

# **Emphasizing Sustainability in a Course on Reinforced Concrete Design**

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## Abstract

Concrete is the most widely used building material in the world because of the simplicity of its manufacture, the abundance of raw materials, and the economical method of construction it provides. Invariably, all civil engineering programs in the United States offer courses in the manufacture of the material and the design and construction of reinforced concrete structures. However, students are rarely introduced to sustainability principles and practices that produce "green" reinforced concrete structures, in that raw materials are used efficiently, byproducts are utilized, carbon footprint is reduced, and the resulting structure is energy efficient and durable. Knowledge of sustainability principles will make future structural engineers mindful of the impact of their design on the environment and the society at large. This paper presents an approach for revising a traditional course on reinforced concrete design to include an emphasis on sustainability in all topics. This course is being referred to hereafter as Sustainable Reinforced Concrete Design (SRCD) course.

The major drawback of concrete is its environmental impact occurring along four phases: production of materials, construction, lifecycle, and demolition. The common critical element between these phases is the polluting emissions resulting from embodied energy or chemical reactions. The SRCD course will integrate sustainability into the planning, designing, and construction stages of reinforced concrete. It will emphasize strategies and practices for using concrete in smart and innovative ways to achieve sustainable, "green" buildings. Sustainability principles will be addressed from two perspectives: materials and structural design.

From the standpoint of materials, production and use of ultra-high performance concrete will be presented, explaining the associated benefits of consuming fewer raw materials while providing higher durability and longer service life. Emerging technologies for manufacturing and using "green" cements and their impact on future concrete construction will be addressed. Concrete mixture design with less Portland cement content through the incorporation of byproducts, such as fly ash, slag, and rubber tire wastes, will be covered, to illustrate the compounded benefit of using byproducts for eliminating waste and enhancing the properties of concrete.

Sustainability in structural design will be addressed from various angles, such as using highperformance concrete (with compressive strength in excess of 10,000 psi), which is not explicitly addressed in the ACI 318 Building Code. Design examples will be shown to illustrate the sustainability benefits of using high-performance concrete.

The benefits of training future engineers to incorporate sustainability in design are numerous. The proposed SRCD course is an effort to integrate sustainability in a traditional course on concrete design. It is expected that the revised course will provide the fundamentals upon which students will continue building in order to develop alternative concrete building strategies for sustainable concrete construction. The objectives of the SRCD course will be met through a number of classroom activities, including lectures, review of technical literature, term papers, and case studies that illustrate the benefits of sustainable concrete design.

### Purpose

A conventional course on reinforced concrete design for undergraduate students in civil engineering includes instruction on the material properties of concrete and on the features and design of various concrete structural elements, such as beams, slabs, columns, and foundations, in accordance with the ACI 318 Building Code. Typically, such a course does not address sustainability. The aim of a revised Sustainable Reinforced Concrete Design (SRCD) course is to integrate sustainability and sustainable practices into all course topics. Practices for producing sustainable concrete, as well as sustainability-enhancing changes in the design of concrete structure engineers to the importance of sustainability and teach them ways to increase the sustainability of concrete for reduced carbon footprint.

Need for a course on sustainable reinforced concrete

The population increase over the last century has exerted significant pressure on the natural resources and has negatively affected the environment. Sustainability measures have become a necessity for enhancing human health and the environment.<sup>[1]</sup> Researchers and policy makers are looking for ways to incorporate sustainability into the construction industry on a wider scale. For instance, the U.S. Green Building Council, one of the leading non-profit organizations promoting sustainability in the building and construction industry, has developed the LEED rating system, which provides a framework for identifying and implementing practical and measurable solutions for green design, construction, operations, and maintenance.<sup>[2]</sup>

The SRCD course will address sustainability of concrete from a life cycle perspective. The four key stages concrete goes through during its life will be covered. These stages are: 1) raw materials (extraction, processing, manufacturing, and transporting), 2) construction, 3) structure's operation and maintenance, and 4) disposal, reuse, or recycling. Minimizing environmental and economic impacts during these stages is a major step towards sustainability. The major goal is reducing emissions through each stage. This involves the selection of the concrete material ingredients, such as using byproducts, or recycled materials to supplement portion of the cement in order to reduce CO2 emissions. Other aspects of concrete that can impact its life cycle sustainability include UHPC as it will reduce material consumption and result in more durable material that has a longer life and possibly maintenance free.

