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A STATE OF THE ART REVIEW OF GREEN CONCRETE

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ABSTRACT

Global warming is a critical global issue given that it has the potential to jeopardize all human society. Among many causes, the cement and concrete industry is responsible for a major portion of greenhouse gas emissions. This review described perspectives on the uses and potential uses of cement and concrete as a green material, guidelines for green concrete. Related to cleaner technologies for the production of concrete, the major targets are achieving (a) a significant reduction in CO_2 emissions, (b) a significant reduction in energy consumption and fossil fuel in the cement-manufacturing process, (c) a significant reduction in the use of substances that endanger health and/or the environment, (d) significant savings associated with the use of cement by partially replacing it with fly ash waste and/or other kinds of waste materials, (e) a significant increase in the use of new cement replacement materials, and (f) significant development of various possibilities relevant to recycling cement/concrete and the use of alternative aggregates.

Keywords: Green concrete, Sustainable development, Cleaner production

Introduction

Climate change, signified principally by global warming, is a critical global issue given that it has the potential to jeopardize all human society. Among many causes, the construction industry is responsible for a major portion of greenhouse gas emissions. For example, the process through which cement is produced yields approximately 7%

of total CO_2 emissions worldwide (Kim et al., 2013). With increasing interest in sustainable development on the part of the public, industry, and government, environmental assessment in construction is becoming more important. Society and the social changes that have occurred worldwide have brought a high demand to bear on the construction industry in terms of the world's material and energy resources. As it consumes considerable resources and, therefore, has a significant impact on the environment, the construction industry must address certain consequential issues in the effort to achieve sustainable development (Edvardsen & Tølløse, 2001). With the exception of water, concrete is the most widely used material on earth, with nearly three tons used annually for each man, woman, and child (PCA, 2015). In addition, the use of concrete is evolving. Modern concrete is more than simply a mixture of cement, water, and aggregates. Instead, modern concrete is more likely to contain mineral components, chemical admixtures, fibers, etc., than earlier concrete and to use these in larger quantities than was previously the case. The development of these smart concretes resulted from the emergence of a new science of concrete, a new science of admixtures, and the use of sophisticated scientific apparatus to observe the microstructure and even the nano structure of concrete (Aïtcin, 2000). Sustainable industrial growth will influence the cement and concrete industry in many respects. One important issue is the use of environmentally friendly ("green") concrete to enable worldwide infrastructure growth without incurring an increase in CO_2 emissions (Edvardsen & Tølløse, 2001). Concrete for the environment is defined as sustainable development through the planned management of a natural resource or of the entire environment of a particular ecosystem in order to prevent exploitation, pollution, destruction, or neglect and to ensure the future use of the resource. Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their needs (fib, 2012). To support the global consensus in favor of sustainable development, technical strategies for ensuring the sustainability of concrete construction have been presented, which suggest saving materials in building design, maximizing the durability of concrete, using waste or supplementary cementitious materials (e.g., fly ash and slag), and recycling concrete (Kim et al., 2013). Finally, the concrete of tomorrow will be green. Concrete will have to evolve with reference to the environment within a sustainable development perspective, which means that more mineral components will be blended with clinker and water-binder material ratios will be lowered in order to increase the lifecycle of concrete structures (Aïtcin, 2000).

Concrete as a green material

Concrete is by far the most widely used construction material worldwide. Its huge popularity is the result of a number of well-known advantages, such as its low cost, general availability, and wide applicability. But the popularity of concrete comes at a great cost to the environment. The billions of tons of natural materials mined and processed each year, by their sheer volume, are bound to leave a substantial mark on the environment (Table 1). Most damaging are the enormous amounts of energy required to produce Portland cement as well as the large quantities of CO_2 released into the atmosphere in the process.

Table 1 The Environmental Costs of Concrete (Meyer, 2005).

