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Laboratory Investigation of Lightweight Concrete Properties

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16. Abstract:

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The purpose of this study was to evaluate the density (unit weight), splitting tensile strength, and elastic modulus of LWC mixtures under different curing conditions to achieve a better understanding of the LWC properties that are essential for long-lasting and cost-effective structures. Further, the study examined the correlation between the results of the rapid chloride permeability test and the surface resistance test using the Wenner probe to investigate whether the latter could be used to predict the permeability of LWC mixtures, as it is faster and more convenient. The scope of the study was limited to LWC mixtures having different lightweight aggregates prepared and tested in the laboratory.

The results indicated that measured densities are different than those calculated from batch weights; curing conditions affect the splitting tensile strength and elastic modulus values; and the correlation between the results of the rapid chloride permeability test and the surface resistivity test for a given lightweight aggregate was good.

The study recommends that fresh concrete densities be used in designing for dead load computations of LWC structures; that the curing condition be stated for the hardened concrete properties; and that the surface resistivity test be permitted for screening or acceptance of LWC specimens for permeability after the test is standardized by the American Association of State Highway and Transportation Officials.

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FINAL REPORT

LABORATORY INVESTIGATION OF LIGHTWEIGHT CONCRETE PROPERTIES

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In Cooperation with the U.S. Department of Transportation
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ABSTRACT

Lightweight concrete (LWC), with its reduced weight and improved durability, enables longer spans, fewer piers, and longevity for bridge structures. The current emphasis on upgrading structures makes LWC highly desirable as a construction material since superstructures with wider shoulders or more lanes can be upgraded without major work on the substructure.

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The results indicated that measured densities are different than those calculated from batch weights; curing conditions affect the splitting tensile strength and elastic modulus values; and the correlation between the results of the rapid chloride permeability test and the surface resistivity test for a given lightweight aggregate was good.

The study recommends that fresh concrete densities be used in designing for dead load computations of LWC structures; that the curing condition be stated for the hardened concrete properties; and that the surface resistivity test be permitted for screening or acceptance of LWC specimens for permeability after the test is standardized by the American Association of State Highway and Transportation Officials.

FINAL REPORT

LABORATORY INVESTIGATION OF LIGHTWEIGHT CONCRETE PROPERTIES

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INTRODUCTION

Lightweight concrete (LWC) has been used for more than 2,000 years (ACI 213R) (American Concrete Institute [ACI], 2003). Early notable LWC structures include the Port of Cosa, the Pantheon Dome, and the Coliseum. In modern times, structural LWC structures are widely used but to a much lesser extent than normal weight concrete. With the current emphasis on upgrading structures, LWC will be very beneficial since it provides improvements in the superstructure such as wider shoulders and more lanes without the necessity of any major improvements to the substructure. LWC can also provide longer life with low maintenance. There are many examples of the successful use of LWC in and outside the United States (Fidjestol, 2003; Ramirez et al., 2000).

ACI defines *structural LWC* as structural concrete made with low-density aggregate that has an air-dry density of not more than 115 lb/ft^3 and a 28-day compressive strength of more than 2,500 psi (ACI 116R) (ACI, 2000). Air-dry density is referred to as equilibrium density. It is defined by ASTM International (ASTM) in ASTM C567 (ASTM, 2005) as the density reached after exposure to a relative humidity of 50 ± 5% and a temperature of 73.5 ± 3.5 ºF for a period of time sufficient to reach constant mass. The fresh concrete density is determined by dividing the weight of the fresh concrete by the volume and is the practical value measured during placement. The density of LWC at the fresh state is usually considered to be less than 120 lb/ft^3. In design, the equilibrium density is generally used. ASTM C567 provides procedures to determine the equilibrium densities of LWC from calculated or measured values. To calculate equilibrium density, a fixed quantity is added to either the calculated oven-dry density or the measured oven-dry density. To calculate the oven-dry density, both the dry mixture quantities and the volume of concrete produced are needed. Oven-dry density is measured from actual cylinders by obtaining oven-dry weights and volumes of the specimens. The equilibrium density can also be measured from actual cylinders by dividing the weight of the conditioned specimen by the volume (ASTM C567).

