Solidia Concrete™

Part Two of a Series Exploring the Chemical Properties and Performance Results of Sustainable Solidia Cement™ and Solidia Concrete™

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Authors: Jitendra Jain, Ph.D., Sr. Research Scientist, Omkar Deo, Ph.D., Research Scientist, Sada Sahu, Ph.D., Principal Scientist, and Nicholas DeCristofaro, Ph.D., Chief Technology Officer, Solidia Technologies

Abstract

Solidia Concrete™ is a new, sustainable concrete that consumes carbon dioxide in the curing process. It is defined by both its proprietary curing process and its formulation—a blend of water, coarse and fine aggregate, and Solidia Cement™.¹ Solidia Concrete can be adapted easily by manufacturers of conventional concretes.

Solidia Cement, a requisite ingredient in the formulation of Solidia Concrete products, is composed primarily of low-lime containing calcium silicate phases. The curing of concrete products made using Solidia Cement is derived from a reaction between these low-lime calcium silicate phases and carbon dioxide (CO₂) in the presence of moisture. During the carbonation curing process, calcite (CaCO₃) and silica gel (SiO₂) are formed and are responsible for the development of strength within the concrete. This is in contrast to the hydration process occurring in Portland cement-based concrete, which involves the hydration reaction between high-lime calcium silicate phases and water to form calcium-silicate-hydrate gel and calcium hydroxide.

Solidia Concrete contains the same raw materials as those used in concrete products made with, ordinary Portland cement (OPC), namely, fine and coarse aggregate, supplementary cementitious materials, and chemical admixtures. In addition, the manufacturing of Solidia Concrete products is performed using identical mixing and forming processes as those adopted in OPC-based concrete production.

¹ Solidia Concrete and Solidia Cement are interdependent materials; Solidia Concrete can only be made with Solidia Cement. All calculations herein are based on trials using Solidia’s patented processes. For more information on Solidia Cement, see part one of this series, Solidia Cement™, published December 2013.
The curing process of concrete made using Solidia Cement sequesters up to 300 kg of CO₂ per tonne\(^2\) of cement used. When the reduced CO₂ emissions associated with Solidia Cement production are considered along with the ability of that cement to sequester CO₂ during concrete curing, the CO₂ footprint associated with the manufacturing and use of cement can be reduced by up to 70% compared to OPC.

Solidia Concrete can be produced by manufacturers of traditional concretes, and can be designed to address virtually any precast concrete application. These products, which include paving stones, concrete blocks, railroad ties, roof tiles, and pervious concrete, match or exceed the properties and characteristics of concrete products made using OPC. Additionally, the Solidia Concrete curing process can be completed in a matter of hours, allowing for rapid deployment. As water is not consumed during the Solidia Concrete curing process, it can be collected and reused, with recycle rates in excess of 60%, and potentially as high as 100%.

1. Introduction

Concrete is the world’s second most utilized substance, exceeded only by the consumption of water. Over 30 billion tonnes of concrete, containing approximately three billion tonnes of Portland cement, are manufactured and used every year. According to a 2005 study by the World Resources Institute (WRI) on greenhouse gas emissions by major industries, the cement industry is responsible for 3.8% of the total global greenhouse gas emissions, which is equivalent to 5-7% of industrial CO₂ emissions (reference 1). Likewise, other studies show that the cement industry accounts for about 5% of global anthropogenic carbon dioxide emissions (reference 2). According to the International Energy Agency (IEA), the cement industry must reduce CO₂ emissions by 66% in order to help limit global temperature rise to 2-3°C by 2050 (reference 3). Though current industry strategies, which include the use of energy-efficient process technologies, alternative fuels, and supplementary cementitious materials, may help reduce emissions moderately, there is a clear need for a transformative innovation.