Key impact	Impact on the environment
Worldwide	Over ten billion tons of concrete are produced each year. In the United States, the annual production of over 500 million tons translates to about two tons for each man, woman, and child. Such volumes require vast amounts of natural resources for aggregate and cement production.
CO_2	The production of one ton of Portland cement causes the release of one ton of CO_2 into the atmosphere. CO_2 is a greenhouse gas that contributes to global warming, and the cement industry alone generates about 7% of it.
Energy-intensive	North American plants have improved their energy-efficiency considerably in recent decades to the point where this is now comparable to that of plants in Japan and Germany. It is technically next to impossible to increase that energy-efficiency much further below the current requirement of about 4 GJ per ton.
Environment	The demolition and disposal of concrete structures, pavements, etc., constitutes another environmental burden. Construction debris accounts for a large fraction of our solid waste disposal problem, and concrete constitutes the largest single component of this debris.
Water requirements	The water requirements are enormous and particularly burdensome in regions of the world that are not blessed with an abundance of fresh water. The concrete industry uses over 1 trillion gallons of water each year worldwide, and this does not include wash water or curing water.

Because of limited natural resources, concern over greenhouse gases (GHGs), or, both, cement production is being curtailed, or at least it is not being increased in order to keep up with the population increase in some regions of the world. It is, therefore, necessary to look for sustainable solutions for future concrete construction.

A sustainable concrete structure is constructed to ensure that the total environmental impact during its lifecycle, including its use, will be minimal. Sustainable concrete should have a very low inherent energy requirement, be produced with little waste, be made from some of the most plentiful resources on earth, produce durable structures, have a very high thermal mass, and be made with recycled materials. Sustainable constructions have a small impact on the environment. They use green materials, which have low energy costs, high durability, low maintenance requirements, and contain a large proportion of recycled and/or recyclable materials. Green materials also use less energy and fewer resources than do non-green materials and can be used to produce high-performance cement and concrete. Concrete must keep evolving to satisfy the increasing demands of its users. Therefore, designing for sustainability means accounting for the short-term and long-term environmental consequences in regard to every aspect of design (Naik, 2008).

Traditionally, the design of concrete structures has concentrated on the construction phase, optimizing construction costs and short-term performance. The notion of sustainable development raises the issue of a strong need for an integrated lifecycle design such that all phases during the entire service life of the structure are considered, as shown in Fig. 1. It is a fact that concrete structures exposed to an aggressive environment require extensive maintenance and repair work. The environmental loads associated with the maintenance and repairs needed by structures in such conditions very often dominate sources the entire service life of the structures (Edvardsen & Tølløse, 2001).

As the service life of a concrete structure is often 50–100 years, a lot of people can be expected to use such structures and play a part in their repair and maintenance throughout their lifecycle (fib, 2012). There are multiple aspects to the design and production of concrete structures as follows:

- Design – The design is established as a cooperative venture between the building owner and the consultant. The design should be in accordance with relevant specifications, rules, and legislation. The time scale is months.

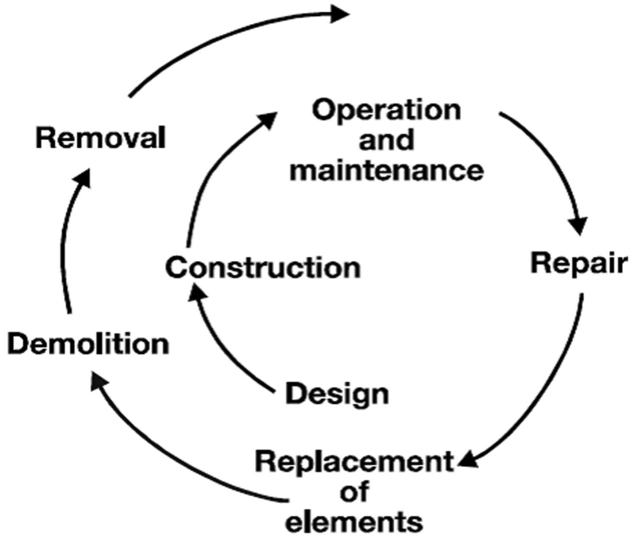

Figure 1 Phases in the lifecycle of a concrete structure to consider in the lifecycle inventory (Edvardsen & Tølløse, 2001).

- **Construction** – The construction is mainly governed by the material suppliers and the contractors. The design specifications act as minimum requirements. Sometimes, the contractor overrules the design if an alternative solution is more suitable. During this phase, the time schedule is often tight, which may negatively influence the environmental footprint of the structure. The time scale is months.
- **Operation and use of the structure** – During the service life of a structure, the building owner and the end-user are responsible for its operation and maintenance. If the initial design is successful, the construction will function for decades without any need for major repairs or alterations. The time scale is decades.
- **Maintenance** – Most often, buildings and structures need maintenance and modifications after about 30 years because during the pre-construction phase it is not generally possible to foresee necessary changes. However, the design phase is important in order to obtain sound low-maintenance and durable solutions. This phase involves choosing appropriate materials and design details and also executing the design. The time scale is decades.

