

11.2.3.2 Hydrophobic impregnation

By coating the surface of hardened concrete with hydrophobic agents (water repellent) such as silane and/or siloxane (Johnson et al., 2009; Li, H. et al., 2012; Medeiros and Helene, 2008; Pan et al., 2017a; Woo et al., 2008a), the surface of interior-pores of concrete can be increased increasing the surface contact angle between concrete and liquid to more than 90° (Kulkarni and Shaw, 2015). Thus, this technique inhibits water and other aggressive liquid from penetrating through the pores of concrete by capillarity, even though humidity can enter or exit. This strategy can be also applied by incorporating nanoparticles (Esposito Corcione et al., 2018; Li, G. et al., 2018), acrylic-silicon resin (Edao et al., 2012), micro silica particles (Mora et al., 2019), GGBS (Qu and Yu, 2018), and stearic acid emulsion (Feng et al., 2019).

Recently, superhydrophobic coatings have also been developed by researchers. They can include ammonium polyphosphate(Chen et al., 2015), calcium carbonate nanoparticle (Chen, B. et al., 2016), candle soot (Deng et al., 2012; Iqbal et al., 2017; Li, J. et al., 2017; Seo et al., 2014), carbon black/polybutadiene elastomeric composite (Hu et al., 2017), cyanoacrylates (Pan et al., 2018), epoxy resin (Peng et al., 2018), graphene oxide/diatomaceous earth/polydimethylsiloxane (Liu, Hui et al., 2017), polyelectrolyte complexes

(Coclite et al., 2012), silver nanoparticles (Liu, F. et al., 2014), SiO_2 (de Francisco et al., 2015; Zhi et al., 2017), TiO_2 (Ghosh et al., 2014; Lu et al., 2015), wax (Wang et al., 2016), and RHA (Husni et al., 2017; Junaidi et al., 2016; Ramachandran et al., 2016).

11.2.3.3 Pore blocking surface treatment

This strategy intends to block the capillary-pores in the concrete surface to increases its watertightness and hardness. For that purpose, fluosilicate (Jia et al., 2016; Jiang, L. et al., 2015; Pan et al., 2016) and silicate-based solutions (e.g. sodium silicate (Dai et al., 2010; Jiang, L. et al., 2015; Pan et al., 2016), calcium silicate (Moon et al., 2007)) have been used as an effective agent to block capillary-pores in concrete surfaces.

Electro-kinetic nanoparticle treatment (Kupwade-Patil et al., 2012; Wu et al., 2016b) and brushing nano-SiO_2 (Hou et al., 2014; Hou et al., 2015) and nano MgO (Pan et al., 2017a; Shah et al., 2016) can be also used as a pore blocking surface treatment. Additionally, this strategy can be also be made with self-healing coating by using epoxy coating containing microencapsulates (Chen et al., 2017; Nesterova et al., 2011; Samadzadeh et al., 2011), fibres distributed in a shape-memory epoxy matrix (Luo and Mather, 2013), hydrogel coatings (Yang et al., 2015), polymer coatings (Bode et al., 2013; Cho et al., 2009; Huang et al., 2012; Song et al., 2013). Although the results of this path are very promising, there are only few studies focused on this strategy.

11.2.3.4 Super skin concrete

The term super skin concrete can be defined as a thin ultra-high-performance concrete used to protect and be filled with ordinary concrete. It may resist the ultimate load of the structure and improve durability. It can work as a typical concrete-filled steel (Han, L.-H. et al., 2014; Yang, H. et al., 2008; Yuan and Yang, 2013) or FRP (Zhang, B. et al., 2015) tubular cross-section. This strategy is normally used in rehabilitation to cover old concrete. However, there are only few scientific works on this path for beams (Martins et al., 2018) and columns (Kim et al., 2017).

11.3 Reduce degradation rate of concrete

11.3.1 Alkali-aggregate reaction

Generally, aggregates can be considered an inert material from a chemical point of view. However, some of them may react with the alkali-hydroxides in concrete, resulting in expansion and cracking over time. The alkali-aggregate reaction may induce concrete damage in two forms: alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR).

ASR damages concrete due to the presence of reactive silica in the aggregate, alkalis mainly from cement, and moisture (FHWA-RD-03-047, 2016; Lindgård et al., 2012; Liu, K. et al., 2018; Thomas et al., 2012). To prevent or mitigate ASR, the following paths have been considered: (i) SCMs, namely FA, are the most common solution to prevent ASR (Shayan et al., 1996; Shehata and Thomas, 2002; Sibbick and Page, 1995; Thomas et al., 2011; Thomas et al., 1997). Other SCMs, such as SF (Shehata and Thomas, 2002), GGBS (Arano and Kawamura, 2000; Bleszynski et al., 2002; Thomas et al., 1997), metakaolin (Ramlochan et al., 2000) and other calcined clays, RHA (Khan et al., 1985) and natural zeolites (Naiqian and Tingyu, 1998), can be also used for the same purpose; (ii) chemical admixture, such as lithium salt (Ohama, 1992; Sakaguchi, 1989), air-entraining admixtures (Ohama, 1992; Ratinov and Rosenberg, 1989), hydration controller (Ekolu et al., 2007; Hobbs, 1988), ilanes, siloxanes, and silicofluorides (Nakajima et al., 1992; Saucier and Neely, 1987), and phosphate (Diamond, 1992); (iii) using nonreactive aggregates complying with standards ASTM C294 (ASTM C294-05, 2005) and C1293 (ASTM C1293, 2018), CSA A23 (Rogers, 1990); BS 7943 (Institution, 1999), RILEM AAR (Sims and Nixon, 2003), AASHTO PP65 (AASHTO PP65, 2016) and other standards collected in a review study (Lindgård et al., 2012); (iv) limiting the total alkali content of concrete to 1.8-3 kg Na_2O_e per m^3 (ASTM C1293, 2018; FHWA-RD-03-047, 2016; Rogers, 1990). Apart from cement, alkalis may have also come from some specific SCM, aggregate, chemical admixtures, recycled water and outer sources such as de-icing salts and seawater (FHWA-RD-03-047, 2016; Lindgård et al., 2012; Swamy, 2002).