Solidia Technologies’ patented cement chemistry and curing process offer the building materials and construction industries the ability to manufacture cement and concrete products within existing plants and use traditional design specifications to meet the IEA’s CO₂ emissions reduction goal, with minimal requirements for new supply chains and capital investment. Solidia Cement\(^\text{TM}\) is composed of a family of “green,” low-lime calcium silicate phases, similar, but not identical to the chemistry of ordinary Portland cement (OPC). As a result, it can be produced in existing cement kilns using the same raw materials that are used to make OPC, albeit in different proportions. Solidia Cement is produced using less limestone and at lower temperatures than are necessary for Portland cement. These factors translate into a reduction in the CO₂ emissions during cement manufacturing, from 816 kg per tonne of OPC clinker to 570 kg per tonne of Solidia Cement clinker (~30% reduction). Other pollutants associated with cement production, such as mercury, are also reduced by approximately 30%.

To create Solidia Concrete\(^\text{TM}\) products, water, aggregates and Solidia Cement are mixed, formed into the desired shape and then reacted with gaseous CO₂ to produce a durable binding matrix. The curing process sequesters up to 300 kg of CO₂ per tonne of cement used.

\(^2\) All calculations are based on the tonne, also known as the metric ton, equaling 1,000 kilograms.
Solidia Concrete outperforms traditional concretes in a range of properties including strength, abrasion resistance and durability. Additionally, the curing of Solidia Concrete can be completed in a matter of hours, allowing for rapid deployment.

As water is not consumed during the Solidia Concrete curing process, it can be collected and reused, with recycle rates in excess of 60%, and potentially as high as 100%.

The reduced CO\textsubscript{2} emissions associated with the production of Solidia Cement and the CO\textsubscript{2} sequestration associated with the curing of Solidia Concrete combine to reduce the CO\textsubscript{2} emissions of cement and concrete by up to 70%, approaching the 2050 cement industry goal referenced above.

2. General Characteristics of Concrete

The following are some of the valuable characteristics of concrete products made with ordinary OPC:

a) Strength, durability and versatility: Concrete is used as the primary construction material for most roadways, bridges, tunnels, runways, sewage systems, dams and buildings. Not weakened by fire or moisture, concrete structures can withstand natural disasters such as earthquakes, floods and hurricanes.

b) Low maintenance: Being inert and compact, concrete does not attract mold, is unaffected by pests, and maintains its key properties over time.

c) Affordability: Compared to other building materials such as steel, concrete is less expensive to produce and remains extremely affordable.

d) Low-thermal conductivity: Concrete walls and floors slow the passage of heat, thereby improving insulation and reducing temperature swings. This reduces energy needs from heating and air conditioning, offering year-round energy savings over the life of the building. A study by the National Ready Mixed Concrete Association (NRMCA) found that concrete walls reduce energy requirements for a typical home by more than 17% (reference 4).

e) Fire-resistance: Concrete’s resistance to fire and its low-thermal conductivity make it a highly effective barrier to fire spread.

f) Locally produced and locally used: The relative expense of land transport usually limits cement and concrete sales to within 300 km of a plant site. Very little cement and concrete are traded and transported internationally. This saves significantly on transport emissions of CO\textsubscript{2} that would otherwise occur.

Solidia Concrete shares all of the abovementioned characteristics. Thus, it can be used for virtually any precast concrete element. Examples of precast concrete products made with Solidia Cement are offered below (See Section 5).
3. Concrete Production

Concrete is produced from a variety of raw materials that are mixed, formed, set and hardened into desired shapes. This section describes the different constituent raw materials for concrete based on OPC and on Solidia Cement, the methods used for concrete mixing and forming, the concrete fresh-state (uncured) properties, and the processes used for concrete setting and hardening.

3.1 Constituent Raw Materials

The constituent raw materials used for concrete include cement, fine and coarse aggregates, supplementary cementitious materials, chemical admixtures and water. These raw materials typically conform to ASTM/AASHTO standards or other proprietary specifications (references 5-8).

3.1.1 Cement

Solidia Cement is a low-lime alternative to OPC. Its primary constituents are CaSiO$_3$ (wollastonite) and Ca$_3$Si$_2$O$_7$ (rankinite) along with complex CaAlSiO$_4$-based phases (melilite). By contrast, OPC consists primarily of Ca$_3$SiO$_5$ (alite) and Ca$_2$SiO$_4$ (belite). While OPC sets and hardens by virtue of a chemical reaction between water and high-lime calcium silicate and calcium aluminate compounds, Solidia Cement reacts with CO$_2$ in the presence of moisture. The exact chemistry and phase composition of Solidia Cement will vary somewhat from one manufacturing site to another, just as for OPC.