- **Demolition, reuse, and recycling** – At the end of its service life, a structure is most likely to be demolished and recycled to a certain degree. In cases in which structures included built-in harmful substances allowed at the time of construction but later banned, recycling may be restricted significantly. However, even though it is very difficult to foresee future changes during the pre-construction phase, this effort should still be attempted in order to cover the potential reuse and recycling of materials used in construction with contemporary state-of-the-art technology.

The National Ready Mixed Concrete Association (NRMCA, 2009a) presents a vision for sustainability initiatives according to which the concrete industry is seen as uniquely positioned to meet the challenges of sustainable development. The NMRCA sees the industry as capable of creating products that help improve the overall footprint of the built environment. To fully realize this vision, the concrete industry must approach sustainable development through the lifecycle perspective. The lifecycle phases of concrete include material acquisition, production, construction, use (operations and maintenance), and recycling. The industry evaluates and will continue to evaluate all phases of its product lifecycle in order to reduce its environmental footprint.

The concrete industry is dedicated to continually improving through developing its products and processes. The industry continues to increase its use of recycled materials, including industrial byproducts, thus conserving valuable natural resources and reducing the energy required to manufacture concrete. The industry continues to explore new ways to further reduce its carbon footprint through the development of innovative cements and concrete mixtures. Concrete companies also strive to improve manufacturing processes, including the use of alternative energy sources, to minimize the energy used in production and associated greenhouse gas emissions. Finally, the industry continues to enhance transportation efficiency and delivery methods to reduce the environmental impact of the construction process.

This review outlines goals for reducing the overall environmental footprint of concrete construction and provides strategies for achieving these goals. The concrete industry has been a key contributor in building this nation’s infrastructure and will continue to enhance the sustainability of our built environment for generations to come (NRMCA, 2009). The principles of Sustainable Development and Green Buildings have penetrated the construction industry at an accelerating rate in recent years. Yet, despite making significant improvements in terms of sustainability, as discussed, the concrete industry has an enormous environmental footprint and, therefore, has a long way to go in terms of becoming greener and of shedding its negative image.

The idea of using recycled materials in concrete production was widely unknown only a few years ago, yet concrete producers now know that they need to change. The goals in regard to becoming more environmentally friendly in terms of producing concrete can be summarized as follows: (1) replace or add as much Portland cement as possible with supplementary cementitious materials (SCM), especially those that are by-products of industrial processes, such as fly ash, ground granulated blast furnace slag, and silica fume; (2) use recycled materials in place of natural resources; (3) improve the durability and service life of structures, thereby reducing the amount of materials needed for their replacement; (4) improve concrete’s mechanical and other properties, which can also reduce the amount of materials needed; (5) reuse wash water (Meyer, 2009).

Various strategies have been followed, separately or in combination, to improve the sustainability of concrete and even to develop green or ecological concrete. These strategies consist of incorporating recycled materials into concrete, optimizing the mix design, reducing CO_2 emissions by decreasing the Portland cement content, partially replacing Portland cement with cementitious by-product materials, increasing the durability of concrete in order to extend its service life and to reduce long-term consumption of resources, and selecting low-impact construction methods (Long et al., 2015). Basically, an environmentally green concrete structure is one in which all these issues have been considered and addressed effectively in the design and construction phase and during operation and maintenance likewise. This is achieved by drawing on the inherent environmentally friendly properties of concrete. The concrete structure should be designed and produced so that it meets the needs of end-users; i.e., the right concrete is chosen for any given application (fib, 2012). A sustainable concrete structure is one that is constructed so that the total negative societal impact during its entire lifecycle is minimal. Designing with sustainability in mind includes accounting for the short- and long-term consequences of the structure. To decrease the long-term impact of structures, maximizing durability is paramount (Naik, 2008).

