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# Corrosion of Steel Reinforcement in Pervious Concrete with Conventional Concrete Cover

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*Corrosion performance of reinforced pervious concrete was evaluated through field and laboratory evaluations. Two reinforced pervious cemetery walls in Chicago, IL, were visually evaluated, and samples were investigated through petrographic examination. Corrosion performance of two-layered concrete samples, with an outer layer of conventional concrete and an inner layer of pervious concrete, was evaluated in the laboratory. Results indicated that pervious concrete around the reinforcement can significantly delay the cracking and spalling of samples compared to conventional concrete. Chloride profiles of samples and instantaneous corrosion rate measurements showed that corrosion of reinforcement embedded in two-layered samples was similar to conventional concrete although two-layered samples provided a longer time to cracking. Laboratory results are in agreement with long service life performance observed in the field and with prior pervious concrete corrosion studies.*

**Keywords:** chloride content; concrete cracking; corrosion; durability; pervious concrete.

## INTRODUCTION

Steel reinforcement and concrete work together in reinforced concrete to resist tensile and compressive loads. If properly designed and constructed, steel reinforcement in conventional concrete resists corrosion due to the formation of a thin protective oxide film (passive film) in the highly alkaline pore solution environment adjacent to the steel.<sup>1</sup> Pervious concrete, a material used to construct permeable pavements, has much higher porosity and permeability compared to conventional concrete due to a larger and interconnected pore structure.<sup>2</sup> High permeability of pervious concrete is achieved with gap-graded aggregates with little or no fine aggregates. Porosity of pervious concretes typically ranges from 15 to 30% voids and primarily depends on aggregate gradation and the adopted compaction method.<sup>3</sup> Due to its high permeability and filtering benefits, pervious concrete is typically used in applications such as parking lots, driveways, pavements, and walkways to reduce or eliminate surface stormwater runoff.<sup>2</sup> Pervious concrete is not typically used in reinforced concrete applications because there is a lack of knowledge of the corrosion behavior of reinforcing steel in pervious concrete with very limited number of studies in the literature.<sup>4,5</sup>

Two important mechanisms can disturb the protective passive layer and initiate corrosion of steel reinforcement in conventional concrete. The first mechanism is atmospheric carbonation. Carbon dioxide in the atmosphere penetrates the concrete and reacts to convert free calcium hydroxide to calcium carbonate, decreasing the pH. Once carbonation has advanced beyond the cover depth to the steel reinforcement, its passive layer becomes unstable, leaving the steel

vulnerable to the onset of corrosion.<sup>6,7</sup> The second mechanism is chloride-induced corrosion. Chlorides, typically originating from the external environment, can penetrate the concrete and reach the concrete-steel interface. Once the concentration of chlorides at the steel interface reaches a critical threshold, and sufficient moisture is present, corrosion is initiated.<sup>6</sup> Chlorides in the external environments may come from different sources such as deicing chemicals, seawater, and others. Once corrosion initiates, steel reinforcement continues to corrode as long as sufficient moisture and oxygen are available in the surrounding concrete.<sup>8</sup> Over time, depending on the pore solution environment, different corrosion products can build up and increase in volume up to six times greater than that of the initial steel.<sup>9</sup> Volume expansion due to conversion of steel to iron oxide corrosion products in hardened concrete causes development of tensile stresses, and ultimately leads to cracking and spalling of the concrete cover. Therefore, current practice recommends use of dense, low-permeability concrete mixtures in corrosive environments to delay carbonation and ingress of chloride ions.

Carsana and Tittarelli<sup>4</sup> evaluated corrosion of reinforcement in pervious concrete mixtures using an accelerated carbonation test. Tests indicated that pervious concrete samples were rapidly carbonated and did not provide the necessary alkaline environment for the passive layer. However, evaluation of corrosion rates showed that corrosion of embedded reinforcement was negligible as long as the samples were dry. The study also indicated that pervious samples dried quickly after temporary wetting, decreasing the corrosion rates back to negligible levels. There are no studies in the literature that evaluated corrosion of reinforcement in pervious concrete under chloride exposure. These findings in the literature are in line with our observations in the field with two cemetery walls built in Chicago around the 1920s with pervious concrete. Although there are no records why these walls were designed with pervious concrete, it is stated in the literature that there was an extensive use of no-fines concrete for load-bearing walls, retaining walls, and ground-drainage slab systems in the post-World War II era.<sup>10</sup> The conditions and corrosion performance of these walls were examined over a period of 15 years between 2000 and 2015. Over time, steel reinforcement corroded and caused spalling of the walls predominantly on lower

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portions and spalling was more prevalent on the traffic side of the wall exposed to deicers. Some spalls were repaired with mortar, which inhibited drainage of rainwater entering the wall followed relatively quickly by even more spalling both adjacent to or within repairs. More information on the conditions of the walls is provided later. The large and connected pore structure of pervious concrete may be advantageous by reducing overall saturation through rapid drying once corrosion initiates. In conventional concrete, transport of moisture to the surface and evaporation is a very slow process and therefore conventional concrete rarely dries out completely except for a thin layer at the surface.<sup>11</sup>

Another important observation of the cemetery walls was that although extensive corrosion of the steel took place over the years, corrosion products did not cause an immediate spalling of the wall as it would have in conventional concrete. It is believed that the connected voids in the pervious concrete provided space for the expansion of corrosion products, dissipating the disruptive pressure. A recent study evaluated the penetration of corrosion products from steel reinforcement into the surrounding conventional concrete.<sup>12</sup> The study found that corrosion products accumulated at the steel/concrete interface and that corrosion products could also penetrate the cement paste depositing between hydration products. As corrosion increased, the pores became blocked and subsequent corrosion products were forced to accumulate at the steel/concrete interface inducing expansive pressures. A 100  $\mu\text{m}$  thick corrosion product development on 20% of reinforcing bar perimeter was enough to induce the first visible crack. Alonso et al.<sup>13</sup> also concluded that porosity plays a key role in concrete crack propagation and a delay in crack initiation can be observed as porosity of the concrete adjacent to the steel increases. The large and connected pore structure of pervious concrete should take longer to become blocked and allow further penetration of corrosion products into the surrounding matrix delaying crack initiation.

