New Generation Concretes – Properties and Applications

Piotr Dybel 1, Milena Kucharska 1

1 AGH University of Science and Technology, Department of Geomechanics, Civil Engineering and Geotechnics, al. Mickiewicza 30, 30-059 Cracow, Poland
dybel@agh.edu.pl

Abstract. Concrete is one of the most commonly used building materials in the world. Its production is increasing year by year, and is associated with harmful emissions of carbon dioxide (CO₂) and particulates (PM10) into the environment, as well as the deterioration of natural resources. In accordance with the policy of sustainability, new technologies have being introduced into the civil engineering industry for several decades, for example new generation concrete. Depending on the specific application and innovation needs, they are characterised by different mechanical properties, structure, mix composition or behaviour in comparison to conventional concretes. These changes are intended, among other things, to minimize environmental impact during production, increase the durability and resistance to environmental hazards, prolong the reliability of the structure and reduce the life cycle costs of the structure. Examples of concretes belonging to the group of new generation concretes are above all: high performance concretes, self-compacting concretes, eco-efficient concretes, self-healing concretes. The paper presents a general outline of the issues related to the new generation concretes. The differences between each new generation concrete and conventional concrete are described. Possible applications of new generation concretes in civil engineering are presented. An attempt was made to determine the advantages and disadvantages of each of the discussed concretes.

1. Introduction

It has become common knowledge that, among other things, due to construction industry, rapid consumption of many natural resources caused a serious environmental problem. With the development of science and technology, including construction materials, the crisis should be constantly reduced. One of prevalent solution is an implementation of smart materials into the industry. The most widely used construction material is concrete thanks to its uniformity, general availability, favourable mechanical characteristics and relatively low price. In concrete technology, a group of new generation concretes has emerged, meeting the increasingly demanding requirements for building materials. The new generation concretes characterize in unique properties, such as higher compressive strength, larger durability, lower environmental impact and so on. There is a trend in the concept of concrete structures to implement materials that combine not only better mechanical properties but also intelligent functions, such as self-sensing, self-curing, self-healing or self-adjusting.

It seems impossible to sufficiently gather the whole issue of new generation concretes in one paper due to their multiple performance and qualities. The scope of this review was limited only to several...
types of concrete, namely high-performance concrete (HPC), self-compacting concrete (SCC), eco-efficient concrete and self-healing concrete.

2. High-performance concrete

Continuous development of the building industry and increasing requirements placed on constructions initiated the creation of high-performance concrete (HPC). They exhibit better durability and strength properties compared to normal concretes. The durability and service life of HPC concrete structures compared to those made of ordinary concrete can be even twice as big. This can be a major factor in the use of this type of concrete in structures exposed to difficult environmental conditions or in structures with a prolonged service life [1]. In addition, HPC offers much better possibilities for architectural and structural design in comparison to normal concretes due to their higher strength properties. This concrete is increasingly being used in structures such as bridges, high rise buildings, tunnels, sewage-treatment plants, tanks, silos, marine structures [2, 3].

In the literature as well as in concrete technology the concepts of HPC and high-strength concrete (HSC) are interchangeable. The main difference is the basic area of main properties – predominant is strength and durability in HSC and HPC, respectively. According to EN 206:2016 [4], high strength concrete is either normal or heavy concrete with a compressive strength class of at least C50/60 and lightweight concrete with a class higher than LC50/55. HPC concrete does not have a standardised and precise definition. These are concretes in which one or more characteristics have been improved by selecting the right type and proportion of components to suit the specific needs of investors. The composition of HPC concretes and the rules for adjusting their components are based on a similar concept to ordinary concrete. The increase in strength and durability of HPC is achieved by lowering its porosity. This requires a significant reduction of the water-to-cement ratio (w/c = 0.21 ÷ 0.38) and the use of mineral additives, which seal the structure of the slurry and increase its homogeneity. For this purpose, it is best to use silica fume. Other mineral additives, e.g. fly ash or blast furnace slag, can also be used to achieve positive effects. The required workability of the mixture with such a small water-to-cement ratio is obtained by using a superplasticizer. In HPC, due to the assumption of small values of the water-to-cement ratio, higher cement content is required in comparison to ordinary concretes. The optimal amount of cement in HPC concretes is adopted at the level of 450÷550 kg/m³ [5].