In summary, green concrete is defined as a concrete that uses waste material as at least one of its components and/or its production process does not lead to environmental destruction. Further, to be considered green, concrete must also have high performance and lifecycle sustainability. In other words, green concrete is an environmentally friendly material. Green concrete represents a significant improvement over traditional concrete in regard to the three pillars of sustainability: environmental, economic, and social impact. The key factors used to determine whether concrete is green are the percentage of materials used to replace Portland cement, the manufacturing process and methods used, and the performance and lifecycle sustainability impact. Green concrete should be produced in accord with reduce, reuse, and recycle techniques or any two of these processes in terms of the concrete technology use. The three major objectives governing the green concept in concrete are to reduce greenhouse gas emissions (i.e., carbon dioxide emissions) from the cement industry; to reduce the use of natural resources such as limestone, shale, clay, natural river sand, and natural rocks that are being consumed and cannot be returned to the earth; and the use of waste materials in concrete, which results in air, land, and water pollution. The objective underlying the production of green concrete is to effect sustainable development—i.e., development that takes place without destroying natural resources (Suhendro, 2014).

Guidelines for green concrete

Water, sand, stone, gravel, and other ingredients make up about 90% of traditional concrete mixture by weight. The processes of mining sand and gravel, crushing stone, combining the materials in a concrete plant and transporting concrete to the construction site require very little energy and, therefore, result in the emission of a relatively small amount of CO_2 into the atmosphere. The amounts of CO_2 produced by concrete are primarily a function of the cement content in the mix designs. It is important to note that structures are built with concrete and not cement.

Depending on its performance requirements, concrete uses about 7% or 15% cement by weight. The average quantity of cement is around 250 kg/m^3. One cubic meter of concrete weighs approximately 2400 kg. As a result, approximately 100 to 300 kg of CO_2 is emitted for every cubic meter of concrete produced or approximately 5 to 13% of the weight of the concrete produced, depending on the mix design. A significant portion of the CO_2 produced during the manufacture of cement is reabsorbed into the concrete during the product lifecycle through a process called carbonation. According to NRMCA (2012) estimates, between 33% and 57% of the CO_2 emitted from calcination is reabsorbed through carbonation of concrete surfaces over a 100-year lifecycle. The global cement industry accounts for approximately 5% of global CO_2 emissions. Therefore, whichever way one looks at the issue of CO_2 emission, the production of concrete accounts for a very small percentage of overall CO_2 emissions. This is not to say that progress should not be made in reducing the CO_2 emissions from concrete as produced. However, reductions in CO_2 emissions reductions in the production of concrete have the potential to account for at best a 2% reduction in the emission of CO_2 globally. Obla (2009a, 2009b) summarizes this point of view in What is Green Concrete? as follows:

- CO_2 emissions from 1 ton of concrete produced vary from between 0.05 to 0.13 tons. In total, 95% of all CO_2 emissions from a cubic yard of concrete are from cement manufacturing. It is important to reduce CO_2 emissions through the greater use of SCM.
- It is important not to focus solely on CO_2 emissions from cement and concrete production. Doing so limits the total global CO_2 reduction possible to at best 2%. Keeping a holistic cradle to cradle perspective and using life cycle assessment (LCA) can help reduce CO_2 by a much greater amount, as there is evidence to show that most of the energy is consumed during the operational phase of the structure (heating and cooling). Concrete is very effective in reducing energy consumption due to its high solar reflectivity and high thermal mass among other benefits.
- Focusing solely on CO_2 emissions from cement and concrete production increases the perception that concrete is not sustainable. This is inaccurate, as operationally concrete has substantial sustainability benefits. An incorrect perception can lead to a less sustainable material choice.
- Focusing solely on CO_2 emissions from cement and concrete production does not encourage the use of recycled or crushed returned concrete aggregates; use of water from ready-mixed concrete operations; use of sustainable practices such as energy savings at ready-mixed concrete plants; and use of sustainable transport practices. This is because only 5%

of CO_2 emissions from a cubic yard of concrete is due to the use of virgin aggregates, water, plant operations, and material transport to the plant.

- The removal of prescriptive specification restrictions and a focus on performance and the use of incentives is an effective way to encourage the production of sustainable concrete with a low CO_2 emission.