3.1.2 Fine and Coarse Aggregates

Concretes made with Solidia Cement typically utilize the same fine and coarse aggregates that are used for concretes made with OPC. The choice of aggregate size, shape and type has a major influence on concrete performance. For example, selection of aggregate with a range of particle sizes will ensure good particle packing and yield a concrete with superior performance and texture.

3.1.3 Supplementary Cementitious Materials (SCMs)

The vast majority of concretes are produced by partially replacing cement with industrial byproducts known as supplementary cementitious materials (SCMs). These include fly ash, silica fume, and ground-granulated blast furnace slag (GGBFS). SCMs are generally added during the concrete mixing process as an ingredient or by pre-blending with cement.

When incorporated into OPC-based concrete, the addition of SCMs creates secondary calcium-silicate-hydrate (C-S-H) gels, which help to improve overall strength. In concretes based on Solidia Cement, these same SCMs improve the overall packing density of the concrete, reduce the water demand and increase the strength. In general, up to 20% (by weight) of the Solidia Cement can be replaced with fly ash or GGBFS as a filler material.
3.1.4 Chemical Admixtures

Chemical admixtures are powders or liquids that are mixed along with the other raw material components of fresh concrete. Their function is to influence the forming and placement of fresh concrete (water-reducers, plasticizers and viscosity-modifiers), the rate at which the concrete hardens (set-controlling agents), and the properties of the fully hardened concrete (air-entraining agents and corrosion inhibitors). The performance of these admixtures is influenced by a number of factors such as variation in particle size distribution of the fine aggregate, the cement type and the ambient temperature.

Solidia Concrete is compatible with different types of chemical admixtures that reduce water demand and improve the viscosity or rheology of the fresh concrete.

3.2 Concrete Mixing

Vertical-axis mixers, twin-shaft mixers and drum mixers are all able to blend the raw material constituents of either OPC-based concrete or concretes made using Solidia Cement. Solidia Concrete follows the same mixing sequence and mixing duration as that of OPC-based concrete.

3.3 Properties of Fresh Concretes

The rheology and workability of fresh concrete affect the strength and durability of the hardened concrete element. The concrete mixture should contain sufficient water to make it cohesive, thus avoiding any segregation and bleeding. This applies to both OPC-based concrete as well as Solidia Concrete.

The desired workability of the fresh concrete is generally influenced by the nature of the application. Dry mixtures with low workability and low slump are typically used for pressed forms such as paving stones and concrete blocks. Wet mixtures with high slump are typically used in cast forms such as wet cast stones. In the case of fresh Solidia Concrete, proper workability can be achieved by modifying the water content and mixture proportions, and by using mineral (e.g., fly ash) and chemical (e.g., commercial water reducers and viscosity modifying agents) admixtures.

3.4 Concrete Curing Processes

3.4.1 Curing of OPC-Based Concrete

Concretes made with OPC set and harden by virtue of a chemical reaction between water and high-lime calcium silicate compounds $\text{Ca}_3\text{SiO}_5$ and $\text{Ca}_2\text{SiO}_4$. The hydration of the $\text{Ca}_3\text{SiO}_5$ phase, which is the most abundant mineral in OPC, contributes mostly to early strength development. This hydration can be written as:

\[
\text{Ca}_3\text{SiO}_5 + (1.3+x) \text{H}_2\text{O} \rightarrow \text{CaO} \cdot 1.7\text{SiO}_2 \cdot (\text{H}_2\text{O})_x + 1.3\text{Ca(OH)}_2 \quad \text{Eq. (1)}
\]

where $\text{CaO} \cdot 1.7\text{SiO}_2 \cdot (\text{H}_2\text{O})_x$ is a calcium silicate hydrate gel phase, and $\text{Ca(OH)}_2$ is calcium hydroxide (also known as portlandite). The variable $x$ in Equation 1 represents the amount of water associated with the $\text{CaO} \cdot 1.7\text{SiO}_2 \cdot (\text{H}_2\text{O})_x$ gel, which varies from about 1.4 to 4 depending
on the relative humidity inside the concrete. The water associated with CaO•1.7SiO$_2$•(H$_2$O)$_x$ is considered to be part of its actual gel composition. Much of the reaction occurs during the first few days and imparts substantial strength while reducing capillary porosity.