Mechanical properties, including high compressive strength, of high-performance concretes result from their designed microstructure. The high homogeneity of the material microstructure, the absence of local defects and weaknesses in the form of air pores remained after free water, as well as the lack of shrinkage cracks fundamentally change the behaviour of HPC compared to ordinary concretes. In normal concretes, the failure takes place through the weakest element of the concrete microstructure, which is the contact zone between the coarse aggregate grains and the cement matrix. In HPC, the contact zone can be improved by using crush-stone aggregate, superplasticizers that reduce the water-to-cement ratio, pozzolane additives, high-grade cements. Tight microstructure and much better mechanical properties cause the failure of HPCs to be routed through the coarse aggregate particle. Therefore, HPC cannot assume the same relationship between the basic mechanical characteristics as ordinary concretes [6].

Behaviour of HPC subjected to higher temperatures may be a serious limitation of their application in the construction industry. The HPC may be prone to explosive splintering of surface layers during high-temperature conditions [7]. The splinters usually expose temperature-sensitive reinforcing steel, hence creating a serious threat to the load capacity and stability of a structural element. However, it should be noted that several methods have been developed to prevent the formation of concrete splinters during a fire. Proposed methods are the usage of thermal barriers in the form of mineral thermal insulation materials, surface reinforcement grids, steel fibres or air-entraining admixtures. A highly effective method of improving the resistance of HPCs to high temperatures is the use of polypropylene
fibres as an additive to the concrete mixture [8, 9]. Under the impact of high temperatures the fibres melt and leave a web of open pores, contributing to an increase in permeability and therefore to a decrease in internal pressure in the heated concrete. This leads to a significant increase in the service life of HPC under high temperature conditions.

The application of high performance concretes is usually the result of specific technical and operational requirements, as well as expected economic benefits. In theory, the production of HPC is more expensive, but it can be compensated by savings resulting from the reduction of the self-weight of the structure while ensuring the load bearing capacity of the structural elements. Due to higher compressive strength, required amount of reinforcing steel can be reduced. Increased growth in strength of early-age concrete results in reduced investment execution time due to the possibility to dismantle and relocate the formwork earlier. By analysing the entire life cycle of a building, the total investment costs are reduced. In the final total cost analysis, the use of HPCs becomes as cost-effective as conventional concrete solutions. This is one of the factors contributing to the growing interest in HPC as a construction material in recent years.

Compared to normal concrete technology, HPC technology appears to be less environmentally friendly due to the higher volume of cement. Its production is the most energy-consuming and contributes significantly to carbon dioxide emissions. However, it should be mentioned that HPC makes it possible to reduce the size of the structural elements, which leads to a drop in the rate of construction material consumption and environmental imprint [10].

3. Self-compacting concrete

One of the innovative concretes increasingly used in the construction industry is self-compacting concrete (SCC). The innovation of SCC is confirmed by the very short period of time between the formulation of the concept of its properties and its application in concrete construction industry. A wide range of SCC applications currently being observed is a consequence of beneficial economic effects. SCC is defined as concrete whose composition and components are selected mainly due to the specific rheological properties of the mixture, ensuring its ability to fill the mould properly, to cover the reinforcement and compaction under its own weight without the need for mechanical compaction [11].

Meeting the requirements of the self-compacting mix is possible by modifying the concrete composition [12] mainly based on an increase in the amount of powders (500-600 kg/m3), reducing the maximum aggregate size to 20 mm and raising the sand content to 40-50% of aggregate mass. A water-to-binder ratio in SCC should be below 0.35. Cement and mineral additives, usually in the form of fly ash, stone filler, blast furnace slag or silica fume, are used as binders. Similar to the case of HPC, meeting the requirements of low water-to-binder ratio is ensured by the use of superplasticizer. Additionally, Viscosity Modifying Admixtures are often used to improve the stability of the mixture and hence reduce the phenomenon of segregation.

The use of SCC concretes in engineering structures brings a number of benefits. The main advantage is the reduction of the time of concrete works, resulting from the elimination of mechanical compaction, distribution of the concrete mix in the formwork and reduction of its surface finish. In the case of densely reinforced structures, the use of SCC facilitates tight and homogeneous formwork filling. Thanks to the improved quality of the surface, the use of SCC allows to limit corrections, which in turn reduces the total cost. In the environmental context, the elimination of mechanical compaction has a positive impact on the health and safety of workers, as well as eliminating the unfavourable effects of vibrations and noise.