An essential step toward achieving sustainable development of concrete was taken with the establishment of a large Danish research project called Resource Saving Concrete Structures (colloquially Green Concrete), which ran from 1998 to 2002. The project involved partners from all sectors related to concrete production, i.e., cement and aggregate producers, a contractor, a ready-mix plant, a consultant, building owners, the Danish Technological Institute, and two technical universities. The purpose of the project was to study holistic approaches to the production of concrete whereby considerations pertaining to material characteristics and to structural performance would be integrated into the following tasks (Table 2):

- To develop green cement and green concrete types, e.g., concrete in which the percentage of cement is decreased considerably because high amounts of cement replacement materials (> 40 %wt.) are used instead. Such replacement materials include fly ash, silica fume, other natural pozzolans, and waste materials such as stone dust, crushed concrete, concrete slurry, cement stabilized foundations with waste incineration and other inorganic residual products.
- To develop green design strategies, which require less maintenance and repair work, using, for example, stainless steel instead of black reinforcement. This is of particular interest, as it is well known that in concrete structures located in aggressive environments the highest environmental loads result from maintenance and repair work during the service life of the structure.
- To develop green structural designs and structural solutions for green concrete, e.g., optimized structural detailing by minimizing the structural dimensions using high performance concrete.

Table 2 Combination of Traditional and Green Concrete/Concrete Structures (Edvardsen & Tølløse, 2001).

	Traditional structure	Green concrete
Traditional structure	Restricted amount of fly ash and microsilica	High amount of fly ash and microsilica Green types of cement Use of stone dust, slurry, waste incineration
Green concrete	Cladding with stainless steel Stainless steel reinforcement	Green concrete (see above) plus stainless steel cladding or stainless steel reinforcement

Proske et al. (2013) presented a step-by-step approach implemented in order to develop eco-friendly concretes with reduced cement and water content. In parallel, several experimental attempts were made to evaluate the required concrete performance for practical purposes. According to the results, the following conclusions can be derived:

- CO_2 emissions can be reduced significantly in structural concretes. A significant reduction in Portland cement demand can be achieved by using high-performance superplasticizer, high-strength cement, and optimized particle-size distribution.
- The replacement of Portland cement and water with mineral fillers, such as limestone powder, provides an optimal paste volume in a low-water mixture. It was shown that concretes with cement clinker and slag contents as low as 150 kg/m^3 can meet the usual requirements for workability, compressive strength (approx. 40 N/mm^2), and other mechanical properties.
- The carbonation depth of eco-friendly concretes with at least 175 kg/m^3 clinker and slag were observed to be lower than that of conventional concretes for exterior structures.
- A reduction in the global-warming potential of up to 35% compared with that of conventional concrete can be seen as well as a reduction of more than 60% when granulated blast-furnace slag is used. An allocation of slag of this magnitude, however, would decrease the extent to which the concrete's global-warming potential could be decreased.

- Practical applications were verified in precast and ready-mixed concrete plants. The results showed that eco-friendly concretes in both fresh and hardened states are of an acceptable standard for use in the aforementioned industries.

The use of concrete can facilitate the process of obtaining Leadership in Energy and Environmental Design (LEED) Green Building certification. LEED is a point rating system devised by the U.S. Green Building Council (USGBC) to evaluate the environmental performance of buildings and to encourage market transformation toward sustainable design, as shown in Table 3. The system is credit-based, allowing projects to earn points for environmentally friendly actions taken during the construction and use of a building. LEED was launched in an effort to develop a consensus-based, market-driven rating system to accelerate the development and implementation of green building practices (PCA, 2005).

Table 3 Five Properties of Concrete that Contribute to the Construction of Greener Buildings.

No.	Main categories
1	Concrete creates sustainable sites
2	Concrete enhances energy performance
3	Concrete contains recycled materials
4	Concrete is manufactured locally
5	Concrete builds durable structures

Concrete is a key element in green buildings and when used effectively can play an important role in obtaining a LEED certification. For illustrative purposes, the advantages of concrete for efforts to obtain LEED 2015 certification are considered in detail in this section. LEED has become one of the most standard widespread and well-known certifications for rating green practices in construction worldwide. LEED uses a system of points to determine which of its various certifications to award any given project. Platinum level is the most rigorous and marks industry best practices with 80 or more points. Gold level requires 60 points, Silver needs 50 points, and the minimum level of certification is achieved with 40 points, as shown in Table 4 (Blanco-Carrasco et al., 2010).