**Equation 2** shows the hydration of the Ca$_2$SiO$_4$ phase. The hydration products are the same as in Equation 1, but less calcium hydroxide is formed in this reaction. As Ca$_2$SiO$_4$ is less soluble in water than Ca$_3$SiO$_5$, the rate of hydration is much slower. Therefore, Ca$_2$SiO$_4$ hydration does not contribute to early strength of cement, but it makes substantial strength contributions to long-term or mature strengths of cement paste and concretes.

$$\text{Ca}_2\text{SiO}_4 + (0.3+x) \text{H}_2\text{O} \rightarrow \text{CaO}\cdot1.7\text{SiO}_2\cdot(x\text{H}_2\text{O}) + 0.3\text{Ca(OH)}_2$$  Eq. (2)

As an OPC-based concrete structure hardens over an extended period of time, the structure must be kept moist to allow hydration to proceed to the desired level. For example, concrete structures are often sprayed with water, maintained in a humid environment, and/or covered with tarps to minimize drying. The designed strength of an OPC-based concrete structure is typically reached over a 28-day period.

### 3.4.2 Curing of Solidia Concrete

As noted above, Solidia Concrete is characterized by the incorporation of Solidia Cement as the primary binding element in the concrete mix, and by the use of a proprietary, CO$_2$-curing process. Both of these requirements can be readily deployed in any facility that produces traditional concretes.

For concretes made with Solidia Cement, curing is achieved by a reaction between the low-lime calcium silicate compounds CaSiO$_3$ and Ca$_3$Si$_2$O$_7$ and gaseous CO$_2$ within a moist environment. Unlike its OPC-based counterparts, Solidia Concrete does not react with water.

Solidia Concrete derives its strength from the formation of CaCO$_3$ (calcite) and SiO$_2$ (silica gel) as given in **Equations 3 and 4**. The overall curing reaction is succinctly written as:

$$\text{H}_2\text{O} \quad \text{CaSiO}_3\text{ (s)} + \text{CO}_2\text{ (g)} \rightarrow \text{CaCO}_3\text{ (s)} + \text{SiO}_2\text{ (s)}.$$  Eq. (3)

$$\text{H}_2\text{O} \quad \text{Ca}_3\text{Si}_2\text{O}_7\text{ (s)} + 3\text{CO}_2\text{ (g)} \rightarrow 3\text{CaCO}_3\text{ (s)} + 2\text{SiO}_2\text{ (s)}.$$  Eq. (4)

Note that no water is consumed in either reaction. The curing reaction is exothermic and releases -87 kJ/mole of heat. The heat generated during the reaction is dissipated by the evaporation of water. The curing process is controlled by counter diffusion of CO$_2$ and H$_2$O molecules.

The ability of Solidia Cement to avoid hydration and cure via a reaction with gaseous CO$_2$ opens the possibility for the permanent sequestration of CO$_2$ in the cured concrete structure. The curing process described in Equations 3 and 4 enables Solidia Concrete products to sequester between 250 and 300 kg of CO$_2$ per tonne of Solidia Cement used in the concrete formulation. Depending on the specific ratios of fine and coarse aggregate and Solidia Cement
used in the concrete mix, the final Solidia Concrete part may contain between about 3 and 7 wt.% of sequestered CO$_2$.

Solidia Concrete products react rapidly, typically achieving desired strengths within 24 hours. Curing times are dependent on the thickness of the concrete part, as the part thickness limits the rate at which gaseous CO$_2$ can permeate through the porous concrete structure. For example, thin concrete products such as roof tiles (thickness ~ 10 mm) can reach target strength within 6 hours. Thicker concrete products such as railroad ties (thickness ~ 250 mm) can reach target strength within 24 hours. Fast curing times offer the concrete manufacturer greater flexibility in equipment utilization, inventory management and production planning.