Based on described field observations and limited prior research in the literature, this study evaluated the corrosion of steel reinforcement embedded in a two-layer concrete system. An outer layer of conventional concrete was placed around a pervious concrete layer, which contained steel reinforcement. The low permeability conventional concrete outer layer was expected to prevent quick carbonation and quick ingress of water and dissolved chloride ions into the porous pervious concrete layer. Samples were periodically exposed to a chloride solution and their corrosion was electrochemically monitored. In addition to corrosion rates, time to cracking of these samples due to corrosion product accumulation was also evaluated and compared to conventional reinforced concrete samples. The two-layer concrete system is expected to provide a comparable time for corrosion initiation as conventional concrete but to significantly delay the cracking of concrete due to corrosion. Corrosion-induced damage in reinforced concrete structures can range from loss of steel cross section, loss in stiffness, loss of steel-concrete interface bond, cracking of concrete cover, to local or global failure of the structures. Service life prediction models define an acceptable level of one of these damage effects to

denote the end of service life (limit state). Although a variety of limit states are available, most of the available models have adopted corrosion induced cracking of the concrete cover as a limit state.<sup>14</sup> Cracking and spalling of concrete due to corrosion may significantly reduce the load-bearing capacity of reinforced concrete structures and furthermore make the steel more accessible to the aggressive agents such as chlorides leading towards further corrosion at an accelerated rate.<sup>14</sup> In addition to the laboratory evaluation of the two-layered concrete system, field observations from reinforced pervious concrete cemetery walls in Chicago and evaluation of cores obtained from these cemetery walls are also included.

## RESEARCH SIGNIFICANCE

Delaying corrosion-induced deterioration, such as cracking and spalling, of reinforced concrete structures to improve their service life is of great importance to owners, designers, and society in general. This study evaluated if highly connected porosity of pervious concrete mixtures can be effective in delaying the cracking and spalling of structures. Researchers evaluated a novel combination of conventional and pervious concrete systems to extend the service life of corroding reinforced concrete structures.

More information on the corrosion behavior of reinforcement in pervious concrete can help extend the use of pervious concrete for a wide range of applications that can take advantage of its acoustic and thermal insulation properties and other characteristics.<sup>14,15</sup> There is limited data in the literature that evaluated steel corrosion rates in pervious concrete mixtures due to carbonation.<sup>4</sup> This study provides data on corrosion rates in pervious concrete under chloride exposure within this novel combined concrete system.

## Field observations

The walls of Rosehill and St. Boniface cemeteries in Chicago, IL, were constructed around 1928 using reinforced pervious concrete. The walls exhibited fairly uniform mixture appearance, consistent placement, and consolidation. Little freezing-and-thawing damage was observed in the walls and in the early 1990s, cemetery management indicated some pilaster caps were in danger of falling. Spalling of concrete associated with corrosion of embedded reinforcing steel was observed with increasing frequency predominantly on lower portions of the walls in the most recent 5 years of the observations between 2000 and 2015. In numerous areas, the exterior side of the walls was adjacent to sidewalk and faced traffic where deicers were routinely applied. Damage occurred on both sides of the wall but cracking and spalling was more prevalent on the outer or traffic side of the wall. Use of a non-porous repair mortar to repair cracks and impending spalls in the walls caused relatively quickly even more frequent spalling within and adjacent to the repairs. Evaluation of cores with phenolphthalein (pH indicator) indicated that concrete was mostly carbonated with the exception of small mortar patches in the inner portions of large mortar fractions. Similar to the findings in the literature, it is believed that rainwater entering the pervious wall could either drain or evaporate, slowing down reinforcement



Fig. 1—(left) Cemetery maintenance of walls consisted of mortar application over cracks or spalls, photo taken in September 2013; and (right) photo of pervious wall at nearby St. Boniface Cemetery in good condition.



Fig. 2—Recent spall revealing corrosion products deposited in voids adjacent to steel.

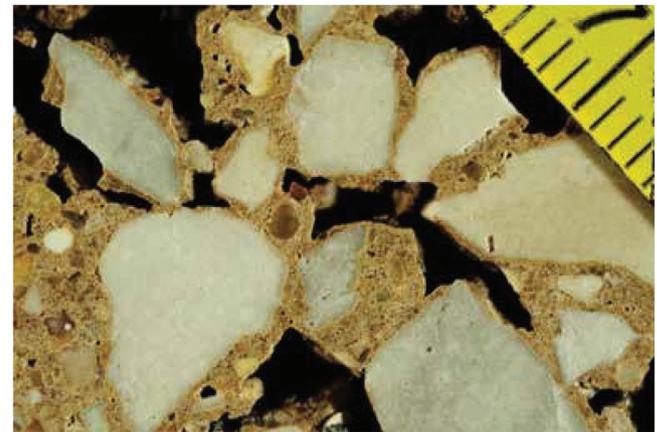


Fig. 3—Saw-cut and polished sections of pervious concrete sample from cemetery wall (scale in millimeters) (photo courtesy of Ronald D. Sturm).

corrosion although the walls were carbonated.<sup>4</sup> Restriction of drainage at the foot of the walls where repairs with non-porous mortar sealed the surface voids, elevated levels of moisture could sustain corrosion reactions. Application of deicers on the traffic side could be why cracking and spalling was more prevalent on the outer side of the wall.

Figure 1 (left) shows the street side of Rosehill cemetery walls with exposure to deicer spray from adjacent traffic. The photograph shows lighter-colored areas where mortar was applied to repair deterioration of the pervious concrete. Figure 1 (right) shows the condition of the walls facing the interior of St. Boniface cemetery, which are in much better condition. The wall foundation of the pervious concrete walls was also pervious concrete covered with a thin uniform coat of mortar. Figure 2 shows the steel condition at a lower wall spall location. Spalls exhibited extensive corrosion of the steel and loss of section of the bar. It is believed that the voids of this pervious concrete provided space for accumulation of corrosion products over the years without causing large enough tensile stresses to crack the concrete. The amount of observed corrosion products would have caused conventional concrete to crack sooner. Spalled samples detached from the cemetery walls were collected

for petrographic examination. A typical cross section of the saw-cut and polished samples is shown in Fig. 3. Sections exhibited interconnected network of coarse voids and spaces (dark areas) between coarse aggregate and hardened cement paste. The amount of cement paste is sufficient to bind the coarse aggregate but still allow entrapment of large and interconnected voids spaces, estimated at 20 to 30% by volume. The cement paste exhibited a small amount of sand aggregate particles (estimated up to 5% by volume). The cement grains are coarser than typically seen in modern cement, but typical of coarsely ground portland cement commonly available in the early 1900s. The microscopical examinations found the paste adhered to the aggregate particles was low in porosity, likely due to a relatively low water-cement ratio ( $w/c$ ) of the cement paste. The longevity and durability of the concrete largely relates to the good quality of the cement paste, and use of good quality, durable aggregate adequately bonded by the paste.