With regard to the properties of LWC and normal weight concrete, the former has a lower modulus of elasticity; a more continuous contact zone between the aggregate and the paste; a better compatibility between the elastic moduli of the aggregate and the paste; and more moisture in the pores of aggregates for continued internal moist curing (Holm and Ries, 2006). These improvements lead to lower permeability and less cracking in the concrete and are highly desirable in bridge decks (Neville, 1995). Further, normal weight concrete weighs about 150 lb/ft^3, leading to significant dead load that results in stresses higher than those with an LWC for the same external loading. The low modulus is desirable for minimizing cracks in decks; however, it can increase the prestress losses and deflections in the members. The splitting tensile strength of LWC varies from approximately 70% to 100% compared to normal weight reference concrete at equal compressive strength (ACI 213R) (ACI, 2003).

The Virginia Department of Transportation (VDOT) has been successfully using LWC in bridge structures since 1959, mainly in deck-widening projects. In the late 1990s, studies with high-performance LWCs (HPLWC) were conducted that led to the construction in 2001 of the first HPLWC bridge structure in Virginia: the Route 106 Bridge over the Chickahominy River near Richmond (Ozyildirim and Gomez, 2005). Then, VDOT completed two long bridges on Route 33 near West Point, with long spans containing HPLWC bulb-T beams and deck (Ozyildirim, 2009). HPLWC was chosen because of poor soil conditions.

One of the Route 33 bridges is over the Mattaponi River. It is 3,454 ft long, with 2,195 ft of its length constructed with HPLWC. HPLWC was used in the longer spans of 145 ft, 200 ft, and 240 ft. The latter two spans were constructed using 160-ft-long drop-in beams spliced to haunched girder segments over the piers with post-tensioning. For the beams, the specifications required a minimum compressive strength of 8,000 psi and a maximum permeability of 1500 coulombs. Permeability is determined by the rapid chloride permeability (RCP) test performed in accordance with Virginia Test Method 112 (VTM 112) (VDOT, 2007), which is based on ASTM C1202 (ASTM, 2007). VTM 112 includes accelerated wet curing; 1 week at room temperature and 3 weeks in a 100 ºF water bath. The other Route 33 Bridge is over the Pamunkey River. It is 5,354 ft long, with 2,169 ft being HPLWC with span lengths of 136 ft 4 in, 200 ft, and 240 ft. Again, the latter two spans were constructed using drop-in beams spliced to haunched girder segments over the piers. The deck on the HPLWC beams in both bridges is also constructed with HPLWC, with the specifications requiring a minimum compressive strength of 5,000 psi and a maximum permeability of 2500 coulombs. During testing of the LWC for the bridges, the splitting tensile strength and the elastic modulus of the LWCs were found to be related to the curing condition and the moisture state of LWC (Ozyildirim, 2009).

The RCP test takes a couple of days to conduct: Samples are conditioned in the vacuum chamber with epoxy or duct tape around the sides and kept in water overnight. The following day, the samples are subjected to 60 V DC for 6 hours while attached to two cells at the end, each containing a different ionic solution. However, there is an easier test that uses a surface resistivity (SR) meter with a Wenner four-point probe (hereinafter called the SR test) (Kessler et al., 2008). In this test, the Wenner probe is touched perpendicular to the concrete at 90 degrees around the circumference, and the resistivity value recorded. This test takes only a few minutes. The results of the two tests have been shown to have a good correlation (Kessler et al., 2008). The Florida Department of Transportation (2004) has adopted the SR test to predict the permeability of concretes. An American Association of State Highway and Transportation Officials (AASHTO) task group that includes representatives from VDOT is working on standardizing the SR test (AASHTO, 2008). This task group addresses concretes with normal weight aggregates. It is also desirable to evaluate the test with LWCs because of differences in the conductivity of the aggregates.

For cost-effective structures with an appropriate factor of safety, it is desirable to have a better understanding of (1) the relationship between the oven-dry, fresh, and equilibrium densities of LWC; (2) the relationship between LWC moisture condition and the splitting tensile strength or the elastic modulus; and (3) if the SR test is a convenient and rapid method of determining permeability.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the density (unit weight), splitting tensile strength, and elastic modulus of LWC mixtures under different curing conditions to achieve a better understanding of the LWC properties that are essential for long-lasting and cost-effective structures. Further, the study examined the correlation between rapid chloride permeability and surface resistance to investigate whether the latter could be used to predict the permeability of LWC mixtures, as the SR test is faster and more convenient.

The scope of the study was limited to LWC mixtures having different lightweight aggregates prepared and tested in the laboratory.

METHODS

To achieve the study objectives, two tasks were carried out.

1. Fresh and hardened concrete properties of LWC mixtures under different states of moisture with lightweight aggregates from six different sources were determined.

2. The correlation between RCP and SR was ascertained to determine if the SR test could be used to predict permeability, as it is a faster and easier test.