Table 4 LEED Certifications and Points Required for Each Level.

LEED Certification Levels	Points Required
Certified	40–49
Silver	50–59
Gold	60–79
Platinum	80+

To ensure the future competitiveness of concrete as a building material, it is essential to improve the sustainability of concrete structures. Great potential for reducing the environmental impact and consumption of scarce resources has been identified in the field of concrete construction, especially in the production of raw materials, concrete technology, and structures. For concrete that is developed, produced, and used in an environmentally friendly way the term “green concrete” is commonly used. Based on experimental results, a step-by-step procedure for the development of low-carbon concretes with efficient use of reactive materials has been devised by Proske et al. (2014), who recommend the following key steps:

- Selection of cement of a high-strength class and composed of eco-friendly constituents such as limestone, granulated blast-furnace slag (GBFS) or fly ash.
- Optimization of water content and cementitious material in the concrete paste.
- Optimization of the paste volume.

Glavind et al. (1999) presented three development projects through which the researchers produced and studied green concrete in three ways:

- To minimize the clinker content, i.e., by replacing cement with fly ash, microsilica in larger amounts than are allowed today, or by using extended cement, i.e., Portland limestone cement. The preliminary plan is to analyze concrete for the passive environmental class with fly ash amounts of up to 60% of the total amount of cement and fly ash, concrete with Portland limestone cement for the aggressive environmental class, and concrete with dry desulphurization products for the passive environmental class.

- To develop new green cements and binding materials, i.e., by increasing the use of alternative raw materials and alternative fuels, and by developing/improving cement with low energy consumption, a new, rapid hardening low-energy cement based on mineralized clinker is currently ready for testing.
- Concrete with inorganic residual products (stone dust, crushed concrete as aggregate in quantities and for areas that are not allowed today) and a cement-stabilized foundation with waste incinerator slag, low-quality fly ash, and/or other inorganic residual products. Currently, an information screening of potential inorganic residual products is being carried out. The products are described by origin, amount, particle size and geometry, chemical composition, and possible environmental impact.

The main goal of producing green concrete is to reduce the harmful residuals generated across industry and to produce concrete in a way that is more economical than are the standard processes currently in use, as shown in Table 5. To enable concrete of this nature to be produced in this way, new technology is under development. The technology is designed to account for all phases of a concrete construction's lifecycle, i.e., structural design, specification, and manufacturing and maintenance. Further, the technology applies to all aspects of performance, i.e., mechanical properties (strength, shrinkage, creep, static behavior, etc.), fire resistance (spalling, heat transfer, etc.), workmanship (workability, strength development, curing, etc.), durability (corrosion protection, frost, new deterioration mechanisms, etc.), and environmental aspects (CO_2 emission, energy use, recycling, etc.) (Tafheem et al., 2011).

The knowledge and experience in Denmark pertaining to how to produce concrete with a reduced environmental impact can be divided into two areas, concrete mix design and cement and concrete production, as shown in Table 6:

Table 5 Goals of Producing Green Concrete.

Goals related to residual reduction and economy	Environmental Goals
● Concrete with minimal clinker content ● Concrete with green types of cement and binders ● Concrete with inorganic residual products ● Operation and maintenance technology for green concrete structures ● Green structural solutions and structural solutions for green concrete	● CO_2 emission caused by concrete production must be reduced by at least 30% ● The concrete industry's own residual products must be used in concrete production ● New types of residual products, previously landfilled or disposed of in other ways, must be used in concrete production ● CO_2-neutral, waste-derived fuels must replace at least 10% of the fossil fuels in cement production

Table 6 How to Produce Concrete with Lower Environmental Impact (Glavind et al., 1999).