#### LABORATORY STUDY—EXPERIMENTAL METHODS AND SETUP

Following the field observations, a two-layer reinforced concrete system comprised of an outer layer of conventional

**Table 1—Mixture proportions, fresh, hardened properties of concretes**

Mixture designation	C	P1	P2	P3
Coarse aggregate, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	980 (1655)	0 (0)	1332 (2250)	1489 (2516)
Fine aggregate, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	719 (1215)	1752 (2959)	114 (192)	0 (0)
Cement, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	334 (564)	210 (354)	390 (658)	316 (533)
Water, kg/m <sup>3</sup> (lb/yd <sup>3</sup> )	167 (282)	63 (106)	125 (211)	95 (160)
HRWR* (oz/cwt)	0.00% (0)	0.31% (5)	0.31% (5)	0.31% (5)
Hydration stabilizer* (oz/cwt)	0.25% (4)	0.25% (4)	0.25% (4)	0.25% (4)
Air-entraining agent* (oz/cwt)	0.03% (0.5)	0.06% (1)	0.06% (1)	0.06% (1)
Aggregate/cement ratio	—	8.35	2.19	4.71
Unit weight, kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	—	1954(122)	1906(119)	1842(115)
Void content, %	—	17.3	21.5	29.3
Compressive strength, MPa (psi) at 28 days	39 (5740)	4.1 (594)	15.3 (2212)	11 (1598)

\*Percent by weight of cementitious material.

concrete and an inner layer of pervious concrete around the reinforcement was tested. The inner pervious concrete layer with interconnected void space was expected to provide space for corrosion products to build up without generating significant tensile stresses and the outer layer of conventional concrete was expected to control the rate of ingress of chlorides, water, and carbonation. The laboratory study was performed in two phases. The first phase evaluated the delay of cracking and spalling due to pervious concrete around reinforcement using an accelerated corrosion test: Florida Test Method 5-522.<sup>16</sup> After observing that the pervious concrete was effective in delaying the cracking of samples, the second phase was performed where two-layer concrete samples were tested using half-cell potential and linear polarization to evaluate corrosion rate over time when exposed to chlorides.

Table 1 shows the concrete mixture proportions used to cast the two-layer samples in the laboratory study. Type I/II portland cement and potable water was used for all mixtures. Pervious mixture designs, P1, P2, and P3 are low, medium, and high permeability mixtures, respectively. P1 mixture had no coarse aggregate and P2 mixture contained coarse aggregate with nominal maximum size of 6.4 mm (1/4 in.). The coarse aggregate used in high permeability pervious mixture (P3) had a nominal maximum size of 25 mm (1 in.) and no fine aggregate. The pervious mixtures were designed with different aggregate/cement ratios to reach target void ratio and avoid clogging. The conventional concrete mixture design (C) had a *w/c* of 0.5, crushed limestone and silica sand meeting the distribution requirements of ASTM C33.<sup>17</sup> A commercially available polycarboxylate high-range water-reducing agent, hydration stabilizing admixture, and vinsol resin air entraining admixture was also used in the pervious concrete mixtures. The cover part of two layered samples were cast using the conventional mixture and the reinforcement was embedded in one of the pervious mixtures. Control samples were cast using only the conventional mixture.

### Phase 1: Florida Test Method 5-522

Cylindrical samples, 150 x 150 mm (6 x 6 in.), were cast with a vertical 150 mm (6 in.) 13MM (No. 4) (ASTM A615<sup>18</sup>) steel reinforcement bar at the center and 25 mm (1 in.) above the bottom of the cylinder. Steel bars were etched in dilute sulfuric acid, power brushed, and cleaned in ethyl alcohol using ultrasonic cleaning equipment prior to placing in the fresh concrete. Five control samples were cast using only the conventional concrete mixture C shown in Table 1. Two-layered test samples had a 75 mm (3 in.) diameter pervious concrete layer around the steel reinforcement (63 mm [2.5 in.] thick due to reinforcement) and a 75 mm (3 in.) thick outer layer of conventional concrete. Two-layered samples were cast over a duration of 2 days. Initially a 75 mm (3 in.) mold was used around the suspended reinforcement bar to cast the pervious concrete layer. After 1 day, the 75 mm (3 in.) mold was stripped and a 150 mm (6 in.) mold was used to cast the outer layer of conventional concrete. All samples were cured at laboratory conditions for 28 days under plastic sheeting and wet burlap and then placed in plastic containers filled with a 5% by weight sodium chloride solution as shown in Fig. 2. A DC power supply was used to apply a 6 V voltage between the embedded reinforcing bar and a bare reinforcing bar suspended in solution to accelerate the penetration of negatively charged chloride ions into the concrete. Testing was continued for 60 days and current flowing in the circuit of each sample was measured using a 0.1 Ohm shunt resistor.

### Phase 2: Half-cell potential and linear polarization

Cylindrical samples, 150 x 100 mm (6 x 4 in.), were cast with a 200 mm (8 in.) long No. 4 (13 mm) (ASTM A615<sup>18</sup>) steel reinforcement bar placed horizontally at mid-height as shown in Fig. 5. Steel bars were etched in dilute sulfuric acid, power brushed, and cleaned in ethyl alcohol using ultrasonic cleaning equipment. Steel bars were coated with a two-part epoxy at both ends to leave a 4 in. (100 mm) long bare section in the middle. The bottom and top 50 mm (2 in.) of each mold was filled with rodded and tamped conventional concrete mixture C (Table 1) and the middle 50 mm (2 in.) of the samples were filled with pervious concrete.