Choosing an appropriate construction material is the first step toward sustainability. Concrete is the most common, most efficient, and most economical construction material because of its simple manufacturing and the abundance of the raw materials. It is typically produced by mixing large amounts of coarse and fine aggregate and moderate amounts of hydraulic cement and water. Small amounts of admixtures can be used to control the cement's properties.

As concrete is the most widely used construction material worldwide, new technologies in concrete manufacturing can contribute enormously to sustainable development that fosters economic growth and social progress while minimizing environmental impact.<sup>[3]</sup> Enhancing the sustainability of concrete is beneficial in several ways. The reduced operating and maintenance

costs of sustainable concrete will produce economic benefits. Sustainable concrete will improve the quality of life and enhance human health. Finally, it will lead to environmental benefits by promoting biodiversity, reducing air and water pollution, and conserving and restoring natural resources.<sup>[1]</sup>

Benefits of incorporating sustainability in a course on reinforced concrete

Even though concrete has less environmental impact than steel, it still has a significant carbon footprint. <sup>[4]</sup> Large greenhouse gases (CO<sub>2</sub>) result from the energy consumed in the production of concrete (extracting, manufacturing, and mixing its components). The energy spent for producing Portland cement represents about 80% of the total energy required for producing concrete. <sup>[4]</sup> One ton of CO<sub>2</sub> emissions are generated from each ton of cement production. Cement production alone is responsible for 5% of global greenhouse gases, not to mention other harmful pollutants such as NO<sub>x</sub> and particulates. <sup>[5]</sup>

The SRCD course will address sustainability by introducing strategies for reducing Portland cement in concrete, improving concrete's performance by using less material, and making it more durable in order to increase its lifespan with minimum maintenance costs. <sup>[6]</sup> For example, the course will investigate the effects of adding various materials to concrete as partial substitute for one or more of its ingredients, and will discuss structural design of unconventional concrete with ultra-high strength. Applying these concepts on a wider scale will reduce cost, preserve resources, minimize energy consumption, and enhance the environment and human health.

Integration of sustainability in a course on reinforced concrete

The sustainability of materials is related to their life stages: production of components, construction, life cycle, and demolition. The SRCD course will emphasize the importance of each stage for increasing the sustainability of concrete. Thus sustainability will be approached from two perspectives: materials and structural design. In addition, the LEED rating system will be introduced.

Upon completing the course, students will be able to: (1) know concrete mix proportioning and design that provide sustainable concrete material, (2) understand the parameters underlying the manufacture and use of ultra-high performance concrete, (3) select concrete building strategies that will result in sustainable concrete construction, (4) suggest alternative designs using sustainable concrete options, and (5) discuss how concrete can play a role in sustainable engineering design. Students will be introduced to the American Concrete Institute (ACI) and Precast Concrete Institute (PCI) resources and technical publications related to sustainable concrete design practices.

Utilizing byproducts in concrete components increases the sustainability of concrete because it reduces the use of virgin materials (either manufactured, such as Portland cement, or extracted by mining, such as aggregates) and energy required for their preparation and production. For example, using fly ash or slag in hydraulic cement reduces the required amount of Portland cement. Slag and recycled concrete may be used also to replace natural aggregate.<sup>[4]</sup> Steel

reinforcement may be used for improving the mechanical properties of concrete as well as for reducing designed cross sections, resulting in the use of less material.

Thus the SRCD course will expose students to three strategies for improving sustainability: use of byproducts in concrete, structural design to reduce carbon footprint, and using high-strength concrete to reduce cross sections and increase spans, thus reducing used materials. Additionally, improved applications of concrete integrating sustainability in construction will be covered.

Sustainability of reinforced concrete from the standpoint of materials

The finiteness of available resources has become evident over the past century. The significant population growth and the continuously increasing resource consumption per individual pose with urgency the problem of managing, conserving, and restoring natural resources as well as searching for new ones. The waste increase and environment deterioration additionally exacerbate the situation.

The use of waste byproducts in concrete materials not only will reduce industrial waste but will add value to it. It will reduce the consumption of virgin materials, leading to decrease of used energy and emitted pollutants in the process of manufacturing. Notably, it may even improve the conventional properties of concrete and make the material more reliable. Therefore, the SRCD course will address the utilization of various waste materials and byproducts in the manufacturing of concrete to replace a portion or all of the cement content or aggregate and increase concrete's sustainability.