The use of SCC is subject to certain restrictions. Self-compacting mixes are extremely sensitive to any changes in the composition, technological conditions or properties of the components [13]. It is
also dangerous to expose the mixture to vibrations which may disturb its stability. Therefore, the use of SCC makes it necessary to ensure strict technological supervision both at the production stage and at the construction site.

The unique rheological properties of the self-compacting mix also make it possible to place it in variants other than the traditional mix. Formwork or mould can be filled from above or from the bottom. The traditional and most frequently used method is top-moulding. An alternative option is bottom-up casting, which is ensured by pumping the mixture through a special valve permanently placed in the system formwork. This method is most often used for making vertical elements, such as walls or columns, with complex geometry, dense reinforcement or which are difficult to access from above [14]. Bottom-up casting of the concrete mix improves the deaerating of the mix, which consequently improves the surface finish of the concrete. Moreover, the continuous upward movement of the mix in the form reduces the risk of segregation, leading to an increase in the strength of the concrete [15]. The study [16, 17] also shows that the application of the mix from below improves and unifies the bond conditions of concrete to reinforcing steel. Thus, it can be assumed that this casting technology will be increasingly applied. On the other hand, application from the bottom increases the concrete pressure on the formwork and demands additional support [18].

The mechanical properties of the hardened SCC as well as its durability depend mainly on its microstructure. In studies [6, 12, 19] these relationships have been analysed. It was also noted that the method of compaction does not affect them directly. Therefore, if the microstructure of SCC and vibratory compacted concrete is similar, their mechanical properties will also be at a comparable level. The compressive strength of SCC may be slightly higher (up to 10%) than normal concrete due to the tighter contact zone [12]. The homogeneity of the SCC concrete structure results in its increased tensile strength [20, 21]. The bond strength of both concretes to reinforcing steel is generally at a similar level [22–24].

4. Eco-efficient concretes

The term of eco-efficiency in concrete industry was introduced many years ago. It is well known that concrete is currently the most extensively used material but also the most environmentally hazardous. The main component of concrete binder, Portland cement, has almost 80% share in CO₂ emissions of concrete that is approximately 6-7% of total CO₂ emissions [25]. Although, in comparison to other materials, concrete is relatively green and has low environmental imprint, so ecological improvement of concrete performance need to be multistage and aligned with location of implementation [26]. Suggested strategies to develop eco-efficient concrete are connected with among other things replacement of Portland cement by supplementary cementitious materials and natural aggregates by industrial wastes or reduction of binder contribution in mix composition.

4.1. Concrete with supplementary cementitious materials (SCMs)

Due to significant contribution of Portland cement production to the environmental imprint of concrete, it is highly suggested to extend usage of supplementary cementitious materials (SCMs) instead. Supplementary cementitious materials exhibit hydraulic or pozzolanic behaviour and one can distinguish natural and artificial materials that meet those properties. Natural SCMs are pyroclastic rocks or highly-siliceous sedimentary rocks. Artificial SCMs are obtained by thermal activation of kaolin-clays (metakaolin) or as waste or by-products from high-temperature processes (silica fume, fly ash, blast furnace slag) [27]. It was observed that 50% replacement of cement with high-volume SCMs could develop cost-effective SCC with high compressive strength and good workability of fresh mixture in comparison to reference SCC of 100% of Portland cement [28]. High volumes of fly ash could withhold a creation of high-strength concrete, so the fly ash replacement is suggested as 30-50% for 60-90 MPa compressive strength of concrete [29]. As for HPC and Ultra-High-Performance Concrete (UHPC), silica fume is used as a replacement of Portland cement. Eco-efficient UHPC was developed with a
content of silica fume and ultra-fine fly ash that perform good flow-ability and strength [30]. What is more, replacing 30% of cement with SCMs allowed on reducing CO₂ emissions by 40% for 1 cubic metre of SCC [31].

4.2. Concrete with recycled aggregate

In order to limit the consumption of natural aggregates, recycling aggregates are increasingly being used. As an example, secondary aggregates made of concrete or brick waste, glass aggregate or for example granulates made of rubber tyres [32]. Recycling materials and post-industrial by-products can be a suitable substitute for natural aggregates used in the production of both ordinary concretes [33] and new generation concretes [34].