Three pervious mixtures with different permeability values were used (Table 1). For each sample, fresh pervious concrete to fill the 50 mm (2 in.) thick space with 20% voids was weighed prior to placing each sample. The fresh pervious concrete was placed on fresh conventional concrete layer and was pressed using a 50 mm (2 in.) thick, 150 mm (6 in.) diameter wooden jig to make sure there was space for a 50 mm (2 in.) conventional concrete top layer in each sample. Sections cut from a 100 mm (4 in.) diameter plastic pipe were placed on top of the samples in the fresh state to pond a chloride solution during testing. Control samples were cast using only the conventional concrete mixture. After 1 day, all samples were stripped and cured for 28 days at laboratory conditions under plastic sheeting and wet burlap. Samples were epoxy coated on the sides and on the top except inside the plastic pipe to allow penetration of chlorides from the chloride solution. Samples were ponded with chloride solution and dried periodically at 2-week intervals. A 5% by weight sodium chloride solution was used and all electrochemical measurements were performed while the samples were ponded with the solution. A total of 19 samples were tested; five control samples (only conventional concrete), four samples with mixture P1, five samples with mixture P2, and five samples with mixture P3 around the reinforcement.

Half-cell potential is the potential difference between the embedded steel reinforcement (working electrode) and a standard reference electrode. Half-cell potential of the embedded steel bars was measured using a potentiostat and a saturated calomel reference electrode placed on the top surface of the samples (Fig. 5). According to ASTM C876,<sup>19</sup> if the potential of the reinforcement measured using a saturated copper/copper sulfate (CSE) electrode is below  $-350$  mV, the probability of corrosion is more than 90%. The half-cell measurements provide an estimation of the likelihood of corrosion but does not provide information on the actual rate of corrosion. Factors such as moisture, access of oxygen, high resistivity layers of concrete, age of concrete, and position of the reference electrode may affect the half-cell measurements.<sup>20-22</sup>

Instantaneous corrosion current density,  $i_{corr}$ , of embedded steel reinforcement was measured using linear polarization method. Current density,  $i_{corr}$ , is the corrosion current divided by the area of exposed steel reinforcement. In linear polarization method, the half-cell potential of the embedded steel reinforcement is changed incrementally ( $\Delta E$ ) using a potentiostat and a counter electrode and the corresponding change in current density ( $\Delta i$ ) is measured. A saturated calomel reference electrode and a graphite counter electrode were used as shown in Fig. 4. The slope of the potential-current density curve when the current density is equal to zero is defined as the polarization resistance,  $R_p$  of the working electrode as shown in Eq. (1).

$$R_p = \left( \frac{\Delta E}{\Delta i} \right)_{\Delta E \rightarrow 0} \quad (1)$$

The  $i_{corr}$  can be calculated by dividing the Stern-Geary constant,  $B$ , by the polarization resistance,  $R_p$  as shown in

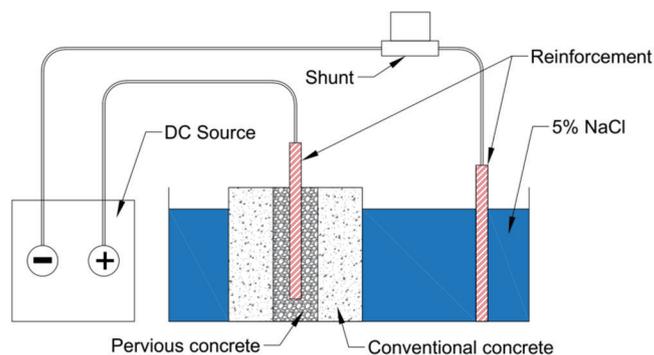


Fig. 4—FM 5-522 setup with two-layered test sample.

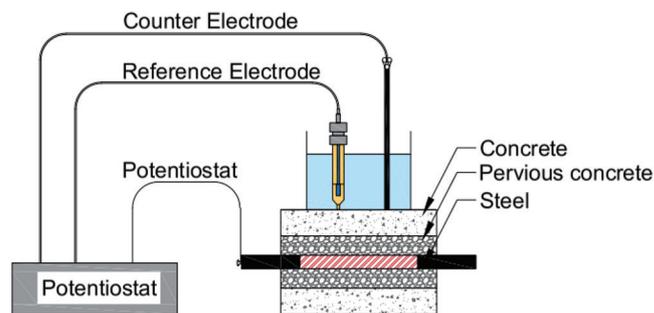


Fig. 5—Linear polarization test setup.

Eq. (2).  $R_p$  is measured in Ohm-cm<sup>2</sup> and  $B$  in Volts. The value of Stern-Geary constant,  $B$ , is recommended to be taken as 26 mV for bare reinforcement steel in active state and as 52 mV in passive state for current density calculations.<sup>23</sup> The  $i_{corr}$  is a direct indicator of how fast the steel reinforcement is corroding and when in passive state  $i_{corr}$  is relatively low in the order of  $10^{-9}$  to  $10^{-7}$  Amp/cm<sup>2</sup> and in the active state in the order of  $10^{-6}$  to  $10^{-5}$  Amp/cm.<sup>2,24</sup>

$$i_{corr} = \frac{B}{R_p} \quad (2)$$

Half-cell potential and corrosion current measurements were continued more than 9 months for 283 days. It should be noted that the objective of this phase of testing was to evaluate the corrosion rate of the two-layered samples and to compare it to the control samples cast with only conventional concrete. Although none of the samples showed a significant increase in corrosion current indicating initiation of active corrosion, 9 months was long enough to compare the corrosion current of control samples and two-layered test samples. At the end of testing period, the samples were washed to remove any chlorides from the surface and were stored at laboratory conditions before being cut and analyzed for chloride penetration and acid soluble chloride content.