Relatively to ASR, ACR damage in concrete is rare and it mainly happens when a specific type of aggregates (dolomitic rocks) or clay is present in the matrix (Farny and Kosmatka, 1997; Swenson and Gillott, 1964). In terms of mechanism, there is no consensus on how ACR affects concrete (Beyene et al., 2013). Future paths to prevent ASR and ACR damage in concrete have been identified in (Lindgård et al., 2012).

11.3.2 Freeze-thaw resistance

Water expands when it freezes. Accordingly, as water inside concrete pores freezes, its volume increases and consequently generate pressure. This may rupture and dilate the concrete voids if it is higher the tensile strength of concrete. As reported in (Ebrahimi et al., 2018), frost resistance can be improved in four ways: (i) hindering crack propagation by using CNT (Kumar et al., 2015; Li, W.-W. et al., 2015), PVA fibre-reinforcement (Jang et al., 2014; Nam et al., 2016), graphene oxide (Mohammed et al., 2016; Tong et al., 2016) nano silica (Behfarnia and Salemi, 2013) and nano TiO_2 (Salemi et al., 2014); additionally, there are some novel surfactants that can work as air entraining agents (Chen et al., 2018; Qiao et al., 2017); (ii) refining pores and decreasing the porosity of concrete by using SCMs (e.g. FA (Chung et al., 2010), SF

(Hooton, 1993; Sabir, 1997), metakaolin (Duan et al., 2013; Moradgholi and Irandegani, 2014), RHA (Park et al., 2014; Salas et al., 2009), GGBS (Duan et al., 2013; Li et al., 2011)) and fillers; (iii) reducing water absorption by using hydrophobic admixtures in concrete (Ebrahimi et al., 2018); (iv) introducing additional space for ice-expansion in concrete by adding air-entraining admixtures (Shang et al., 2014; Shang and Yi, 2013).

11.3.3 Resistance to other physical and chemical attacks

The effect of aggressive soils (sulphates and other salts), abrasion, marine salt exposure, soft water and cyclic wetting-drying must also be considered in advance to predict the service life of concrete. For example, a study (Douglas Hooton, 2019) collected all current specifications and codes and showed requirements for each of the mentioned issues in various standards in America, Europe, Australia, Canada, and China. To improve durability regarding the mentioned issues, industrial SCM (§4.2), slowing down or stopping penetration of aggressive agents (§11.2) and unconventional reinforcement (§11.1) have been used in concrete. Additionally, the durability design (§11.4) is the most important factor to overcome the mentioned issue.

11.4 Durability design

The factors that affect durability design are shown in Figure 17. All the factors at the material level, structural level, external factors and design stage must be considered in advance to obtain a durable design. In other words, such design may not increase the service life of a new concrete structure, but rather it guarantees/controls a given service life of concrete by providing a baseline for the engineering judgment of the most relevant factors affecting durability of concrete. Nevertheless, durability design has been considered as key to improve concrete's sustainability (Hooton and Bickley, 2014) and it should be considered based on concrete's application.

Besides quality control and quality assurance, reliability of the considered data (input parameters) (von Greve-Dierfeld and Gehlen, 2016) (Pacheco et al., 2019) and of modified models (e.g. DuraCrete (DuraCreteR17, 2000), Life-365® (Thomas and Bentz, 2001), STADIUM®(STADIUM®), fib Bulletin 34 (Helland, 2013), concrete Works (Folliard et al., 2008) LIFEPRED (Andrade and Tavares, 2012), ClinConc (Tang, 1996), DuraCon (Gjørv, 2009), durability Index (Mackechnie, 1995) and approach (Alexander et al., 1999)) is required to estimate the service life of concrete (Alexander and Beushausen, 2019; Müller, 2010). Future paths for durability design of concrete structures have been identified in (Alexander and Beushausen, 2019; Demis and Papadakis, 2019; Douglas Hooton, 2019).