Determination of Concrete Properties

Mixtures

Mixtures containing lightweight aggregates with a nominal maximum size of ½ in from six different sources were prepared. The six types of aggregates had different absorption characteristics and composition that could affect the density, splitting tensile strength, elastic modulus, and electrical conductivity used to indicate permeability. The properties of the six coarse aggregates provided by the manufacturer are given in Table 1 (Stone, 2009).

From the six aggregate sources, 14 batches of concrete were prepared (Table 2). Two additional batches were made with aggregate from only the North Carolina source to determine the correlation between RCP and SR.

Table 1. Coarse Aggregate Properties Provided by Manufacturer

Coarse Aggregate Source	Plant Location	Aggregate Type	Absorption (%)	Specific Gravity	Bulk Loose Unit Weight (lb/ft^3)
Colorado	Boulder	Shale	22	1.73	50.1
Indiana	Brooklyn	Shale	10	1.20	N/A
North Carolina	Gold Hill	Slate	6	1.52	46
New York	Mt. Marion	Shale	N/A	N/A	N/A
California	Frazier Park	Clay	21.8	1.75	46.5
Louisiana	Erwinville	Clay	N/A	N/A	34-37

The 14 batches were prepared at three water–cementitious material ratios (w/cms): 0.43, 0.39, and 0.35 (Table 2). The w/cm of 0.43 is considered for bridge deck concrete having a minimum compressive strength of 4,000 psi. The mixtures with a w/cm of 0.43 were designed to provide an air content of 6% and a density of 118 lb/ft^3.

The w/cm of 0.35 is for beams with a minimum compressive strength of 8,000 psi. At the 0.35 w/cm level, the mixture was designed for an air content of 5% and a density of 121 lb/ft^3.

The mixture with a w/cm of 0.39 was tested as a middle point with a minimum compressive strength of 6,000 psi, an air content of 5.5%, and a density of 120 lb/ft^3.

Table 2. Mixture Proportions (lb/yd^3)

Batch No.	CA Source	w/cm	Portland Cement	Slag Cement	Fly Ash	CA	FA	Water
1	Colorado	0.43	395	263	---	1164	1085	280
2	Indiana	0.43	395	263	---	504	1745	280
3	North Carolina	0.43	395	263	---	826	1423	280
4	North Carolina	0.35	480	320	---	804	1383	280
5	New York	0.43	395	263	---	866	1383	280
6	New York	0.35	480	320	---	842	1346	280
7	California	0.43	395	263	---	1206	1042	280
8	Louisiana	0.43	395	263	---	544	1705	280
9	North Carolina	0.39	420	280	---	848	1423	270
10	Louisiana	0.39	420	280	---	566	1705	270
11	Indiana	0.39	420	280	---	526	1745	270
12	New York	0.39	420	280	---	888	1383	270
13	California	0.39	420	280	---	1228	1042	270
14	Colorado	0.39	420	280	---	1184	1085	270
Additional Batches for Permeability Study								
15	North Carolina	0.40	420	0	180	830	1517	240
16	North Carolina	0.40	300	300	0	900	1442	240

CA = coarse aggregate; w/cm = water–cementitious material ratio; FA = fine aggregate.

The mixture proportions are given in Table 2. The cementitious materials were portland cement and slag cement, which is a ground-granulated blast furnace slag. The fine aggregate was locally available natural sand. The two additional mixtures for the permeability study had a w/cm of 0.40. One of the batches contained Class F fly ash, and the other slag cement.

Tests for Concrete Properties

For the first 14 batches shown in Table 2, cylinders measuring 4 by 8 in were prepared and tested at the fresh and hardened states. The fresh concrete tests were density (ASTM C138), air content by the volumetric method (ASTM C173), and slump (ASTM C143). The density was measured at the fresh state (ASTM C138), measured and calculated at the oven-dry and equilibrium states (ASTM C567) (ASTM, 2005).

In the hardened state, 27 cylinders were cast from each batch, as indicated in Table 3. Concretes were tested for compressive strength (ASTM C39), splitting tensile strength (ASTM C496), elastic modulus (ASTM C469), and permeability using the RCP and SR tests. The same cylinder was tested for elastic modulus and then for compressive strength.

As described previously, the RCP test was conducted in accordance with VTM 112 (VDOT, 2007). The same specimen was first subjected to the SR test and then to the RCP test. The various curing conditions affecting the state of moisture of LWC are summarized in Table 3 and included steam curing, moist curing, outdoors exposure, and a combination of the three.