### Chloride profile and diffusion of chlorides

Two control samples and two from each two-layered test samples with pervious mixtures P1, P2, and P3 were randomly selected for chloride profiling and diffusion coefficient determination. Powder samples were collected from four depth layers after discarding the initial 3 mm from the surface. Based on the casting process, the first two layers—from 3 to 12 mm and 12 to 25 mm—were

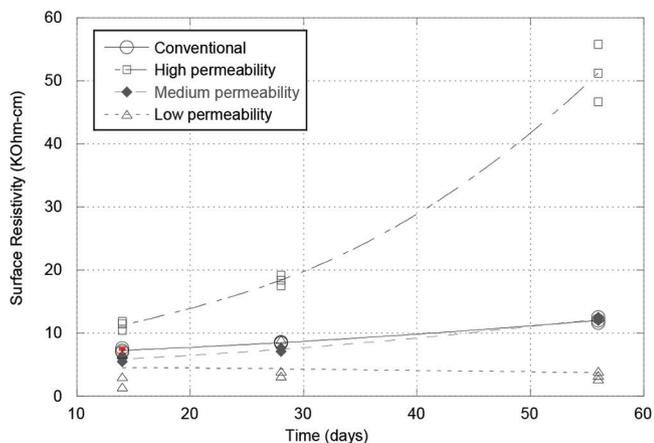


Fig. 6—Surface resistivity of conventional and pervious mixtures.

from the conventional concrete, and the last two layers—from 25 to 34.5 mm and 34.5 to 44 mm—were from the pervious concrete. The samples from first two layers were collected using a profile grinder and the samples from the remaining two layers were collected using a drill press due to depth limitation of the profile grinder. The third and fourth layers were drilled using 25 mm (1 in.) and 12 mm (0.5 in.) drill bits, respectively. A smaller drill bit was used for the deeper layer to prevent contamination from the sides of the upper layer during drilling. A powder sample of 10 g was tested from each layer for total acid soluble chloride content following the ASTM C1152 procedure for sample preparation.<sup>25</sup> An automatic potentiometric titrator was used to determine the chloride contents. The apparent diffusion coefficient of profiled samples was calculated following the ASTM C1556 procedure.<sup>26</sup>

The remaining test samples were dry cut (to avoid chloride washing) in half perpendicular to the embedded steel reinforcement using a masonry saw. The cut surfaces were immediately sprayed with a 0.5 N silver nitrate solution and left to dry to visually determine the chloride diffusion profile of the samples.

### Fresh and hardened properties of mixtures

Additional 4 x 8 in. (100 x 200 mm) cylindrical pervious and conventional concrete samples were cast in phase 2 to test their compressive strength, unit weight, void content, and surface resistivity. Surface resistivity of samples were tested at 14, 28, and 56 days following AASHTO TP 95-11.<sup>27</sup> The unit weight and void content of pervious mixtures were determined at 56 days following ASTM C1754.<sup>28</sup>

## RESULTS AND DISCUSSION

### Fresh and hardened properties

Table 1 shows the unit weight, void content, and compressive strength at 28 days of the conventional and pervious mixtures. Unit weight of the pervious mixtures decreased as expected with increasing void content values. The compressive strength of pervious mixtures with high void contents was lower compared to the conventional concrete. Although P2 and P3 mixtures had higher void contents compared to P1, their compressive strength was higher due to their higher

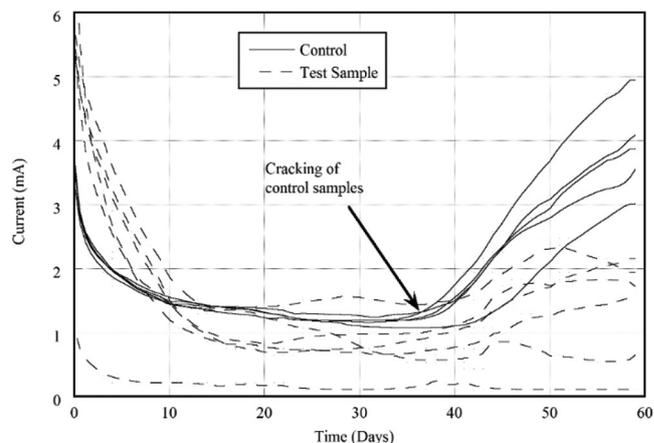


Fig. 7—FM 5-522 test results showing current versus time.

cement content. This paper evaluates the corrosion performance of the two-layered system; however, issues such as bond strength between the pervious concrete and reinforcement and the lower compressive strength of pervious mixtures compared to conventional concrete should be further evaluated for the structural feasibility of this system.

Figure 6 shows the surface resistivity values measured from 100 x 200 mm (4 x 8 in.) samples using a Wenner probe following AASHTO TP 95-11.<sup>27</sup> The surface resistivity of the high permeability pervious mixture (P3) was higher than other mixtures at all ages but the difference was much more significant after 56 days of drying at the laboratory conditions, prior to resaturation before testing. High connected porosity structure and low paste content of this mixture resulted in the high resistivity values. The medium permeability pervious mixture (P2) and conventional concrete mixtures exhibited similar surface resistivity values. The surface resistivity of samples cast from the low permeability pervious mixture (P1) was lower compared to all other mixtures at all ages and contrary to other samples did not show an increase after 56 days of drying at the laboratory conditions.

### Phase 1: Florida Test Method FM 5-522

Figure 7 shows the current values measured over time for the control (conventional concrete) and two-layered samples containing medium permeability (P2) pervious mixtures. Initial current readings stabilized in approximately 10 days. The stabilized current value is an indicator of the average resistance of concrete samples. The two-layered samples showed similar or lower stabilized current values compared to the conventional concrete samples. As corrosion products build up and start to crack the concrete cover, the resistance in the circuit decreases and the measured current starts to increase. Results showed that control samples exhibited a rapid increase of current after approximately 37 days, which indicates cracking of concrete cover. Although some of the two-layered samples showed a small current increase after 40 days, at the end of 60 days of testing their current values were lower than the controls samples indicating higher concrete resistivity.

Visual inspection of samples at the end of testing fit to the observed current measurements. All the conventional

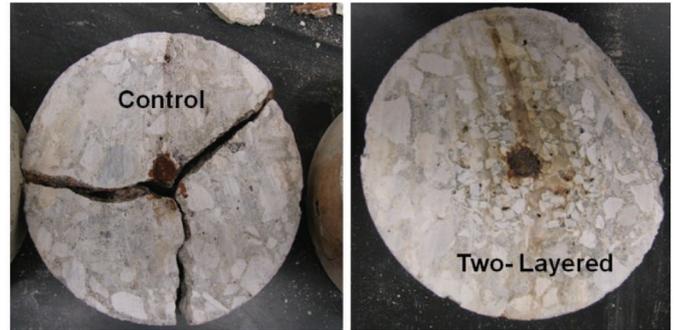
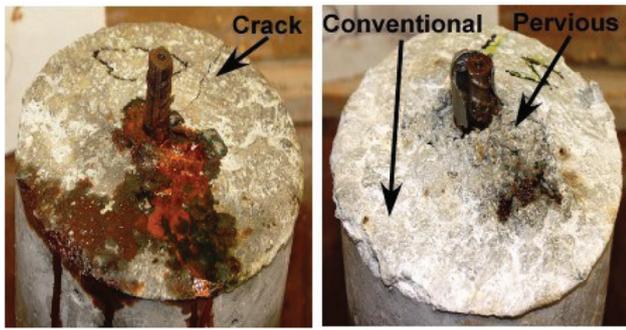


Fig. 8—(left) Control and two-layered samples with P2 around reinforcement; and (right) cross section of samples.