12 CO_2 mineralization and utilization (carbon capture and storage)

The greenhouse gases emission generated by the cement industry can be decreased by capture (storage and sequestration) of CO_2 directly from cement plants (§8.1) or by CO_2 sequestration by mineral carbonation. Generally, alkaline earth (e.g. Mg and Ca), alkali (e.g. K and Na) and other metals such as Zn, Cu, Ni, Co, Fe and Mn can be carbonated to capture CO_2. Nevertheless, most of these elements are either very expensive or rare and not suitable to be used as feedstock for CO_2 mineralization. For example, alkali metals have a great affinity to CO_2 and they are very soluble for CO_2 sequestration, especially in the long-term. In addition, although there is a substantial amount of Fe in nature, it is not suitable to be carbonated because it involves valuable iron ore. In fact, Mg (e.g. serpentinite (Krevor and Lackner, 2009; Li, W. et al., 2009; Zevenhoven et al., 2008), dunite- olivine (Andreani et al., 2009; Koukouzas et al., 2009) and basalt (Olajire, 2013) rocks) and Ca (wollastonite (Bałdyga et al., 2010; Daval et al., 2009; Kawatra et al., 2011) and basalt (Olajire, 2013) rocks) are the most suitable elements to capture high amounts of CO_2 because they are more common in nature than other potential metals (Huijgen and Comans, 2003). As reported in (Jang et al., 2016; Peter et al., 2008), CO_2 capture in CBM can be made by carbonation of calcium hydroxide (Johannesson and Utgenannt, 2001; Peter et al., 2008), calcium silicate hydrates (Bukowski and Berger, 1979; Goto et al., 1995; Kobayashi et al., 1994; Suzuki et al., 1985; Young et al., 1974), calcium sulfoaluminate hydrates (Grounds et al., 1988; Nishikawa et al., 1992), cement clinker minerals (Brunauer and Copeland, 1964; Chang et al., 2016; Goodbrake et al., 1979), and magnesium-derived hydrates (Bobicki et al., 2012; Pu and Unluer, 2016). CO_2 sequestration is affected by exposure conditions (e.g. CO_2 partial pressure/content (Bukowski and Berger, 1979; Mo et al., 2016), temperature (de Larrard et al., 2010; Liu et al., 2001), CO_2 source (Haselbach and Thomle, 2014; Jang et al., 2015)) and properties of cement-based materials (e.g. water content (Fattuhi, 1988; Fernández Bertos et al., 2004; Walton et al., 1997), chemical composition (Meier et al., 2007; Peter et al., 2008), particle size and surface area (Fernández Bertos et al., 2004; Jang et al., 2016), porosity and permeability (Poon et al., 1986; Roy et al., 1999)).

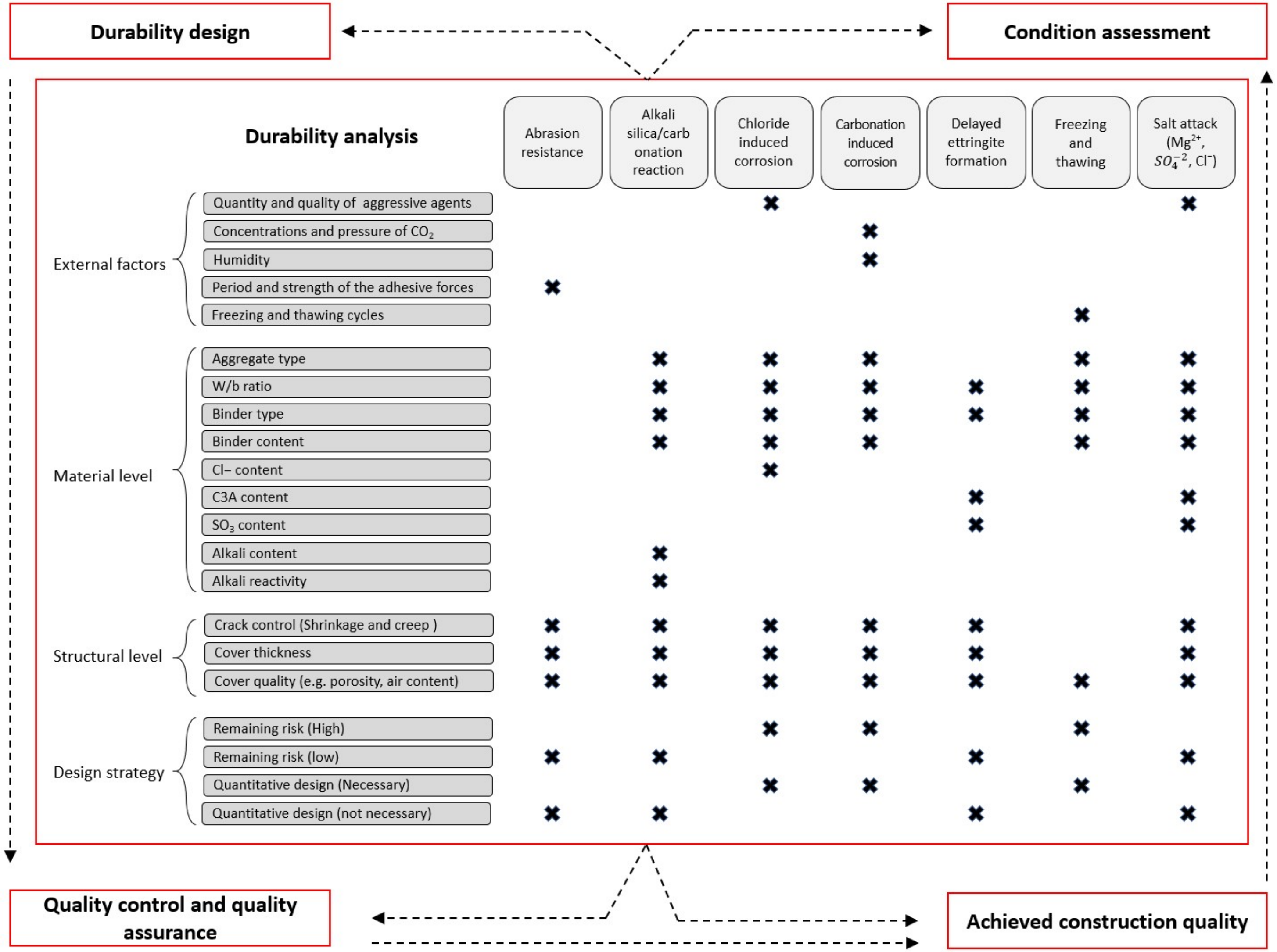


Figure 17 - Durability design, quality assurance and operation of new concrete in severe environments (adapted from (Demis and Papadakis, 2019; Douglas Hooton, 2019; Ebrahimi et al., 2018; Gjørv, 2008, 2016; Jianxia, 2012; Li, K. et al., 2019))