4. Concrete Microstructure

Understanding the microstructure of cured cement paste is a valuable tool that can be used to manage the properties of the cement paste and of the overall properties of the concrete.

The microstructure of cured Portland cement paste is shown in Figure 1. As described in section 3.4.1, the main hydration product of the curing reaction is a calcium silicate hydrate gel (C-S-H). The C-S-H gel occupies about 50% of the paste volume and is the primary binding phase in Portland cement-based concrete. As illustrated in Figure 1, the C-S-H gel forms a continuous layer that binds the original cement particles into a cohesive matrix. In a concrete structure, the continuous C-S-H gel extends to the coarse and fine aggregate, binding together those particles as well.

The dense C-S-H gel that forms immediately around the original cement grains is referred to as the “inner product.” A less dense, C-S-H gel “outer product” also forms, typically surrounding the inner product. Both the inner and outer products contain nanometer-sized gel pores.

Other hydration products, such as calcium hydroxide (CH), form as discrete crystals both inside and outside the C-S-H gel, but do not form strong connections to adjacent solid phases. While CH crystals are intrinsically strong, they do not contribute significantly to the overall strength of the cured concrete.

CH crystals form with a wide range of shapes and sizes, and occupy about 15% of the paste volume. CH precipitates predominantly in the larger, capillary pore space around cement particles and aggregates, preferentially at the paste-aggregate interface. These CH precipitates tend to form irregular, hexagonal-shaped platelets that are several microns across.

CH crystals may also precipitate as an intimate mixture within the C-S-H gel, particularly in the outer product where the C-S-H gel has low-density. These crystals tend to be much smaller, with many under 1 micron in diameter, because the surrounding solid impedes their growth. Other hydration products such as sulfoaluminate phases, ettringite, and monosulfate also precipitate within the outer products.
Figure 1. SEM-BSE image showing the microstructure of Portland cement paste area of a concrete sample.

The microstructure of paste in Solidia Cement-based concrete is shown in Figure 2. The microstructure development of Solidia Cement paste has some similarity to that of Portland cement paste, even though the reaction products are very different.

The main carbonation products of reacted Solidia Cement are calcite and silica gel. During the carbonation reaction, calcium is dissolved from the surface of each cement particle, reacts with CO$_2$ in the capillary pore space, and precipitates as calcite on the outer surface of the particle. Simultaneously, an insoluble layer of silica gel forms within the outer boundary of the cement particle, maintaining the original contour of the particle. The cores of some cement particles remain unreacted, while others are completely reacted, leaving only silica gel surrounded by calcite.

The calcite and silica gel reaction products occupy ~62% more solid volume than the Solidia Cement reactant. This volume expansion takes place entirely within the capillary pore space and does not cause any volume expansion of the concrete product. Unlike Portland cement, which continues to react in the presence of water, Solidia Cement curing stops once the concrete is removed from the CO$_2$-curing environment.
It is believed that the calcite acts as a binding phase within the Solidia Cement paste and is similar in function to the C-S-H gel in Portland cement paste. The silica gel has nanometer size pores, which are similar to the gel pores of C-S-H in the Portland cement paste.

**Figure 2.** SEM-BSE image showing the microstructure of Solidia Cement paste area of a concrete sample.

5. Solidia Concrete Product Applications

This section briefly describes some of the concrete products that have been produced using Solidia Cement. These products are categorized based on their workability, which is measured by the slump of the fresh concrete mixture. Concrete mixtures that are used for products such as paving stones, blocks, and railroad ties typically have “low-slump,” which is approximately between 0 and 25 mm (0 and 1 in). Products such as roof tiles and pervious concrete typically have “medium-slump,” which is approximately between 50 and 100 mm (2 and 4 in). Wet-cast stones have “high-slump,” which is approximately between 100 mm and 230 mm (4 and 9 in).
5.1 Paving Stones

Paving stones are solid concrete blocks that are formed by a process that combines both mechanical vibration and pressing. Paving stones are typically used to construct walkways or roadways by laying individual paving stones in interlocking patterns. When worn or damaged during their service life, such structures have the advantage that they can be quickly repaired by the removal and replacement of individual paving stones, thereby minimizing service interruption. Walkways and roadways constructed of interlocking paving stones can be designed to have permeable gaps that provide for water drainage directly to sub-layers.