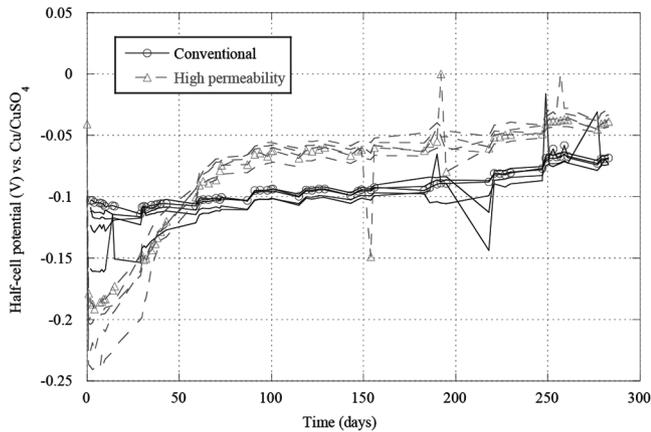


Fig. 9—Half-cell potential of samples with conventional and high-permeability pervious (P3) concrete.

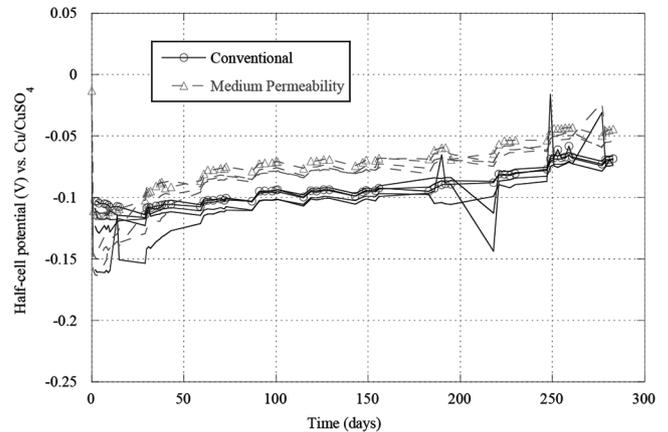


Fig. 10—Half-cell potential of samples with conventional and medium-permeability pervious (P2) concrete.

concrete control samples were cracked and there were no visible cracks on the two-layered samples. Figure 8 (left) shows a cracked control sample and an intact two-layered sample at the end of testing and Fig. 8 (right) shows the cross section at mid-height of the samples. Corrosion products away from the steel reinforcement in the pervious layer of the two-layered samples visible in Fig. 8 (left) supports the idea that the delayed cracking was due to corrosion products being able to move in the connected porosity of the pervious concrete layer.

### Phase 2: Half-cell potential and linear polarization

Figures 9 through 11 show the measured half-cell potentials of the two-layered samples containing high, medium, and low permeability pervious mixtures and the control samples cast with conventional concrete over a duration of 283 days. The half-cell potentials of all the samples start at a negative value above  $-250$  mV and move slowly more positive indicating that none of the samples were showing high probability of active corrosion. Control samples and all two-layered samples followed a similar trend within their groups and do not show much variation. Compared to the control samples, all the two-layered samples start at a more negative half-cell potential but then cross over the half-cell potential of control samples and remain at more positive potentials. The largest difference is observed at the beginning of the testing between the conventional samples and the two-layered samples with high permeability mixture. It took approximately 50 days for the high permeability mixture containing samples to reach the same potential as the control

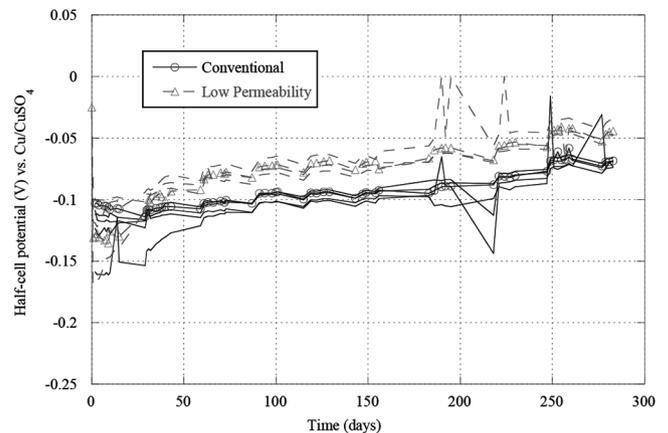


Fig. 11—Half-cell potential of samples with conventional and low-permeability pervious (P1) concrete.

samples. Two-layered samples with medium and low permeability mixtures started at closer half-cell potentials, which is a similar observation as the surface resistivity measurements. These mixtures had similar resistivity values with the conventional concrete mixture.

Figures 12 through 14 show the corrosion current density of conventional samples and the samples containing high, medium, and low permeability pervious mixtures, respectively. All current densities are lower than  $10^{-6}$  indicating passive state, which fits to the half-cell potential measurements. Reflecting the increase and stabilization of half-cell potential measurements, current densities decrease initially and stabilize. All the two-layered samples containing

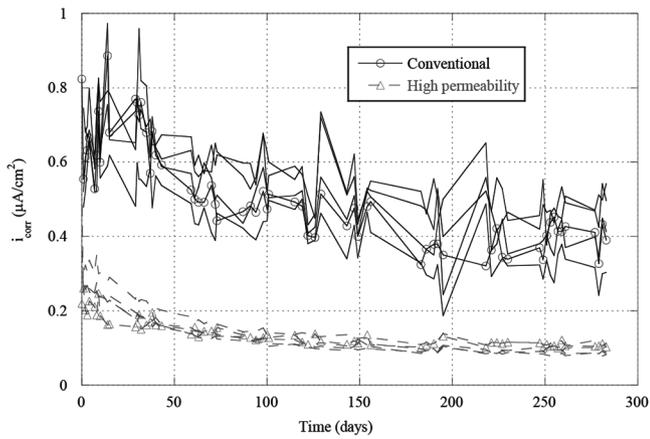


Fig. 12—Corrosion current of samples with conventional and high-permeability pervious (P3) concrete.