Of all concrete ingredients, cement requires highest energy and emits largest amount of  $CO_2$  during its production. Accordingly, to achieve sustainability, the objective is to reduce Portland cement in concrete mix by substituting a portion of it (20% to 60% of its mass) with other binding materials without jeopardizing concrete's mechanical properties. The resulting mix is called cementitious admixture. Because cement is the binding element that determines concrete's strength, its substitutes (supplementary cementitious materials) should have cementitious or pozzolanic properties to be efficient.

The SRCD course will introduce various pozzolanic and cemeticious materials (mineral admixtures) as partial substitutes for cement. Pozzolanic materials (e.g., fly ash and silica fume) are fine siliceous and/or aluminous materials that in the presence of moisture chemically react with calcium hydroxide (in lime produced when Portland cement hydrates) to form cementitious compounds. They can increase concrete's strength and durability to thermal cracking and aggressive chemicals. Pozzolanic materials can be industrial byproducts or may be produced from natural resources. Cementitious materials (e.g., granulated blast-furnace slag) are nearly the same as pozzolanic materials, except that they contain sufficient calcium to react with water and form cementitious compounds.<sup>[7]</sup>

The SRCD course will include instruction on mineral admixtures as partial substitution of ordinary cement for several reasons. Such admixtures increase the ultimate strength of concrete and improve its impermeability and durability to chemical attacks. Further, the hydration of cement (a chemical reaction with water) is exothermal. Substituting a portion of cement with

mineral admixtures reduces this heat and increases the resistance of concrete to thermal cracking. Consequently, tensile strain capacity increases as well. The mineral admixtures may also reduce drying shrinkage and the cracks associated with it by reducing the binder paste to aggregate ratio and the water content. Furthermore, as Portland cement is the most expensive element in conventional concrete and mineral admixtures are mostly industrial byproducts, replacing portion of Portland cement with them will reduce cost and consumed energy significantly. Finally, many waste byproducts contain toxic elements. Disposing of them without affecting human health and the environment is challenging. However, they can be safely incorporated into the hydration products of cement. Ultimately, the use of mineral admixtures leads to reducing the carbon footprint of concrete. <sup>[8]</sup> In the following section we provide three examples of mineral admixtures that can partially substitute ordinary Portland cement.

Fly ash is a product of burning finely ground coal in a boiler to produce electricity. It is a very fine, powdery, pozzolane siliceous material. It consists mostly of silt- and clay-sized glassy spheres. There are several applications of fly ash to enhance concrete's properties. It can be used as raw material to a replace portion (20% to 60%) of the cement in concrete. It can also be a component in flowable fill and pavement.<sup>[9]</sup> Its small particles make the concrete more cohesive and prevent segregation and bleeding.<sup>[8]</sup> The main problem with high volume fly ash in concrete (substituting more than 40% of cement) is the long set time and slow strength development. This can be controlled by using certain chemical admixtures but the process is expensive. Thus usually only 15% to 30% of cement is replaced by fly ash. Mehta<sup>[8]</sup> proposed to overcome this problem by significantly reducing the water to cementitious materials ratio while using chemical superplactisizer and a judicious aggregate grading. Research by Rag Petal et al.<sup>[10]</sup> revealed that a special type of fly ash (fly ash-based hydraulic binder) can replace cement 100% to produce green concrete (zero carbon footprint) that has same or better plastic and mechanical properties as conventional, Portland-cement concrete. This binder consists of 90% to 95% fly ash and 5% to 10% proprietary activators that activate the fly ash and control the set time. For the same binder content and workability, green concrete (with fly ash-based hydraulic binder) has higher compressive strength than Portland-cement concrete.