Secondary aggregates from the demolition and processing of concrete facilities are most often used for the production of recycled aggregate concrete. The parameters of recycled concrete element aggregate will depend both on the technical parameters of the initial aggregate used to produce this component, the properties of the cement matrix and the percentage proportion of both these fractions [35]. All residues of hardened cement matrix in recycled aggregate unfavourably affect technical and mechanical parameters of both the concrete mix and the concrete itself made from such aggregates. The low density of the remaining cement matrix causes increased water demand of the concrete mix and reduced strength and freeze-thaw resistance of the concrete. In order to prevent these disadvantages, various forms of preparation of concrete rubble for re-use are applied. The main directions in this respect are processes removing the remaining matrix from the initial aggregate and methods of sealing the aggregate together with the adjacent matrix [36]. Due to the high energy consumption of these operations, it is necessary to analyse the cost-effectiveness of these actions each time. A less expensive alternative method of using concrete aggregate is the replacing method. It involves partial replacement of natural coarse or fine aggregate with coarse or fine recyclable aggregate in the mixture. In the case of using secondary aggregates from HPC, the implementation of advanced technologies of material preparation is not essential due to its good original physical and mechanical properties and the HPC failure mechanism [37].

The wider use of alternative aggregates contributes to the protection of natural resources, reduction in emissions (CO₂, PM10) during transport of aggregates, reduction of demolition waste and recovery of land occupied by landfills. The use of recycled aggregates supports the local labour market and helps to reduce the intensity of heavy goods traffic, which has a social, environmental and economic impact [38].

4.3. Low-binder concrete

Despite numerous advantages SCC is believed to be slightly less environmental friendly than traditional concrete. In consequence, a green approach to self-compacting concrete was developed for the production of SCC with reduced binder content. In general, Eco-SCC characterise in total powder content (cement, mineral additives such as fly ash, silica fume, blast furnace slag) of 315 kg/m³ or less. That causes a change in rheology of eco-mixture in relation to traditional SCC, namely lower plastic viscosity [39]. This makes Eco-SCC relatively easier to place in a mould. However, low viscosity results in a mixture that is more prone to segregation. One of method to ensure stability of Eco-SCC is a high content of fine aggregate without colloidal particles and implicating the particle-lattice concept [40]. Moreover, it is suggested to use Viscosity Modifying Admixtures and silica fume as a partial replacement of Portland cement. Those methods help to stabilize mixture and prevent bleeding. What is more, the green self-compacting concrete characterise in low shrinkage.

A successful attempt of an in-situ application of Eco-SCC was made in Iceland at a hydro-power plant construction [40]. Initially, the total binder content of 290 kg/m³ with 20% of fly ash was designed. No significant problems arose with the placing of the mixture.
5. Self-healing concrete

Specially modified composition of self-healing concrete endures its durability by ensuring partial or total repair of internal cracks. Repair and reconstruction of concrete structures is one of the most extensive investments. That is why so much emphasis is placed on more and more durable materials. Reduced maintenance costs and longer service life are to some extent triggered by self-healing abilities [41, 42]. Such concrete can be achieved by two possible methods: autogenous and autonomous. Those two approaches of obtaining a self-healing concrete are concisely described in following subsections.

5.1. Autogenous self-healing concrete

The autogenous healing of concrete is ensured by several processes: carbonation of calcium hydroxide, blocking cracks by impurities in the water and loose concrete particles, expansion of the hydrated concrete matrix or ongoing hydration of clinker minerals [43]. It is believed that depending on an age of concrete, the self-healing mechanism is caused by different factors. There are several methods for producing self-healing concrete, by incorporating fly ash which continuingly hydrates or fiber-reinforcement or ensuring high content of unhydrated cement by, for example, lowering water-to-cement ratio.

Materials of slow hydration rate such as fly ash, blast furnace slag, chemical expansive agents, swelling minerals and crystalline components are commonly used in self-healing concrete [46]. These, depending on their type, in different ways are responsible for filling cracks in time with the presence of water. Studies on SCCs with and without high volume of fly ash [47] revealed that its self-healing is mainly generated by the pozzolanic reactions of unhydrated fly ash. Various composites were investigated on the self-healing properties of cementitious materials [48]. It was concluded that in the case of using expansive additives, the most efficient in the case of self-healing ratio is usage of only single mineral. Moreover, combination of silica-based, swelling and crystalline components presented the best crack self-healing ratio.