Examples of a concrete mixer, a paver-press machine, a paver block, and a driveway made using pavers produced with Solidia Cement are shown in Figure 3 (A through D). The dimensions of a typical paver are: 240 mm (9.25 in) in length, 160 mm (6.25 in) in width, and 140 mm (5.25 in) in height or thickness.

**Figure 3:** A) Concrete mixer used for making a paving stone mix; B) Paver-press machine; C) Example of a cured paving stone made using Solidia cement; and D) Driveway made using Solidia Concrete paving stones.

For paving stones made with Solidia Cement, the average compressive strength was found to be approximately 67.6 MPa (9,804 psi). This value exceeds the ASTM C936 Standard Specification for Solid Concrete Interlocking Paving Units (reference 8), which requires an average compressive strength of 55.1 MPa (8,000 psi). The standard also specifies average water absorption to be no greater than 5%, and a resistance to at least 50 freeze-thaw cycles with average material-loss not exceeding 1%. Paving stones made using Solidia Cement and a wide variety of fine and coarse aggregate typically meet or exceed these requirements as well. Paving stones made with Solidia Cement offer several additional advantages when compared to their OPC-based counterparts, including:
• Fresh Solidia Cement-based concrete does not harden within the concrete mixing and forming equipment. The fresh concrete can be re-utilized without wastage after improper mixing, pressing or handling. Additionally, it enables easy cleaning of the mixing and forming equipment. These benefits are made possible because the setting and hardening of Solidia Cement-based concrete does not commence until the concrete mix is exposed to a CO$_2$ atmosphere.

• Solidia Cement-based concrete does not suffer from primary efflorescence. This phenomena involves the leaching of Ca(OH)$_2$ components from cured, OPC-based pavers, and results in the deposit of an undesirable, white-colored mineral residue on the surface of a concrete product. Cured Solidia Cement-based concretes contain CaCO$_3$ components. Unlike their Ca(OH)$_2$ counterparts in OPC-based concretes, these are not water soluble.

5.2 Concrete Blocks

Concrete blocks, also known as concrete masonry units (CMUs), are pre-cast concrete products with thin-walled, hollow structures. They are typically produced by a combination of vibration and mechanical pressing in a manner similar to the way paving stones are made. Blocks made using fly ash or bottom ash are called “cinder blocks.” Concrete blocks provide better structural properties compared to clay bricks and offer a smoother surface when assembled into a masonry wall. In addition, interlocking concrete masonry units do not require mortar to bind the units. Their hollow structure offer superior sound and thermal insulation compared to a solid structure.

Figure 4: A) Example of a block-press machine, B) Blocks undergoing curing inside a CO$_2$-curing chamber; and C) A cured block made using Solidia Cement-based concrete.
The dimensions of the concrete blocks made with Solidia Cement and illustrated in Figure 4 are 400 mm (15.625 in) in length, 200 mm (7.625 in) in width, and 200 mm (7.625 in) in height or thickness, which generally complies with the requirements of ASTM C90: Standard Specification for Loadbearing Concrete Masonry Units (reference 10). Blocks that comply with this standard are ensured to be acceptable with regard to strength, geometry, durability and fire resistance, and are generally acceptable for use in standard commercial construction projects. The average compressive strength of normal weight blocks made using Solidia Cement-based concrete was measured to be approximately 17.2 MPa (2,500 psi), which exceeds the requirement of 13.1 MPa (1,900 psi) as specified by ASTM C90.