Concrete can be cured in a carbonation chamber (Meng et al., 2019; Vandeperre and Al-Tabbaa, 2007) or using other novel techniques such as aqueous CO_2 solution (Lippiatt et al., 2019) to promote and accelerate CO_2 sequestration. Besides magnesium (Choi, S.-w. et al., 2014; Gao et al., 2007; Gao et al., 2013; Mavroulidou et al., 2015; Pu and Unluer, 2016; Unluer and Al-Tabbaa, 2013) or calcium -rich materials (Morales-Flórez et al., 2011), SCMs (Bobicki et al., 2012; Choi, S.-w. et al., 2014; Dindi et al., 2019; Galan et al., 2010; Gao et al., 2007; Gao et al., 2013; Jang et al., 2016; Kurda et al., 2019b; Mavroulidou et al., 2015; Wang, Y. et al., 2019) (mostly FA), cement waste (Uliasz-Bocheńczyk and Pomykała, 2011), CDW (Kaliyavaradhan and Ling, 2019), and nano-materials (Hosseini et al., 2011) can also be used for CO_2 sequestration.

Critical issues and areas for further investigation in this path have been identified in several studies (Ghoshal and Zeman, 2010; Hillebrand et al., 2016; Huijgen and Comans, 2003; Jang et al., 2016; Kaliyavaradhan and Ling, 2017; Naraharisetti et al., 2019; Olajire, 2013; Salek et al., 2013; Sharma et al., 2019). To link this path with industry, recycled aggregates made with concrete containing materials rich in Mg or Ca can be used as a filter to sequestrate CO_2 and other greenhouse gases generated by the industry. For that purpose, a chamber with a given pressure and humidly needs to be built and filled with the aggregates. Then, the greenhouse gases can be passed through this chamber in order to be sequestrated by the aggregates before they are released.

13 Thermal conductivity improvement and energy saving

The energy expenditure in a building throughout its service life can be far greater than that expended for its construction. Saving energy in the form of heat or air conditioning for many years is one of the best approaches to achieve sustainability. One way to decrease the amount of heat transfer through conduction and of energy consumption of buildings is by reducing the thermal conductivity (k-value) of concrete. As reported in (Asadi et al., 2018), the thermal conductivity of concrete may be affected by the following parameters (§13.1-13.4).

13.1 Moisture content and temperature's impact

Since the k-value of air is 25 times lower than that of water (Bessenouci et al., 2014; Shin and Kodide, 2012), the k-value of concrete with high moisture content or in the SSD state is higher than in the oven dry state (Abdou and Budaiwi, 2005; Jin, H.-Q. et al., 2016; Taoukil et al., 2013; Wang et al., 2017a). For example, a study (Zhang, W. et al., 2015) showed that the k-value of SSD concrete is 50% higher than that of dry concrete, and other studies showed that the k-value of concrete increases by 6%

(Valore, 1980) and 5% (Steiger and Hurd, 1978) with 1% increment in unit weight and moisture content, respectively. In addition, the k-value of concrete significantly falls as temperature increases (dos Santos, 2003; Khaliq and Kodur, 2011; Liley, 1984; Shin et al., 2002; Wang et al., 2017a; Weidenfeld et al., 2002).

13.2 Type and proportion of aggregates and other additional materials

Since aggregates have the lion share of the volume of concrete, the k-value of concrete significantly changes by using different types and proportions of aggregates. For example:

(i) Natural aggregates such as basalt (Khan, 2002), limestone (Khan, 2002), siltstone (Khan, 2002), or others contain large amount of the following minerals: quartz (Chan, 2014; Khan, 2002), feldspar (Chan, 2014), (metamorphic) gneiss (Chan, 2014), amphibole/pyroxene (Chan, 2014) and iron ore magnetite (Chan, 2014);

(ii) Lightweight materials (rounded or angular/irregular), mainly EC (commercial names Leca (Real et al., 2016), Argex (Real et al., 2016; Yun et al., 2013)), expanded slate (commercial name Stalite (Real et al., 2016; Yun et al., 2013)), expanded shale (commercial name Asanolite (Yun et al., 2013)), pumice (Newman and Owens, 2003; Topçu and Uygunoğlu, 2007; Uysal et al., 2004) and sintered FA (commercial names Lytag (Real et al., 2016)). There are few studies on the following LWA, namely perlite (Gül et al., 2007; Tandiroglu, 2010), cenospheres (Blanco et al., 2000; Huang et al., 2013), polyurethane foam (Chen and Liu, 2013; Mounanga et al., 2008), diatomite (Topçu and Uygunoğlu, 2007), expanded glass (Chung et al., 2016; Yu et al., 2013), silica aerogel (SA) (Gao et al., 2014; Gomes et al., 2018; Hanif et al., 2016; Li, P. et al., 2019), high-impact polystyrene (Wang and Meyer, 2012), iron ore tailings (Huang et al., 2013), wood shavings (Bederina et al., 2007), manufactured plastic aggregate (Alqahtani et al., 2017), dry lime-hemp (Arrigoni et al., 2017; Dhakal et al., 2017; Piot et al., 2017; Tran-Le et al., 2019), and biochar (Akhtar and Sarmah, 2018b);

(iii) AWAF such as oil palm shell (Abdullah, 1984), palm fibre (Benmansour et al., 2014), coconut shell (Gunasekaran and Kumar, 2008), corncob (Pinto et al., 2011) rice husk (Buratti et al., 2018; Chabannes et al., 2014; Chabi et al., 2018; Marques et al., 2019), tobacco wastes (Ozturk and Bayrakl, 2005), sheep wool fibres (Grădinaru et al., 2016). Studies on this path are very scarce;

(iv) Phase change material and others.