Several types of fibres might be introduced into concrete mix in order to achieve self-healing properties [49]. They can function as a restriction of the crack width as well as the connection point for crystallisation products [42]. Research on engineered cementitious composites during wet-dry cycles [50] showed that instead of exhibiting a big damage, many microcracks appeared. Self-healing concrete with fibres in more bendable than conventional concrete, so that it can be applied on seismic areas where dynamic loads occur. However, the type of fibres must be carefully selected and prepared due to alkaline environment of cementitious matrix, because glass or natural fibres are prone to degradation in such conditions.

5.2. Autonomous self-healing concrete

Autonomous self-healing concrete is developed by using external manual methods. In comparison to autogenous healing, it is successful not only in the presence of water and not limited to small cracks. In past several years many approaches of autonomous self-healing concrete has been researched, mainly vascular [51], microcapsule [52], electrodeposition [53], bacterial [54], shape memory alloy [55].

Microcapsule method of achieving self-healing properties involves uniformly embedding microcapsules with chemical healing agent into concrete. When a propagating crack reaches a
microcapsule, it causes it to rupture and release the healing substance. This is followed by a chemical reaction, which causes the bonding to the crack walls or sealing the crack in order to prevent its propagation and eventually restores the initial properties of the concrete, such as stiffness and strength. A selection of effective microcapsules is still being discussed in the literature. There are several effects that need to be considered when designing a microcapsule based self-healing concrete, namely size, shape and thickness of microcapsules, healing agent as well as good bond with cement matrix, compatibility with concrete and finally proper resistance during mixing and when meeting with cracks. Glass capsules might induce alkali-silica reactions in concrete if cementitious matrix is highly alkaline. Moreover, there microcapsules are not resilient enough during mixing. Thus, polymeric capsules are being introduced and seem to be an efficient system [56–58].

The approach of bacteria insertion into a concrete allows on precipitation of calcium carbonate during activation of bacteria that helps filling the microcracks [59]. Considering highly alkaline environment of concrete and increasing internal compressive pressure from cement hydration, the bacteria need to withstand those unfavourable conditions [46]. The process of self-healing is induced by metabolic activities of bacteria and once it is finished, bacteria recur to its initial hibernation. The procedure is repeated in the case of new cracks. This mechanism is called Microbiologically Induced Calcium Precipitation. Studies with Bacillus Sphaericus [60] showed that pure bacteria cultures were not able to heal the cracks. However, cracks were filled completely when bacteria were protected in silica gel. Moreover, it was revealed that bacteria addition has a positive effect on the compressive strength of concrete and decreases water penetration and chloride ion permeability [61]. The bacterial method seems to be environmental-friendly and could be used in marine concrete [62] and to build construction such as tunnels and pillar bridges [63].

6. Conclusions
This paper reviews applications and properties of several new generation concretes. In general, new generation concrete performs better than normal concrete. Many of disadvantages of new generation concretes showed in the paper could be minimalised by combining different types of approaches, e.g. introducing SCMs into SCC or HPC in order to reduce cement content and consequently the environmental imprint. The prolonged durability of new generation concretes contributes to their cost-effectiveness in the life cycle of buildings. The increasing popularity of new generation concretes in building structures proves their suitability and the fact that they satisfy the requirements of investors. It also shows that continuous investigation of the properties of fresh mixes, mechanical properties and performance of new generation concretes is needed. The authors are well aware that the topic is so extensive that it is difficult to synthesize the knowledge that covers the whole issue. This article proves that concrete is a continuously developing material. The examples of new generation concretes mentioned here indicate that we are becoming more and more familiar with its principles and that we are able to successfully influence its properties. The future of concrete technology is very promising and will undoubtedly be subject to further innovations.

References
[1] P. C. Aïtcin, "The durability characteristics of high performance concrete: A review", Cement and Concrete Composites. 2003.
[2] A. Ajdukiewicz and W. Radomski, "Trends in the Polish research on high-performance concrete", Cem. Concr. Compos., vol. 24, no. 2, pp. 243–251, 2002.
[3] A. Kmita, "New generation of concrete in civil engineering", J. Mater. Process. Technol., vol. 106, no. 1–3, pp. 80–86, 2000.
[4] "EN 206:2016 Concrete: Specification, performance, production and conformity". 2016.
[5] A. Neville and P.-C. Aïtcin, "High performance concrete—An overview", Mater. Struct., 2006.
[6] A. M. Neville, "Properties of concrete Fourth and Final Edition", Perason-Prentice Hall, 2004.
[7] L. Phan, "High-strength concrete at high temperature - An Overview", *Symp. Util. High Strength/High Perform. Concr.*, 2002.