Silica fume is a byproduct from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of silicon and ferrosilicon alloys.<sup>[11]</sup> It is considered the best pozzolanic material for modern high-performance concrete. Silica fume increases the compressive and tensile strength and durability of concrete significantly. Its extremely fine particles (100 times smaller than the average cement particles) fill the microscopic voids between cement particles. Other advantages of applying silica fume to concrete include increased bond strength between aggregate and paste, providing superior resistance to chemical attacks, increased abrasion resistance, reduced permeability and less expansion than traditional concrete (due to alkali-silica reactivity). Silica fume is usually added to concrete in a proportion up to 15% of cement weight. Having large surface area due to its extremely small particles, it requires more water than conventional concrete to provide adequate workability. This drawback can be compensated for by adding high-range water reducer to the mix.<sup>[12]</sup>

Granulated blast furnace slag is the product of rapidly chilling molten iron blast furnace slag by water immersion. The slag is then grounded to cement fineness, resulting in ground granulated blast furnace slag (GGBFS). GGBFS as partial cement substituent is not as efficient as silica

fume or fly ash. There are three grades of GGBFS – 80, 100, and 120 – based on the slag's activity index, which is the cubic compressive strength ratio of mortar made of 50% slag–cement blend to reference mortar (no slag). Only grades 100 and 120 can increase concrete's strength. Yet, the use of grade 80 in mass concrete is more appropriate because of its lower heat of hydration. The advantages of GGBFS are obvious for increasing concrete durability, reducing water demand, decreasing concrete permeability, and reducing concrete expansion caused by alkali-aggregate reaction. Disadvantages, on the other hand, are the long setting time (due to the low rate of hydration, especially at low temperatures) and the slow strength gain, which makes GGBFS concrete more susceptible to drying shrinkage.<sup>[13]</sup> Avoiding these problems requires proper and highly controlled curing. As slag content increases, the compressive strength of concrete decreases. Therefore, the substitution of Portland cement with GGBFS should not exceed 50%.<sup>[14]</sup>

In addition to addressing different supplementary cementitious materials, the SRCD course will introduce other types of cement than ordinary Portland cement (OPC), such as calcium sulfoaluminate cement, calcium aluminate (CaAl<sub>2</sub>O<sub>4</sub>) cement, and calcium alumina-silicate cement. <sup>[15]</sup> They have much less CO<sub>2</sub> emissions than OPC, yet they can be manufactured in the same conventional plants. The SRCD course will introduce also the Solidia cement, which delivers Solidia concrete with up to 70% less carbon footprint than OPC concrete. Its setting and hardening are controlled upon exposure to CO<sub>2</sub> gas streams curing and result in 4,000 psi to 8,000 psi compressive strength gain in one day, while conventional concretes take a week or longer. Solidia cement is manufactured from same raw materials of OPC but without gypsum and bauxite. It requires less limestone and more silica sources. Its production uses less energy than the production of OPC. Its binding is formed by carbonation reactions (the final binder is crystallized calcium carbonate) rather than hydration as it is in OPC.<sup>[16]</sup>

To promote sustainability in concrete materials, the SRCD course will also address alternative aggregates. Aggregate is the filling material in concrete and represents about 70% of its volume. It is usually obtained from natural resources. Substantial amounts of energy are required for the mining, processing, and transportation of the aggregate to the concrete manufacturing sites. The time consumed in that process, along with the considerable  $CO_2$  emissions are additional issues. Relying solely on traditional natural aggregate (virgin materials) for concrete will eventually cause its depletion. It is therefore necessary to look for alternatives. Demolished concrete, which has the largest share of construction waste, can be utilized as aggregate for new concretes. The only problems are its poor structure and the presence of fine particles from the demolishing process. This increases aggregate is the difficulty to predict its properties and performance in the composite action of concrete. The factor that determines the cost of aggregate is its transportation. Consequently, whether to use reprocessed concrete aggregate or virgin aggregate will depend on which of the sources is closer. <sup>[6]</sup>

The steel reinforcement also has a large impact on concrete sustainability. The SRCD will address the use of high strength steel as a way to reduce the concrete cross sectional area and steel reinforcement in a reinforced concrete member. This will contribute to improved aesthetics, reduction in carbon footprint, and will result in easier placement of the concrete during construction due to less congestion.<sup>[17]</sup>

In the SRCD course, the effect of water content relative to cement content will be discussed from sustainability perspective. Water in concrete is measured as a ratio of its weight to the weight of cementitious content (binder). As concrete strength increases when this ratio decreases, it is preferred to reduce water content in concrete. However, low water content affects workability. A portion of the added water is consumed in cement hydration, and the rest provides adequate workability for concrete mix. To compensate for the poor workability associated with reduced water, a range of water-reducing chemical admixtures (plasticizer and super plasticizer admixtures) are used. They disperse the cement agglomerates by electrostatic, steric (adsorbed polymers of admixtures on cement particles), or entropic (adsorbed and solvated polymers) repulsion, or improved wetting (capillary effect of remaining polymers in solution).<sup>[18]</sup>