Phase change materials (PCM) are normally placed inside a building to reduce its energy consumption and enhance indoor thermal comfort due to their potential to store and absorb heat (Sá et al., 2012; Zhang et al., 2013) in the phase change from liquid to solid and vice versa, during exothermic and endothermic phenomena (Souayfane et al., 2016). Based on the review study (Shafigh et al., 2018), PCM can be classified as organic (paraffin and non- paraffin) and inorganic (hydrated salts). Recently, some studies (Eddhahak-Ouni et al., 2014; Meshgin and Xi, 2013; Shafigh et al., 2018) (Aguayo et al., 2017; D'Alessandro et al., 2018; Sakulich and Bentz, 2012; Šavija, 2018; Shi et al., 2014) showed that PCM can be used in CBM to decrease their k-value. Nevertheless, further studies need to be made to see whether there are any negative effects of the PCM on other technical properties of CBM. Other cementitious materials that increase the reflection of sunlight and absorb less heat (Shirakawa et al., 2014; Werle et al., 2016), and soil-based materials (Arooz and Halwatura, 2018; Deboucha and Hashim, 2011; Jayasinghe and Kamaladasa, 2007) can be other promising paths within this strategy.

13.3 Binder content and type

Binder content and type may also affect the k-value of CBM. Nevertheless, their influence is not significant compared to other factors mentioned in other sections. Generally, the most often used SCMs within this path are FA (Demirboğa and Gül, 2003; Kim et al., 2003; Yun et al., 2013), SF (Demirboğa, 2007; Demirboğa and Gül, 2003; Xu and Chung, 2000a) and slags (Demirboğa, 2007; Kim et al., 2003)). In addition, SCMs (e.g. CBA) can be also used as aggregates (Baite et al., 2016). A study (Demirboğa and Gül, 2003) showed that the k-value increases with increasing binder content of concrete.

13.4 Natural fibres

Natural fibres (NF) can also be used in CBM, most commonly to improve their thermal insulation (Benmansour et al., 2014). However, most of the previous studies (Al-Rifaie and Al-Niami, 2016; Belakroum et al., 2018; Hamzaoui et al., 2014; Kriker et al., 2005; Lima et al., 2014; Ozerkan et al., 2013; Tian et al., 2016; Tioua et al., 2017) concluded that the technical properties of the cementitious materials decrease as the incorporation ratio of NF increases. According to these studies (Ali, 2012; Onuaguluchi and Banthia, 2016; Peças et al., 2018; Sanal and Verma, 2017), NF can be divided in two main groups: (i) plant/lignocellulosic fibre such as seed (e.g. cotton (Aghaee and Foroughi, 2013; Binici and Aksogan, 2015) and kapok (Onuaguluchi and Banthia, 2016)), stalk (e.g. tree wood (Bederina et al., 2012; Stahl et al., 2002; Tchehouali et al., 2014), wheat (Merta and Tschegg, 2013), rice (Chabannes et al., 2014; Xie et al., 2016) and barley (Belhadj et al., 2014) straws, and crops such as bamboo (Mohanty and Nayak, 2010) and corn (Jarabo et al., 2013)), leaf (e.g. abaca (Coutts and Warden, 1987), agave, banana and sisal (Ramakrishna and Sundararajan, 2005; Savastano and Agopyan, 1999; Silva et al., 2010; Toledo Filho et al., 2003)), fruit (e.g. coir/coconut (Sanjuán and Tolêdo Filho, 1998)), blast/stem-skin (e.g. jute

(Chakraborty et al., 2013), flax (Coutts, 1983; Fic et al., 2013) and hemp (Arrigoni et al., 2017; Arsene et al., 2007; Dhakal et al., 2017; Piot et al., 2017; Sedan et al., 2008) and banana (Arsene et al., 2007)), grass (e.g. bagasse (Onésippe et al., 2010), elephant (Merta and Tschegg, 2013) and bamboo (Correia et al., 2014)), root (e.g. broom root (Castro and Naaman, 1981; Momoh and Osofero, 2019)), and other by-products of plant (e.g. cellulosic (Savastano et al., 2000), and cellulose pulp (Correia et al., 2018)); (ii) animal fibre (Benaimeche et al., 2019) such as animal hair (wool (Grădinaru et al., 2016)), silk and avian (feathers of birds (Acda, 2010)); further development within this path are summarised in (Onuaguluchi and Banthia, 2016); (iii) mineral fibres (ceramic (Su and Xu, 2013; Su et al., 2014), asbestos (Marino et al., 2001; Xu et al., 2010), and metal (Miroslaw and Surendra; Naaman and Najm; Narayanan and Darwish; Parviz and Cha-Don)).