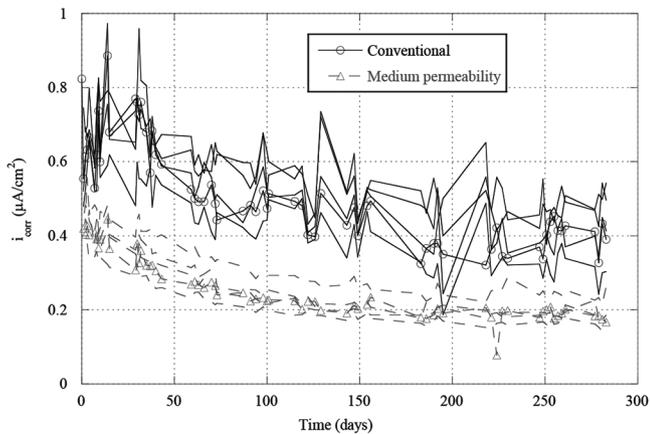


Fig. 13—Corrosion current of samples with conventional and medium-permeability pervious (P2) concrete.

pervious concrete around the reinforcement exhibit consistently lower corrosion current densities compared to the conventional concrete control samples throughout the duration of testing. As mentioned earlier,  $i_{corr}$  is an indicator of how fast the reinforcement is corroding and these results clearly show that corrosion rate in two-layered samples were consistently lower compared to the rates observed in conventional concrete control samples. Results of this test combined with the Phase 1 test results indicate that the evaluated two-layered system can provide better protection against corrosion not only by delaying the concrete cracking but also by decreasing the corrosion rate of the embedded steel. These very low observed corrosion current densities are similar to negligibly low corrosion current densities reported in completely carbonated pervious concrete samples in the literature as long as they were kept dry.<sup>4</sup> This indicates that the conventional concrete cover designed to keep the inner pervious concrete layer dry when exposed to a chloride solution was performing as intended. None of the samples exhibited initiation of corrosion during the 283 days of testing by either showing a half-cell potential more negative than  $-350$  mV or a spike in the corrosion current density. Therefore, this study did not provide any data about the corrosion rate of reinforcement after corrosion initiation, which happens once the chloride content at the steel surface reaches the critical chloride threshold. Determining

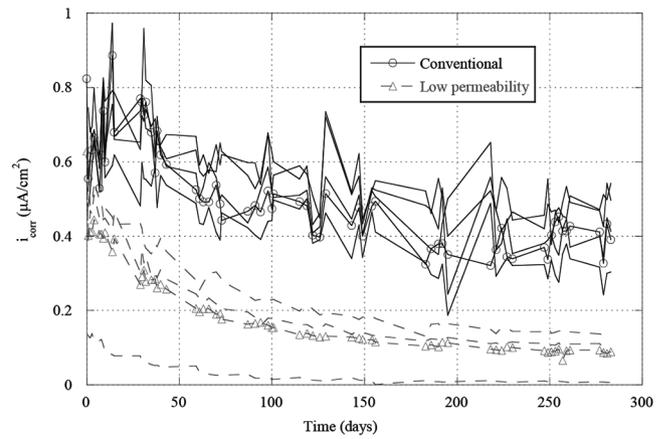


Fig. 14—Corrosion current of samples with conventional and low-permeability pervious (P1) concrete.

the critical chloride threshold of the two-layered system was in the scope of this study. It is interesting to note that the high permeability pervious concrete samples exhibited much lower corrosion current densities at the beginning of the testing compared to the conventional samples although their half-cell potentials were comparatively lower. High porosity and low paste content of these mixtures around the steel reinforcement was probably causing the lower half-cell potential readings while higher resistivity was keeping the corrosion current density low.

#### Chloride diffusion and visual observations

At the conclusion of testing, all samples were washed with tap water to remove all the surface chlorides and kept at laboratory conditions before powder samples were collected for chloride analysis. Table 2 shows the acid-soluble total chloride content values measured as percent by mass of concrete at four different layers and the calculated apparent diffusion coefficients. The reported values on Table 2 are averages of two samples. It should be noted that the first layer is the same conventional concrete for all the samples and the chloride contents are not statistically significantly different from each other at 0.05 level. However, at the second layer, the chloride content of the two-layered concrete samples were statistically significantly different and lower compared to the conventional concrete chloride content. Observations of cut samples showed that there was not a clear separation of conventional and pervious mixtures in the samples but there was a transition from the conventional concrete to the pervious mixtures with the amount of paste decreasing over the depth. At the third and fourth layers, the two-layered samples had lower chloride contents compared to the conventional samples, although the difference in chloride content between the conventional concrete and the high porosity samples were not statistically significant. Visual observations indicate that this was mainly due to the high amount of paste penetrating the high-porosity pervious layer from the top conventional concrete layer during the casting. Due to lower porosity, the medium (P2) and low (P1) permeability pervious mixtures did not allow penetration of paste as much as the high permeability (P3) mixture. This suggests that chloride transportation was mainly

**Table 2—Chloride by mass of concrete and apparent chloride diffusion**

Average depth, mm	Conventional (C)	Two-layered test samples		
	Control	Low (P1)	Med (P2)	High (P3)
(3 to 13)	0.571	0.577	0.522	0.539
(13 to 25)	0.329	0.274	0.239	0.271
(25 to 34)	0.158	0.041	0.089	0.147
(34 to 43)	0.061	0.026	0.050	0.068
Da, mm/s	$3.40 \times 10^{-11}$	$2.06 \times 10^{-11}$	$2.39 \times 10^{-11}$	$3.03 \times 10^{-11}$

taking place in the paste phase and the pervious mixtures with lower mortar phase content were slowing down the penetration of chlorides. Among the two-layered samples, the chloride contents decreased with decreasing porosity, with the low porosity pervious concrete mixture exhibiting the lowest chloride contents. The measured chloride content in the fourth layer (closest to the steel) in the low permeability mixtures was almost half of the content measured in the conventional concrete samples. It should also be noted that the apparent diffusion coefficient values reported in Table 2 for the two-layered samples is actually an average of two different concrete mixtures and not a diffusion coefficient in the traditional sense, which is calculated for only one type of mixture. Comparing to the diffusion coefficient calculated for the conventional concrete, layering of conventional concrete with pervious concrete mixtures was slowing down the ingress of chlorides.