5.3 Railroad Ties

Railroad ties, also known as crossties or railway sleepers, are elongated beams with uniform and trapezoidal cross-sections that are used to support railway tracks. Railroad ties are generally laid perpendicular to the rails to hold the rails upright, to transfer load to the track ballast and subgrade and to keep the rails spaced to the correct gauge. A railroad tie is normally reinforced with steel bars or cables, which are embedded into the structure to improve its mechanical properties and durability. Railroad ties generally employ a fastening system for secure attachment with the rails.

![Figure 5](image_url)

Figure 5. A) Example a railroad tie being cast in its mold, B) A CO₂-curing tarp designed to cure a railroad tie; and C) A cured railroad tie made using Solidia Cement-based concrete
The dimensions of the Solidia Concrete railroad tie illustrated in Figure 5 is 2,590 mm (102 in) in length, 280 mm (11 in) in width, and 230 mm (9 in) in height or thickness. This railroad tie, when fully cured, has a density ranging between 2,200 kg/m³ and 2,600 kg/m³ (137 lbs/ft³ and 162 lbs/ft³), which is on par with the density of conventional OPC-based concrete railroad ties. The average compressive strength of Solidia Concrete railroad ties is approximately 80 MPa (11,600 psi), which is higher than the specifications (68.9 MPa or 10,000 psi) for railroad ties as per Chapter 30, Section 4.2.2 of the Manual on RRTs by the American Railway Engineering and Maintenance-of-Way Association (reference 11). Solidia Concrete railroad ties also show an abrasion index of 23.85 min/mm (606 min/in), which exceeds the ASTM C779 Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces specification (reference 11) of 13.8 min/mm (350 min/in).

5.4 Roof tiles

Concrete roof tiles are composed of a mixture of cement, sand and water formed primarily by using an extrusion process. As the name implies, they are typically used for exterior roofing applications. Roof tiles are produced in various shapes and dimensions depending on the requirement and the region where they are used. They offer several benefits, including durability, strength, wind and heat resistance.

![Image of roof tiles](image_url)

**Figure 6.** CO₂-cured roof tiles produced using Solidia Cement and formed using a vibro-cast method.

The Solidia Concrete roof tiles shown in Figure 6 were made by a vibro-casting method. Their dimensions are 240 mm (9.5 in) in length, 152 mm (6 in) in width, and 14 mm (0.55 in) in thickness. The flexural strengths of the vibro-cast roof tiles as per ASTM C1167: Standard Specification for Clay Roof Tiles (reference 13) were over 6.9 MPa (1,000 psi) after only six hours of CO₂ curing, which are on par with commercial roof tile of similar dimensions made using Portland cement of similar curing time and thickness. The roof tiles made using Solidia Cement also exhibited no visible efflorescence after exposure to open-air for a period of one week, as per the Florida Building Code Test Protocol # 112-95 (reference 14).
5.5 Pervious Concrete

Pervious concrete is a unique class of concrete that has a relatively high proportion of large-sized pores. The pore sizes are typically between 2 mm and 8 mm (0.08 to 0.31 in), while the pore volume fraction may vary between 10% and 35%, as per Report on Pervious Concrete by ACI Committee 522, 2010 (reference 15). These characteristics are achieved by gap grading the aggregates, either by eliminating or minimizing the volume fraction of fine aggregates in the concrete mixture. This leads to the creation of a network of interconnected pores within the cured concrete. Pervious concrete is designed to allow rapid drainage of water.

![Figure 7: A) A pervious concrete cylinder made with Solidia Cement; B) A close-up view of a pervious concrete slab showing the pore-structure; and C) A pervious concrete walkway made using Solidia Cement-based concrete.](image)

There are currently no standards specifying the compressive and flexural strength requirements for pervious concretes. The average compressive strengths of pervious concretes made using Solidia Cement (as shown in Figure 7) ranged between 9.3 MPa (1,350 psi) and 17.2 MPa (2,500 psi). These measurements were slightly higher than the 28-day compressive strengths of OPC-based previous concretes, which typically range between 7 MPa (1,000 psi) and 15 MPa (2,175 psi).