In addition, NF can be also used in composites materials. For example, a natural fibre reinforced polymer composite has been developed using sisal (Fung et al., 2003; Joseph et al., 2002; Joseph et al., 1999; Ku et al., 2011; Li et al., 2000), hemp (Keller, 2003; Khoathane et al., 2008), short jute (Rana et al., 2003) and flax (Li, X. et al., 2009; Panigrahy et al., 2006). A study (Mohammed et al., 2015) collected examples of the application of natural fibre reinforced polymer composites in the industry and reported that it can be used instead of asbestos (Agopyan et al., 2005; John and Thomas, 2008), and is ideal to be used in roofs, ceilings and walls due to its lightweight.

13.5 Density and microstructure

Apart from the parameters shown in §13.2-13.3, the k-value of CBM is significantly affected by w/b (Kim et al., 2003), volume of aggregates (Kim et al., 2003), size and proportion of sand and gravel (Kim et al., 2003; Zhang, W. et al., 2015) (e.g. no-fines concrete (Ghafoori and Dutta, 1995; Malhotra; Riley et al., 2019)), porosity (Khan, 2002; Kim et al., 2003) (e.g. foam concrete/aerated concrete (Ghazi Wakili et al., 2015; Kalpana and Mohith, 2019; Liu, S. et al., 2018; Othuman and Wang, 2011; Pehlivanlı et al., 2016; Tian, S.-Q. et al., 2019; Ulykbanov et al., 2019)), and nature of the pores (Khan, 2002). All these parameters directly affect the density of CBM. As shown in Figure 18, regardless of the type of used materials (i-iii), it can be said that density of concrete is the major parameter to change the k-value of any type of CBM (paste, mortar and concrete).

Figure 18 shows that ACI committee 213 R-03 model (k-value = $0.0864e^{0.00125\cdot density}$)) can be used as a reliable model for any type of materials. By comparing the actual and calculated k-value (Figure 18-inset graphs), the coefficient of determination (R^2) with the ACI committee 213 R-03 model (upper inset graph) was 0.66. This coefficient can be increased to 0.77 (lower inset graph) by modifying the mentioned model (0.85·(0.0764-$\frac{w/b}{40}$) $e^{(0.00141*density*(60\%+w/b))}$), namely by considering the w/b ratio.

In general, most of the studies are focused on the effect of various parameters (e.g. aggregates, SCM and w/b) on either SSD or oven-dried concrete. However, in a real situation, these two states rarely occur in CBM. Therefore, as reported in (Asadi et al., 2018), the focus of the future studies within this path must be on the effect of humidity in concrete for any selected parameters.