Figure 15 shows sample cross sections cut perpendicular to the embedded steel for conventional and two-layered samples after spraying with silver nitrate solution. Upon spraying, silver nitrate reacts with chlorides and forms  $\text{AgCl}_2$  with white color showing the diffusion front for chlorides. Visual observations confirmed the findings of the chloride content measurements. Chlorides were mainly diffusing through the paste phase of the conventional concrete and there was a transition when the diffusion front reached the pervious layers. It was observed that the pervious layer was not clearly separated from the conventional concrete and the paste phase penetrated the pervious layers from the top and the bottom, leaving a thinner more porous layer in the middle around the reinforcement. Although electrochemical testing did not indicate corrosion initiation, both conventional concrete control samples showed that chloride diffusion front in the paste was close to the top of reinforcement. Spray testing did not show any presence of chlorides below the reinforcement level at any of the samples.

Steel samples were extracted from the uncut samples and were visually evaluated for corrosion. The steel samples embedded in conventional concrete control samples showed no visible corrosion. Corrosion products were visible at the steel samples extracted from the two-layered samples. Corrosion products were mostly observed on the side of the steel facing the bottom of the samples away from the chloride solution reservoir. Corrosion was uniform without any significant pits. Pitting would be expected in the case of chloride-induced corrosion. The mortar phase of the conventional concrete at the bottom moved up through the pores of the placed pervious layer during casting and partially

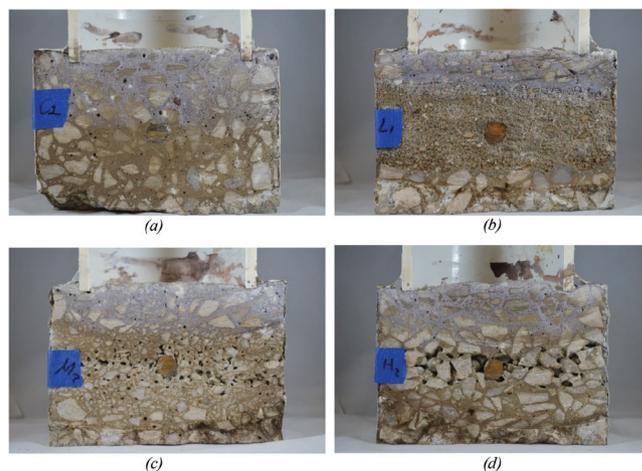


Fig. 15—Cross sections of control and two-layered samples after testing: (a) conventional concrete; (b) two-layered with low permeability; (c) two-layered with medium permeability; and (d) two-layered with high permeability.

covered the surface of the steel reinforcement at the bottom, especially for medium and high porosity mixtures. The parts of the steel reinforcement in contact with high pH paste phase formed a uniform corrosion layer while the top side of the reinforcement, which had access to more oxygen, remained corrosion free. Absence of chlorides below the steel reinforcement level and corrosion pits confirm that the corrosion was not due to chloride exposure. Modifying the casting procedure in future studies and placement of the pervious layer after the initial set of bottom conventional concrete may eliminate this issue and keep the bottom of the reinforcement in a similar environment as the top of reinforcement.

## SUMMARY AND CONCLUSIONS

When reinforced concrete is exposed to a corrosive service environment, typically use of properly consolidated low-permeability concrete is required to slow ingress of aggressive ions and delay the initiation of corrosion. However, once corrosion initiates, service life is reduced with the corresponding buildup of corrosion products causing cracking of concrete. Although high-porosity pervious concrete is typically not used with reinforcement, evaluation of historic pervious concrete cemetery walls in Chicago showed that a long service life of reinforced pervious concrete is possible. Drainage of water quickly through pervious concrete and available space for corrosion products to accumulate without causing tensile stresses were determined to be the causes of this long service life. This concept was further investigated

using a two-layered concrete system consisting of a low-permeability conventional concrete cover layer and a pervious concrete layer with embedded reinforcement. The concrete cover was intended to slow down carbonation and ingress of chlorides and water and the pervious layer was intended to delay the cracking by providing space for accumulation of corrosion products. This study found the following conclusions:

- FM 5-522 accelerated corrosion testing showed that pervious concrete around the steel reinforcement can extend the service life of two-layered reinforced concrete significantly compared to conventional concrete by delaying the cracking of concrete cover. Observation of accumulated corrosion products in the voids confirmed that pervious concrete could provide space for corrosion products and delay cracking.
- Half-cell and linear polarization testing showed that two-layered samples had more positive half-cell potentials and lower corrosion current density values throughout the testing period compared to conventional concrete control samples—that is, the steel reinforcement was better protected in the two-layered system even when exposed to a chloride-containing corrosive environment. None of the samples showed corrosion initiation during 9 months of testing.
- Silver nitrate spray tests indicated that chloride penetration was mainly taking place through the paste in the vertical direction and no chlorides were observed under the steel reinforcement level. Chlorides were not propagating faster through the pervious layer and pooling under the steel reinforcement. Acid-soluble chloride content determination indicated that with the exception of the top layer (which was the same conventional concrete for all samples), chloride content of pervious concrete layers was lower compared to the conventional concrete, especially for the low and medium porosity samples.
- Reinforcement samples extracted from conventional concrete samples were free of corrosion products. Samples from pervious concrete samples showed uniform surface corrosion at the bottom side. Lack of pitting of the bars and observed uniform corrosion at the bottom side of the bars indicated that corrosion was mainly due to paste of the bottom conventional concrete layer covering the bottom of the bars.
- Combined results of the first and second phase testing indicate that this novel layered setup can delay the concrete cover cracking significantly compared to conventional concrete once corrosion initiates and provide similar or lower corrosion rates when exposed to a chloride containing corrosive environment before the initiation of corrosion.

Although presented results are very promising for the novel two-layered system in terms of corrosion performance, evaluation of the mechanical properties, such as combined compressive strength, bond strength between reinforcement and pervious concrete, and others is necessary for applicability of the proposed two-layered concrete system in the field.

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