[8] I. Hager and T. Tracz, "The Impact of the Amount and Length of Fibrillated Polypropylene Fibres on the Properties of HPC Exposed to High Temperature", *Arch. Civ. Eng.*, vol. 56, no. 1, pp. 57–68, 2010.

[9] P. Kalifa, G. Chéné, and C. Gallé, "High-temperature behaviour of HPC with polypropylene fibres", *Cem. Concr. Res.*, 2002.

[10] D. Wałach, P. Dybel, J. Sagan, and M. Gicála, "Environmental performance of ordinary and new generation concrete structures—a comparative analysis", *Environ. Sci. Pollut. Res.*, vol. 26, no. 4, pp. 3980–3990, 2019.

[11] A. Yahia and P. C. Aïtcin, "Self-consolidating concrete", *Science and Technology of Concrete Admixtures*, 2015.

[12] G. De Schutter, P. J. M. Bartos, and P. Domone, "Self-Compacting Concrete". Dunbeath: Whittles Publishing, 2008.

[13] "The European Guidelines for Self-Compacting Concrete (Specification, Production and Use)". 2005.

[14] L. N. Thrane, C. V. Nielsen, and C. Pade, "Guidelines for Execution of SCC". Taastrup: Danish Technological Institute, Concrete Centre, 2008.

[15] G. De Schutter, D. Feys, and R. Verhoeven, "Ecological Profit for a Concrete Pipe Factory due to Self-Compacting Concrete Technology", in *Second International Conference on sustainable Construction Materials and Technologies*, no. 2, pp. 1281–1287, 2010.

[16] P. Dybel, "Effect of casting direction on bond of reinforcement in High Performance Self-Compacting Concrete (HPSCC)", *MATEC Web Conf.*, vol. 262, no. 06004, 2019.

[17] M. Kucharska and P. Dybel, "Influence of casting direction on bond to steel reinforcing bars in self-compacting concrete (in Polish)", *Builder*, vol. 1, pp. 65–67, 2019.

[18] S. Tichko, G. De Schutter, P. Troch, J. Vierendeels, R. Verhoeven, K. Lesage, and N. Cauberg, "Influence of the viscosity of self-compacting concrete and the presence of rebars on the formwork pressure while filling bottom-up", *Eng. Struct.*, vol. 101, pp. 698–714, 2015.

[19] P. Domone, "A review of the hardened mechanical properties of self-compacting concrete", *Cem. Concr. Compos.*, vol. 29, no. 1, pp. 1–12, 2007.

[20] M. Sonebi and P. J. M. Bartos, "Hardened SCC and its bond with reinforcement", 1999.

[21] G. König, K. Holschemacher, F. Dehn, and D. Weiße, "Bond of reinforcement in self-compacting concrete (SCC) under monotonic and cyclic loading", in *Proceedings of Third International RILEM Symposium on Self-Compacting Concrete*, pp. 939–947, 2003.

[22] Y.-W. Chan, Y.-S. Chen, and Y.-S. Liu, "Development of bond strength of reinforcement steel in self-consolidating concrete", *ACI Struct. J.*, vol. 100, no. 4, pp. 490–498, 2003.

[23] W. Zhu and P. J. M. Bartos, "Microstructure and properties of interfacial transition zone in SCC", in *Proceedings of First International Symposium on Design Performance and use of Self Consolidating Concrete*, RILEM Publications SARL, Changsha, pp. 319–327, 2005.

[24] S. Cattaneo and G. Rosati, "Bond between steel and self-consolidating concrete: experiments and modeling", *ACI Struct. J.*, vol. 106, no. 4, pp. 540–550, 2009.

[25] C. Shi and A. F. Jiménez, "New cements for the 21st century: The pursuit of an alternative to Portland cement", *Cem. Concr. Res.*, vol. 41, no. 7, pp. 750–763, 2011.

[26] F. Pacheco-Torgal, S. Jalali, J. A. Labrincha, and V. M. John, "Eco-Efficient Concrete". Cambridge: Woodhead Publishing Limited, 2013.