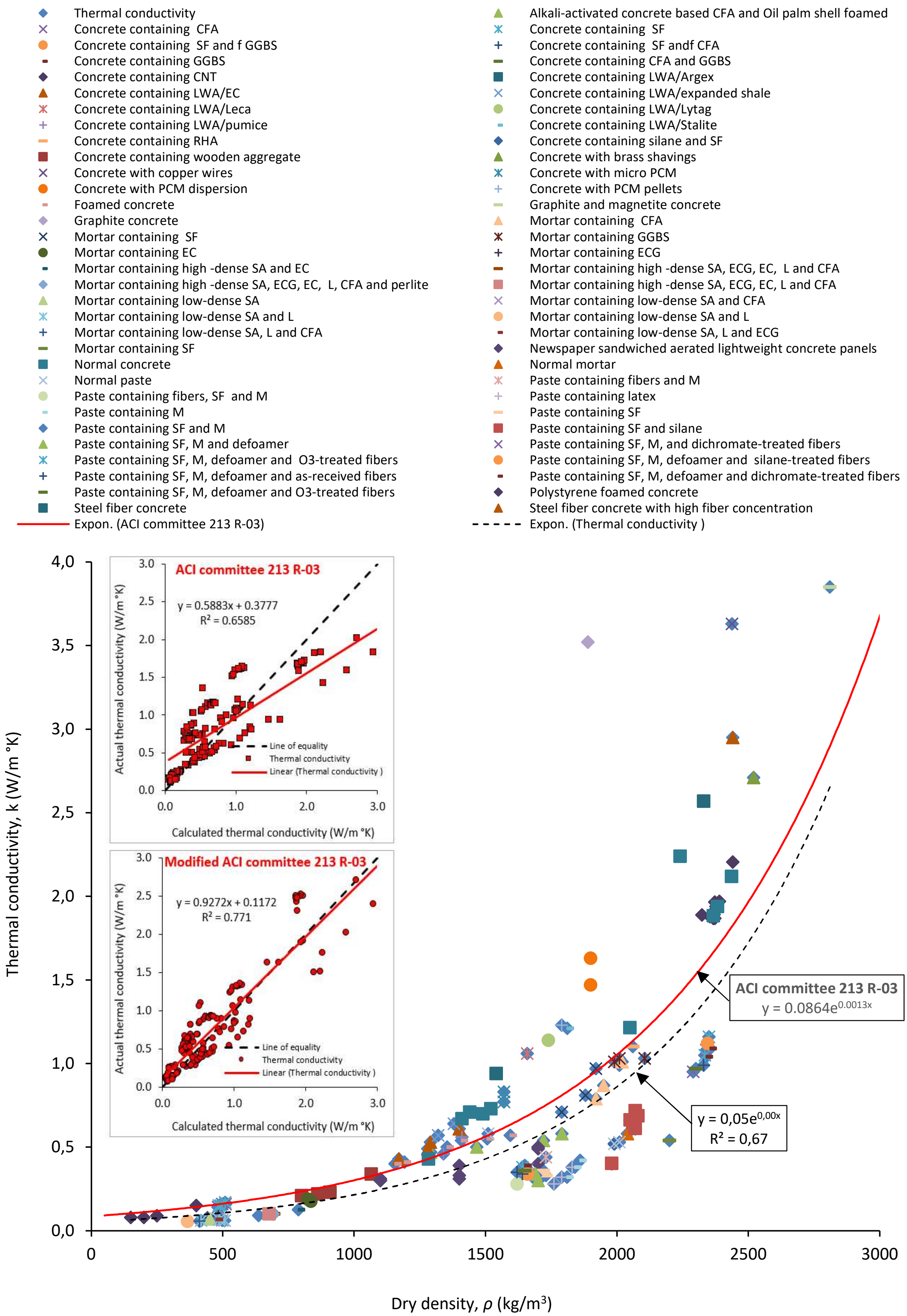


Figure 18 - Density and thermal conductivity of cement-based materials

(i) Normal concrete (Bouguerra et al., 1998; Ferraro and Nanni, 2012; Hawreen, 2017; Nguyen et al., 2017; Wadsö et al., 2012), newspaper sandwiched aerated lightweight concrete panels (Ng and Low, 2010), polystyrene foamed concrete (Sayadi et al., 2016b), alkali-activated concrete based FA and oil palm shell (Liu, M.Y.J. et al., 2014), concrete containing FA (Demirboğa, 2007; Demirboğa and Gül, 2003), SF (Demirboğa, 2007; Demirboğa and Gül, 2003), SF and GGBS (Demirboğa, 2007), SF and FA (Demirboğa, 2007), GGBS (Demirboğa, 2007), FA and GGBS (Demirboğa, 2007), CNT (Hawreen, 2017), lightweight aggregates - LWA/Argex (Real et al., 2016), LWA/expanded clay (EC) (Ng and Low, 2010), LWA/expanded shale (Ng and Low, 2010), LWA/Leca (Real et al., 2016), LWA/Lytag (Real et al., 2016), LWA/pumice (Nguyen et al., 2017), LWA/Stalite (Real et al., 2016), RHA (Ferraro and Nanni, 2012), silane and SF (Xu and Chung, 2000a), wood-based aggregate (Bouguerra et al., 1998), brass shavings (Wadsö et al., 2012), copper wires (Wadsö et al., 2012), micro PCM (Wadsö et al., 2012), PCM dispersion (Wadsö et al., 2012), PCM pellets (Wadsö et al., 2012), foamed concrete (Johnson Alengaram et al., 2013), graphite and magnetite (Wadsö et al., 2012), graphite (Wadsö et al., 2012), and steel fibres (Wadsö et al., 2012);

(ii) Normal mortar (Xu and Chung, 2000b), mortar containing FA (Demirboğa, 2003), SF (Demirboğa, 2003), GGBS (Demirboğa, 2003), EC (Gomes et al., 2017), expanded cork granules (ECG) (Gomes et al., 2017), High-dense SA and EC (Gomes et al., 2017), high-density SA, ECG, EC, lime (L) and FA (Gomes et al., 2017), high-density SA, ECG, EC, L, FA and perlite (Gomes et al., 2017), high-density SA, ECG, EC, L and FA (Gomes et al., 2017), low-density SA (Gomes et al., 2017), low-density SA and FA (Gomes et al., 2017), low-density SA and L (Gomes et al., 2017), low-density SA, L and FA (Gomes et al., 2017), low-density SA, L and ECG (Gomes et al., 2017);

(iii) Normal paste (Fu and Chung, 1997; Wadsö et al., 2012; Xu and Chung, 2000b), paste containing fibres and methylcellulose (M) (Fu and Chung, 1997), fibres, SF and M (Fu and Chung, 1997), latex (Fu and Chung, 1997), M (Fu and Chung, 1997), SF (Fu and Chung, 1997; Xu and Chung, 2000a), SF and M (Fu and Chung, 1997), SF and silane (Fu and Chung, 1997), SF, M and defoamer (Xu and Chung, 1999), SF, M, and dichromate-treated fibres (Xu and Chung, 1999), SF, M, and silane-treated fibres (Xu and Chung, 1999), SF, M, defoamer and O_3-treated fibres (Xu and Chung, 1999), SF, M, defoamer and silane-treated fibres (Xu and Chung, 1999), SF, M, defoamer and as-received fibres (Xu and Chung, 1999), SF, M, defoamer and as-received fibres (Xu and Chung, 1999), SF, M, defoamer and dichromate-treated fibres (Xu and Chung, 1999), SF, M, defoamer and O_3-treated fibres (Xu and Chung, 1999).