Sustainability of reinforced concrete form the standpoint of structural design

Different approaches have been used for incorporating sustainability in the design of reinforced concrete structures. Students will be introduced to a couple of these approaches. First, the SRCD course will address the design of ultra-high performance concrete (UHPC). Most of the current reinforced concrete design codes are based on normal-strength concrete, with a specified limit of maximum compressive strength to validate its applicability. The ACI 318 Building Code does not address concrete design with compressive strength in excess of 10 ksi. An extensive survey by Zhenhua Wu et al. demonstrated that experimental flexural strengths of high-strength concrete beams (compressive strength > 10 ksi) do not match the moment capacity calculated according to LRFD specifications (based on stress block parameters as a function of concrete compressive strength). They also do not predict accurately the limit (c/de) of the balanced beam. Consequently, traditional design procedures per ACI 318 Building Code cannot be applied to reinforced concrete with compressive strength larger than 10 ksi, and need to be adjusted.<sup>[19]</sup>

The first approach will include structural design of UHPC based on standard compressive strength. Students will be introduced to material properties (compressive strength, modulus of elasticity, unit weight, modulus of rupture, and creep and shrinkage coefficients) of UHPC in comparison with ordinary Portland-cement concrete (OPCC). They will be able to conclude the equivalent stress block of UHPC from its stress-strain curve in compression, and to determine the required reinforcement.<sup>[20]</sup>

The failure mechanism of fiber-reinforced UHPC is plastic because it is governed by the bonding between fibers and matrix after its cracking. Thus, the design of fiber-reinforced UHPC should be based on performance criteria (e.g., maximum crack width criterion to limit stresses capacity), rather than on traditional standard strength criteria. The SRCD course will address the principles of this design along with pre-stressed UHPC. The focus will be on shear and bending. <sup>[21]</sup> This will allow students to understand the difference between UHPC and OPCC.

The second approach to increased sustainability through structural design is to reduce the amount of concrete materials and cement while increasing the reinforcement in order not to jeopardize structural ductility. The balancing of  $CO_2$  emissions from steel reinforcement and concrete production should result in an overall structure with minimum  $CO_2$  footprint.<sup>[22]</sup>

Specialized applications of sustainable concrete

In the SRCD course, students will be introduced to various types of sustainable concrete. They will become familiar with their properties, applications, and advantages that enhance sustainability. Examples of these concretes are shown below:

Roller Compacted Concrete: The sustainability of roller compacted concrete results from its low cement content and the use of pozzolanic materials to promote strength and reduce hydration heat. It has lower cost, quicker and easier placement, and better thermal cracking control than conventional plain cement concrete. It has zero slump and mostly needs vibratory steel drum rollers for its compaction. Its applications can be seen in dams, pavements, streets, and parking lots.<sup>[23]</sup>

Pervious Concrete: This sustainable material used in parking areas, alleys, and roads has many environmental benefits. Its high permeability makes it the perfect choice for an efficient storm-water management system. Its high porosity makes it very efficient in reducing noise, while its ability to reduce splash and spray makes it more reliable than traditional concrete or pavement materials alone. Other advantages of pervious concrete are its high durability to freezing and thawing and its high friction resistance as a wearing course. The only drawback of pervious concrete is its low strength caused by its high porosity, which makes it less efficient as a structural material. Pervious concrete can therefore be applied as an overlay material over traditional concrete. Research is being done to enhance the properties of pervious concrete with sufficient strength to sustain loads.<sup>[24]</sup>

Flowable Fill: Also known as controlled low strength material, flowable fill is self-compacting cementitious slurry formed of water, fine aggregate, and cementitious material. It is primarily used as a backfill material instead of compacted earth. It can also be used as embedment material (gap or trench filler). Flowable fill is very efficient in pavement because it provides quick and easy placing (it has low setting time), does not require compaction, can be excavated (it nearly has the strength of the surrounding soil after hardening), does not have settle, and its high flowability eases access to narrow and irregular spaces. Flowable fill may contain pozzolans or slag depending on its application (e.g., non-excavatable and cellular concrete). Additional advantages are its low cost, lower consumption of power in construction (no need for compaction), and the use of local soil in its manufacturing.<sup>[25], [26], [27]</sup>