[27] B. Lothenbach, K. Scrivener, and R. D. Hooton, "Supplementary cementitious materials", *Cem. Concr. Res.*, vol. 41, no. 12, pp. 1244–1256, 2011.

[28] M. Nehdi, M. Pardhan, and S. Koshowski, "Durability of self-consolidating concrete incorporating high-volume replacement composite cements", *Cem. Concr. Res.*, vol. 34, no. 11, pp. 2103–2112, 2004.

[29] P. Dinakar, K. G. Babu, and M. Santhanam, "Durability properties of high volume fly ash self
compacting concretes", *Cem. Concr. Compos.*, vol. 30, no. 10, pp. 880–886, 2008.

[30] I. Ferdosian and A. Camões, "Eco-efficient ultra-high performance concrete development by means of response surface methodology", *Cem. Concr. Compos.*, vol. 84, pp. 146–156, 2017.

[31] O. Taleb, F. Ghomari, M. A. Boukli Hacene, E. H. Kadri, and H. Soualhi, "Formulation and rheology of eco-self-compacting concrete (Eco-SCC)", *J. Adhes. Sci. Technol.*, vol. 31, no. 3, pp. 272–296, 2017.

[32] J. Bolden, T. Abu-Lebdeh, and E. Fini, "Utilization of recycled and waste materials in various construction applications", *Am. J. Environ. Sci.*, vol. 9, no. 1, pp. 14–24, 2013.

[33] J. Thomas, N. N. Thaickavil, and P. M. Wilson, "Strength and durability of concrete containing recycled concrete aggregates", *J. Build. Eng.*, vol. 19, no. May, pp. 349–365, 2018.

[34] S. Santos, P. R. da Silva, and J. de Brito, "Self-compacting concrete with recycled aggregates – A literature review", *J. Build. Eng.*, vol. 22, no. May 2018, pp. 349–371, 2019.

[35] M. Etxeberria, E. Vázquez, A. Marí, and M. Barra, "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete", *Cem. Concr. Res.*, vol. 37, no. 5, pp. 735–742, 2007.

[36] B. Zając and I. Gołębiowska, "Evolution of concrete recycling technology (in Polish)"*, Inż. Ap. Chem.*, vol. 49, no. 5, pp. 134–135, 2010.

[37] D. Walach, "Possibilities of re-use secondary aggregates coming from recycled high-performance concrete (in Polish)", *Logistyka*, no. 6, pp. 14855–14864, 2014.

[38] A. Sobotka, J. Sagan, M. Baranowska, and E. Mazur, "Management of reverse logistics supply chains in construction projects", *Procedia Eng.*, vol. 208, pp. 151–159, 2017.

[39] F. V Mueller, O. H. Wallevik, and K. H. Khayat, "Robustness of Low-Binder SCC (Eco-SCC), Lean SCC and Binder-Rich SCC", in *8th International RILEM Symposium on Self-Compacting SCC2016*, pp. 25–34, 2016.

[40] O. H. Wallevik, F. V Mueller, B. Hjartarson, and S. Kubens, "The green alternative of self-compacting concrete, Eco-SCC", *XVII IBAUSIL Weimar, Vol. 1*, pp. 1105–1116, 2009.

[41] K. Van Tittelboom and N. De Belie, "Self-healing in cementitious materials - a review", *Materials (Basel)*, vol. 6, no. 6, pp. 2182–2217, 2013.

[42] B. Han, L. Zhang, and J. Ou, "Smart and multifunctional concrete toward sustainable infrastructures", 2017.

[43] N. Ter Heide, "Crack healing in hydrating concrete. Dissertation for the Master Degree", Delft University of Technology, 2005.

[44] S. Granger, A. Loukili, G. Piaudier-Cabot, and G. Chanvillard, "Experimental characterization of the self-healing of cracks in an ultra high performance cementitious material: Mechanical tests and acoustic emission analysis", *Cem. Concr. Res.*, vol. 37, no. 4, pp. 519–527, 2007.

[45] K. Tomczak and J. Jakubowski, "The effects of age, cement content, and healing time on the self-healing ability of high-strength concrete", *Constr. Build. Mater.*, vol. 187, pp. 149–159, 2018.