Key factor	How to produce concrete
Concrete mix design:	- use cement with a reduced environmental impact - minimize cement content - substitute cement with pozzolanic materials such as fly ash and microsilica - recycle aggregates - recycle water
Cement and concrete production:	- engage in environmental management

The basic principles of green concrete mix design are introduced and a systematic study of the influence of the cement content on the fresh and hardened properties of concrete as well as on its durability parameters are presented in Müllera et al. (2014). From the results, it can be seen that green concretes are highly sustainable and, depending on the attack scenario, might be sufficiently durable when subjected to exposure associated with corrosion. The key challenge in the development of concretes with minimum environmental impact lies in maintaining sufficient workability at a very low water content. As in the fresh state, water is needed to fill the inter-granular voids in the mix, which consist of aggregates and cement particles. Further, water is needed to lubricate the deformation of this granular system, as a reduction in water content at a constant packing density would inevitably result in a loss of workability and in the formation of voids. Against this background, methods for optimizing the packing density of the granular mix constituents constitute a key step in the mix development process. The mix development algorithm applied in this study (Müllera et al., 2014) is detailed in Fig. 2.

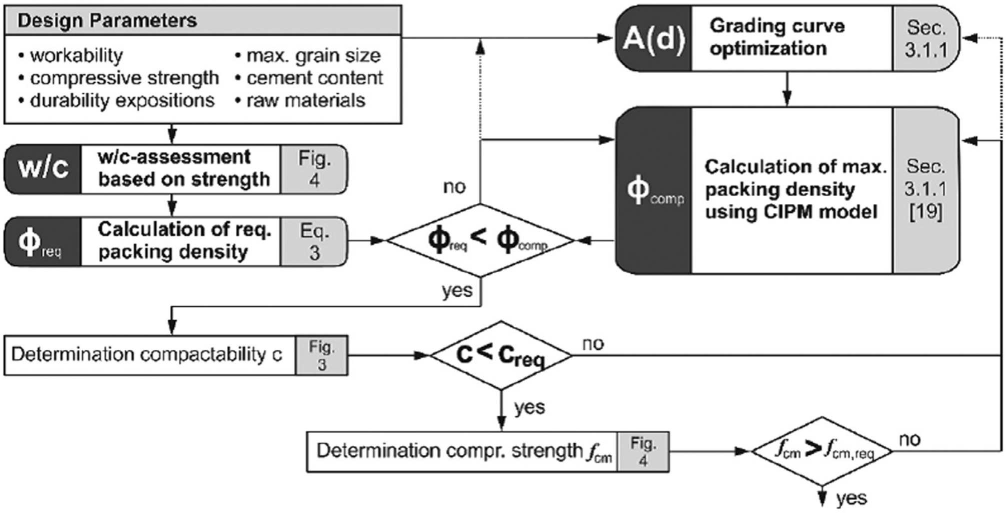

Fig. 2. Schematic sequence of the mixture
development procedure for green concrete (Müllera et al., 2014)

Many concrete programs in industry have a perspective on the broader issue of green technology and environmental performance. Here, the desirable qualifications of green concrete for sustainability are listed (Lu, 2012):

- Long service life and high performance. Reinforced concrete’s durability ensures that the structure will retain its structural capabilities for many years due to the high-performance concrete, e.g., anti-corrosion and anti-cracking concrete. The carbon footprint and high energy consumption of the cement industry are minimized when it is not necessary to replace or repair a concrete structure.

- Maximized recycling materials usage and minimized environmental impact. Concrete producers can replace significant amounts of cement in their mixtures with industrial by-products such as silica fume and blast-furnace slag. The use of these materials in concrete prevents them from entering landfills and minimizes cement consumption, even producing a more durable concrete. Waste industry products can be recycled and, in turn, result in less waste being released into the environment.
- Minimized transportation cost. Producers of concrete should take advantage of local materials, as reinforced concrete components can be made locally anywhere in the world. This turns out to be the key element in reducing emissions due to transportation. Through the use of local materials, the impact of transportation and energy consumption can be minimized.

In determining the suitability of green concrete for any given structure (Garg & Jain, 2014), several factors in favor of green concrete should be considered: The use of green concrete reduces the dead weight of a structure and reduces crane age load; allows handling, given greater lifting flexibility with lighter weight; affords good thermal and fire resistance and better sound insulation than traditional granite rock does; improves the damping resistance of buildings; speeds up construction; reduces the concrete industry's CO_2 emissions by 30%; increases the concrete industry's use of waste products by 20%; produces no environmental pollution and supports sustainable development; requires less maintenance and repairs and sometimes gives better workability than conventional concrete does; yields better compressive strength behavior when its water/cement ratio is more than that of conventional concrete; and offers flexural strength almost equal to that of conventional concrete. A comprehensive list of green concrete technologies is given in Table 7 (fib, 2012).