14 Summary

The aim of this study is to collect and organize the main sustainability strategies considered to offset the negative impact of CBM' production. Thus, the strategies are divided in 12 sections. In each one, a number of sub-strategies, future trends and their limitations are presented. Thus, the outputs of the main sections are briefly presented in the following paragraphs:

- **Reduce the total amount of binder.** Despite few studies on concrete with low binder content, the results of the literature show that, in opposition to the limitations imposed by standards, concrete with an acceptable performance can be produced by following the strategies mentioned in this paper such as using a w/b in which most the water content is absorbed by the hydration products (additional water is the main contributor to porosity);
- **Reduce the EI and resources use of binders.** Most of the strategies that decrease the EI and resources use of binders are related to replacing cement with by-products. Despite many case studies, this strategy may not be one of the best to decrease the EI of concrete, but it is still the most popular one because it is easy to perform. According to many studies, the biggest challenge on the use of many by-products in concrete structures is durability, namely in terms of carbonation (the mechanical characteristics of the concrete cross-sections can be compromised because of reinforcement corrosion). Nevertheless, this output resulted from laboratory tests (accelerated carbonation) that may not correctly reproduce reality. For example, some studies show that, even when carbonation resistance is designed for XC3 and XC4 exposure classes, concrete with common cover depth can protect rebars for more than 50 years even when using varying volumes of by-products;
- **Reduce the EI and resources use of aggregates.** Even though the consumption of natural aggregate is 12 times higher than that of cement, its EI relatively to cement is inconsequential. Nevertheless, the EI of aggregate production is still growing at an alarming rate compared to the capacity of Nature. This study shows that, besides natural aggregates and construction and demolition waste, there are many other potential sources (e.g. agricultural, industrial, municipal wastes) of aggregates in concrete. In most cases, aggregate's content and characteristics do not affect the durability of CBM (the main factor to define service life) as much as those of binders. However, the applicability of most non-traditional aggregates depends on the target-strength of concrete and the influence level varies a lot. Thus, many of the non-traditional aggregates have been recommended to be used in low-strength concrete only;
- **Increase the durability of reinforced concrete.** The biggest challenge of this strategy is the fact that normally the initial cost increases. However, it may also considerably reduce costs over the

structure's life cycle (long-term) because the number of rehabilitations necessary in low-performance concrete is higher than in high-performance concrete (also taking into account the very important role of the reinforcement concerning this issue). Thus, the total cost of low- performance concrete will get closer to that of high-performance concrete with every rehabilitation;

- **CO_2 mineralization and utilization (carbon capture and storage).** Low-carbon to near-zero-carbon cements is not possible without CO_2 capture by mineralization of CBM. This study shows that, apart from Mg, there are many other techniques and other potential metals that can capture high amounts of CO_2.
- **Thermal conductivity improvement and energy saving.** This analysis show that, regardless of the type of used materials (traditional or non-traditional), it can be said that density is the major parameter to determine the thermal conductivity of any type of CBM. Nevertheless, there is not a systematic study to suggest an optimum material among all the non-traditional materials in terms of thermal conductivity and quality of the CBM.
- **Material manufacturing.** This study shows that it is not possible to significantly decrease the EI and resources use of concrete without considering the production stage of the raw materials. Nevertheless, studies on this path for most of the materials are very scarce.

As shown in Figure 19, the following statements can be made about most of the selected strategies. Most of the researchers are mainly focused on the same common non-traditional techniques and materials (e.g. FA, SF, GGBS and RHA) with similar output. Nonetheless, there are many other non-traditional techniques and materials (e.g. low binder concrete; using many types of AWAF and municipal wastes as a binder or aggregates; nonconventional bars, production process of the main products by using different types of raw materials and energy; new site applications) that have not been investigated yet. The analysis also shows that there is a big scatter in characteristics of the uncommon non-traditional materials. Thus, they need to be classified in different categories in order to be used in CBM.

In conclusion, for the same non-traditional materials and techniques, many studies have been focused on few characteristics, ignoring most of the others. Thus, conclusions identifying a sustainable material or technique based on one aspect only (e.g. environmental impact, quality or costs) may not be reliable. For example, some strategies may decrease the CBM's EI. However, the strategy may decrease the CBM's durability performance and therefore reduce its service life. Thus, buildings may require further rehabilitation to obtain a target service life. Similar reasoning could be stated for costs, which is the most important parameter considered in business as decision-making. Thus, adequate strategies can only be defined using a holistic approach, in which all the previous aspects are taken into account.

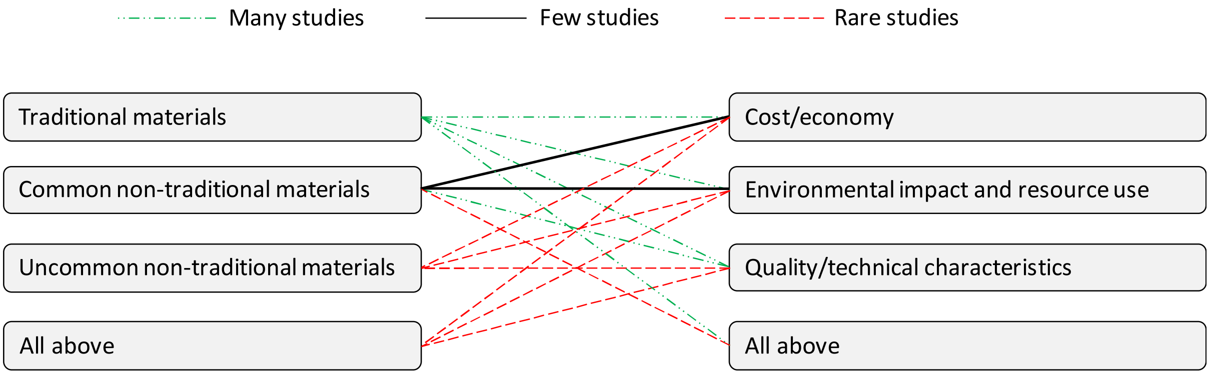


Figure 19 - The predominant flows of previous studies (Right side - uncommon non-traditional materials and all above → left side - all above, no study found)

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