Flow rate studies for water through Solidia Cement-based pervious concrete are still underway.
5.6 Wet-cast stones

Wet-cast stones are concrete paving stones made by casting a fresh concrete mixture into molds of varying dimensions. These products are typically used for outdoor landscaping applications. Since aesthetics for wet cast stones are important, multiple color-type gels or pigments are commonly added to the concrete mixture to achieve the desired color, and the fresh concrete should exhibit high slump to allow the cast product to accurately replicate the shape and surface texture of the mold.

Figure 8. A) A wet-cast stone mixture being poured into different molds; B) A CO$_2$-cured and packaged wet-cast stone made using Solidia Cement-based concrete; and C) A wet-cast stone walkway.

The properties of the wet-cast stones are similar to those of mechanically pressed paving stones.
6. Conclusions

1) Solidia Cement is composed of “green”, low-lime calcium silicate phases. By contrast, OPC is composed predominantly of high-lime calcium silicate phases.

2) Solidia Concrete, made with Solidia Cement, uses the same constituent raw materials as OPC-based concrete, namely: fine and coarse aggregates, supplementary cementitious materials, and chemical admixtures.

3) Most common supplementary cementitious materials can be used in Solidia Concrete. However, the primary functions of fly-ash, GGBFS and fumed silica in Solidia Concrete is used to improve the packing density of the concrete by reducing water demand, thereby increasing the concrete strength. In OPC-based concretes, these supplementary cementitious materials create secondary calcium-silicate-hydrate gels to increase concrete strength.

4) As the Solidia Cement chemistry differs from that of OPC, chemical admixture dosages are different. Therefore, initial compatibility tests are essential before their use. In general, Solidia Concrete is compatible with chemical admixtures that reduce water demand and improve the viscosity or rheology of the fresh concrete.

5) Solidia Concrete can be mixed and formed into desired shapes in the same manner and using the same equipment as OPC-based concretes.

6) Solidia Concrete cures by the reaction of Solidia Cement with gaseous CO₂ in the presence of water to form calcite and a silica gel. No water is consumed in the curing reaction. By contrast, OPC-based concrete cures by a reaction of the cement with water to form a calcium-silicate-hydrate gel and calcium hydroxide.

7) The unique chemistry of cured concrete based on Solidia Cement allows for extremely short curing times. Solidia Concrete products typically reach target strength within 24 hours, while OPC-based concrete products may take up to 28 days to reach target strength.

8) The unique chemistry of Solidia Concrete also allows the production of concrete parts that are immune to primary efflorescence.

9) Solidia Concrete can be designed to address virtually any precast concrete application.

10) Solidia Concrete can achieve a reduction in carbon footprint up to 70% as compared to conventional OPC-based concretes. This is achieved a) by reducing the CO₂ emitted during cement production from 816 kg per tonne of OPC clinker to 570 kg per tonne of Solidia Cement clinker, and; b) by consuming up to 300 kg of CO₂ per tonne of Solidia Cement during the CO₂-curing of Solidia Concrete.

For more information, see the companion paper, Solidia Cement™, published December 2013.
7. References

5. ASTM C33/C33M-13 Standard Specification for Concrete Aggregates.
9. ASTM C936 Standard Specification for Solid Concrete Interlocking Paving Units.
10. ASTM C90 Standard Specification for Loadbearing Concrete Masonry Units.
11. Chapter 30, Section 4.2.2 of the Manual on RRTs by the American Railway Engineering and Maintenance-of-Way Association.

About Solidia Technologies®
Solidia Technologies® is a cement and concrete technology company with patented processes that make it easy and profitable to use CO₂ to create superior and sustainable building, construction and industrial products. A winner of the 2013 R&D Top 100 Award and shortlisted for the 2013 Cleantech 100, Solidia's processes cure concrete with CO₂ instead of water and use a sustainable cement as binder, reducing the carbon footprint of concrete products up to 70 percent, lowering production costs, and enhancing performance. Based in Piscataway, N.J. (USA), Solidia's investors include Kleiner Perkins Caufield & Byers, Bright Capital, BASF, and BP. Follow Solidia Technologies at www.solidiatech.com and on LinkedIn and Twitter: @SolidiaCO2.