[46] V. C. Li and E. Herbert, "Robust Self-Healing Concrete for Sustainable Infrastructure", *J. Adv. Concr. Technol.*, vol. 10, no. 6, pp. 207–218, 2012.

[47] M. Şahmaran, S. B. Keskin, G. Ozerkan, and I. O. Yaman, "Self-healing of mechanically-loaded self consolidating concretes with high volumes of fly ash", *Cem. Concr. Compos.*, vol. 30, no. 10, pp. 872–879, 2008.

[48] Z. Jiang, W. Li, and Z. Yuan, "Influence of mineral additives and environmental conditions on the self-healing capabilities of cementitious materials", *Cem. Concr. Compos.*, vol. 57, pp. 116–127, 2015.

[49] D. Snieck and N. De Belie, "From straw in bricks to modern use of microfibers in cementitious composites for improved autogenous healing - A review", *Constr. Build. Mater.*, vol. 95, pp. 774–787, 2015.

[50] Y. Yang, M. D. Lepech, E. H. Yang, and V. C. Li, "Autogenous healing of engineered cementitious composites under wet-dry cycles", *Cem. Concr. Res.*, vol. 39, no. 5, pp. 382–390,
2009.

[51] D. Gardner, B. Isaacs, R. Lark, C. Joseph, and A. D. Jefferson, "Experimental investigation of adhesive-based self-healing of cementitious materials", *Mag. Concr. Res.*, vol. 62, no. 11, pp. 831–843, 2010.

[52] H. Huang and G. Ye, "Application of sodium silicate solution as self-healing agent in cementitious materials", *Int. RILEM Conf. Adv. Constr. Mater. Through Sci. Eng.*, no. 1993, pp. 530–536, 2011.

[53] J. S. Ryu, "Influence of crack width, cover depth, water–cement ratio and temperature on the formation of electrodeposits on the concrete surface", *Mag. Concr. Res.*, vol. 55, no. 1, pp. 35–40, 2003.

[54] H. M. Jonkers, "Self Healing Concrete: A Biological Approach", *Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science*, S. van der Zwaag, Ed. Dordrecht: Springer Netherlands, pp. 195–204, 2007.

[55] Y. Kuang and J. Ou, "Self-repairing performance of concrete beams strengthened using superelastic SMA wires in combination with adhesives released from hollow fibers", *Smart Mater. Struct.*, vol. 17, no. 2, 2008.

[56] J. Feiteira, "Self-Healing concrete–Encapsulated polymer precursors as healing agents for active cracks", Ghent University, 2017.

[57] N. De Belie, K. Van Tittelboom, V. Cnudde, S. Van Vlierberghen, J.-M. Raquez, S. Chatrabhuti, M. Araújo, E. Gruyaert, N. Alderete, and S. Gurdebeke, "Poly(methyl methacrylate) capsules as an alternative to the proof-of-concept’’ glass capsules used in self-healing concrete", *Cem. Concr. Compos.*, vol. 89, pp. 260–271, 2018.

[58] Z. Yang, L. Lv, E. Schlangen, G. Zhu, F. Xing, G. Chen, and N. Han, "Synthesis and characterization of a new polymeric microcapsule and feasibility investigation in self-healing cementitious materials", * Constr. Build. Mater.*, vol. 105, pp. 487–495, 2015.

[59] R. Pei, J. Liu, S. Wang, and M. Yang, "Use of bacterial cell walls to improve the mechanical performance of concrete", *Cem. Concr. Compos.*, vol. 39, pp. 122–130, 2013.

[60] K. Van Tittelboom, N. De Belie, W. De Muynck, and W. Verstraete, "Use of bacteria to repair cracks in concrete", *Cem. Concr. Res.*, vol. 40, no. 1, pp. 157–166, 2010.

[61] K. Vijay, M. Murmu, and S. V. Deo, "Bacteria based self healing concrete – A review", *Constr. Build. Mater.*, vol. 152, 2017.

[62] D. Palin, V. Wiktor, and H. M. Jonkers, "A bacteria-based bead for possible self-healing marine concrete applications", *Smart Mater. Struct.*, vol. 25, no. 8, 2016.

[63] F. B. Silva, N. Boon, N. De Belie, and W. Verstraete, "Industrial Application of Biological Self-healing Concrete: Challenges and Economical Feasibility", *J. Commer. Biotechnol.*, vol. 21, no. 1, 2015.