Ultra High Performance Concrete: To reduce materials in construction, new technologies have been used to produce ultra-high performance concrete (UHPC), which has better performance than conventional concrete: higher strength, durability, ductility, toughness, better workability, longer service life, and less maintenance. Its tightly packed particles make it exceptionally resistant to fire, radiation, and damage. Embedding microscopic fibers in UHPC enhances its tensile, shear, and flexural strength and improves its resistance to cracks propagation, which in turn improves its ductility and toughness. Consequently, less steel is required for its reinforcement. All these advantages rank UHPC very high among superior sustainable constructing materials. The only disadvantage is its cost (30% to 40% higher than the cost of conventional concrete mix), although it is expected to decline with wider adoption of UHPC in structures.<sup>[20], [21]</sup> Typically, type I or II of cement is used for this concrete because of its

moderate cement particle size that reduces heat of hydration. Mineral admixtures (cementitious or pozzolanic materials) are used as partial supplement of cement to improve concrete's performance. Chemical admixtures are used as well to control setting time, workability, and water content in concrete. Fiber reinforcement, such as steel fibers, may be used in the manufacture of UHPC to improve its mechanical properties.<sup>[20]</sup>

Autoclaved Aerated Concrete: This light-weight concrete with 80% air content is made of cement, fine aggregate, and water. Expansion agent is used to provide the high amount of air in it. It is sustainable because of the large content of air, which provides excellent thermal and sound insulator, and because of its high durability and great fire resistance. What makes it even more sustainable is the use of byproduct materials such as fly ash and rebar in its production and the extremely small amount of raw materials required. It also consumes only 50% of the energy needed to produce conventional concrete. Its final product is recyclable. The autoclaved aerated concrete is manufactured and cut into blocks and panels for easy assembly with minimal waste. It requires no maintenance and has low operating costs. Its applications are in walls, floors, and roofs. <sup>[28], [29]</sup>

## Teaching approach

In the SRCD course, the sustainable aspects of reinforced concrete will be introduced through a variety of techniques outlined below.

Lectures: The course will be conducted through classroom and online lectures that will integrate sustainability into the traditional syllabus. Because of time constraints, the sustainability aspect added to the traditional course topics will be presented in the form of online lectures. Students will discuss what they have learned and ask questions, which will enhance the student-lecturer interaction.

Review of literature: Students will be required to perform a literature search on byproduct materials used in concrete manufacturing. This assignment may be completed in a library or using online databases.

Home assignments: Home assignments will include structural analysis and design of conventional and sustainable concrete as well as mixed design. A bonus assignment will ask for innovative solutions that enhance the sustainability of concrete. In addition, three quizzes will be given throughout the semester to evaluate students' knowledge.

Industry speakers: Students will learn about contemporary issues in the concrete industry and how they can be solved through sustainability. An open discussion at the end of the presentation will encourage student participation. Students will provide notes and a summary of the presentation in the next class.

Term paper and project: A term paper presenting a case study of sustainable concrete building design will be required. Students will also submit two term projects. The first will compare a conventional reinforced concrete to a sustainable reinforced concrete from the perspective of structural design. The second will do the same yet from mixed design perspective.

Poster presentations: Students in teams will present posters on special application of sustainable concrete. Topics will be coordinated in order to cover several concretes. Each poster will include description, implementations, manufacturing, proportioning, and construction and will address sustainability of the particular concrete application, as well as advantages and disadvantages. Students will be encouraged to evaluate and grade their own work with the lecturer's guidance based on quality, clarity, and organization of the presented information, as well as confidence of the presenter and connectivity with the audience.

#### Conclusion

The SRCD course is a milestone in the process of addressing sustainability in the concrete industry for civil engineering students. It highlights the importance of reducing environmental impact while maintaining low cost. After completing the course, students will be able to differentiate between conventional and sustainable concrete and develop structural designs to enhance sustainability and reduce carbon footprint. They will learn about different applications of sustainable concrete and challenged to offer innovative solutions for sustainability.

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