Jin and Chen (2013) summarize the potential barriers to using green concrete. Despite the potential benefits of using green raw materials in concrete production, barriers exist in regard to the properties of the concrete produced, its cost-effectiveness, and industry perceptions:

- Concrete properties: Using waste streams as concrete ingredients could improve certain types of concrete properties while undermining some others.

- Cost-effectiveness: Cost-effectiveness would be the driving force for the industry to implement green concrete. Recycling and reuse of waste materials require extra labor and energy input.
- Industry perception/practice: The construction and building product industry is conservative in nature due to the fear of product failure.

Table 7 Comprehensive List of Green Concrete Technologies (fib, 2012).

Key topics	Green concrete technologies
1. Choice of raw materials	The production and use of blended cements have a long and successful tradition. Today, about 70% of the cement produced and used in Europe has several main constituents. The use of other main constituents along with Portland cement clinker will depend on the availability and quality of these materials at an affordable cost. A number of supplementary cementitious materials (SCM) are used to blend either the cement or the concrete. These materials are used as a supplement to the clinker content. In most cases, they allow the clinker or cement content to be reduced, and in some cases specific concrete properties are improved. The most commonly used SCMs are: - Fly ash from coal-fired power plants - Silica fume - Blast furnace slag - Sewage sludge - Rice husk ash - Recycled ground glass - Limestone powder - Metakaolin - Natural pozzolan The choice of aggregate is very much a local decision. Natural sand and gravel resources are being depleted in some regions and countries, and the trend is toward using more crushed and manufactured aggregates.

Key topics	Green concrete technologies
2. Optimization of the mix design with respect to clinker content	One way for a concrete producer to optimize the mix design and minimize clinker consumption is to use cement with several main constituents. Another way is to mix pure Portland cement with other mineral additions. A concrete producer who is adding new materials to a mix design must demonstrate that these materials do not cause problems in regard to the concrete's performance. It may be that supplementary cementitious materials (SCM) can be used to replace cement or perhaps aggregates.
3. Production method	The concrete industry is a large consumer of water. The water demand for concrete mixing depends on the mix design and the use of plasticizing additives. However, concrete plants also consume a relatively large amount of water for washing the mixer, conveyor belts, formwork, trucks, and laboratory equipment. It is noted that recycling saves money for the producer in terms of a significantly reduced need for fresh water and obviating the need for a chemical treatment plant. Moreover, noise and dust are associated with concrete production. The measures that are necessary depend strongly on the location of the plant and the noise level generated by the equipment.
4. Recycling of demolition waste in concrete production	The technologies for recycling construction and demolition waste (C&DW) back into construction are already widely known and accepted. However, the major hurdle pertains to establishing economic incentives in order to make recycling an option. However, green procurement, especially by the authorities, will probably accelerate recycling in the future. The principal applications of recycled concrete rubble are as follows: - Down-cycling it for road sub-base and back-fill material in connection with construction work. As the quality and homogeneity of recycled concrete material varies significantly, it is mainly suitable for low-tech applications where performance is not a top priority. - Recycling it into concrete as a substitute for natural aggregates. This application is possible, and the

Key topics	Green concrete technologies
	performance of the recycled aggregate concrete can be satisfactory when compared with conventional concrete.
5. Construction phases	One green measure during the construction phase is the use of self-desiccating concrete, which can minimize the energy needed to dry out the concrete in order to obtain the required moisture content. The following recommendations can be given: - Provide appropriate drying times for concrete before applying surface materials. - Be careful in regard to detailing to avoid flanking the transmission of noise in buildings.
6. Use of concrete	For buildings, the appropriate use of exposed concrete on the inner walls can reduce the energy used for heating and cooling by approximately 5–15%. The exact savings depend on the climate, the orientation of the structure, how much of the concrete surface is exposed, and the ventilation system, etc. The following recommendations can be given: - Clarify and utilize the thermal mass effect in regard to energy use and thermal comfort. - Maximize the use of solar and other free energy gains by thermal storage. - Clarify and use the thermal mass effect in regard to the top effect requirement for heating and cooling systems. - Use energy calculation programs that take thermal storage into account. - Use low-energy sources by design for a low top effect. - Expose concrete surfaces for access to thermal storage.

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