The last two batches in Table 2 were tested for compressive strength at 28 days and for RCP and SR. Two cylinders were tested for an average value.

Table 3. Test Specimens and Curing Methods

Curing Method	Age (days)	Splitting Tensile Strength	Compressive Strength and Elastic Modulus	RCP and SR	Density
16 hours steam	1	Z (1)	X (1)	Z (1)	---
16 hours steam + 27 days lab air	28	X (3)	X (2)	Z (1)	---
16 hours steam + 27 days moist	28	X (3)	X (2)	Z (1)	---
28 days moist	28	X (3)	X (2)	---	---
90 days moist	90	Y (2)	Y (2)	---	---
16 hours steam + 6 days lab air + 83 days outside	90	Y (3)	Y (2)	---	---
16 hours steam + 27 days moist + 60 days outside	90	Z (3)	Z (2)	---	---
Moist 1 wk 73 °F + 3 wk 100 °F	28	---	---	X (1)	---
ASTM C567	---	---	---	---	X (1)

RCP = rapid chloride permeability; SR = surface resistivity; X = Batches 1-14; Y = Batches 1-8; Z = Batches 9-14.
Numbers in parentheses indicate the number of cylinders tested to obtain the average value.

Determination of Correlation Between Rapid Chloride Permeability and Surface Resistivity

As stated previously, two batches were made with aggregate from one source to evaluate the correlation between RCP and SR. The same cylinder was tested first with the SR test and then with the RCP test.

The values from the RCP test and the SR test for each sample were plotted, and the trend line (a straight line that best represents the data) was determined. The R^2 value and the equation for the trend line were calculated.

RESULTS AND DISCUSSION

Concrete Properties

Fresh Concrete Properties

For the 14 batches, the fresh concrete properties given in Table 4 indicate workable concretes with air contents ranging from 3.5% to 8%. Fresh concrete densities ranged from 116.8 to 123.6 lb/ft^3 as shown in Table 4. The measured oven-dry densities (O_m) ranged from 105.5 to 120.7 lb/ft^3, and the measured equilibrium densities (E_m) ranged from 111.9 to 126.4 lb/ft^3, as shown in Table 5.

The equilibrium density was higher than the fresh concrete density in few of the samples, which was contrary to the expected result. This anomaly was attributed to the difference in the sampling and the preparation of the samples using the 0.3-ft^3 bowl of the volumetric meter for

Table 4. Fresh Concrete Properties

Batch Number	w/cm	Air (%)	Slump (in)	Density (lb/ft^3)
1	0.43	5.50	3.8	119.2
2	0.43	8.00	2.3	118.8
3	0.43	3.50	2.8	121.2
4	0.35	7.00	6.0	117.2
5	0.43	7.75	5.0	120.4
6	0.35	6.25	6.0	123.6
7	0.43	6.00	2.0	117.6
8	0.43	7.75	2.3	116.8
9	0.39	4.75	2.8	119.2
10	0.39	5.75	5.3	118.0
11	0.39	6.50	4.3	118.0
12	0.39	5.00	5.0	122.8
13	0.39	6.50	2.0	116.8
14	0.39	-	4.3	118.8

w/cm = water–cementitious material ratio.

Table 5. Fresh, Oven-dry, and Equilibrium Densities

Mix No.	Fresh Density (lb/ft^3)	O_c (lb/ft^3)	O_m (lb/ft^3)	E_m (lb/ft^3)	E_c (lb/ft^3) $E_c = O_c + 3$	E_c (lb/ft^3) $E_c = O_m + 3$
1	119.2	101.1	107.8	114.7	104.1	110.8
2	118.8	105.0	113.6	117.7	108.0	116.6
3	121.2	106.0	115.6	119.7	109.0	118.6
4	117.2	110.2	112.0	116.4	113.2	115.0
5	120.4	105.0	114.3	120.3	108.0	117.3
6	123.6	109.2	120.7	126.4	112.2	123.7
7	117.6	104.9	114.7	120.6	107.9	117.7
8	116.8	103.2	105.8	113.7	106.2	108.8
9	119.2	108.6	113.6	118.4	111.6	116.6
10	118.0	107.6	111.0	116.2	110.6	114.0
11	118.0	107.6	114.0	119.2	110.6	117.0
12	122.8	107.6	115.5	120.8	110.6	118.5
13	116.8	103.5	106.6	112.8	106.5	109.6
14	118.8	103.6	105.5	111.9	106.6	108.5

O_c = calculated oven-dry density, O_m = measured oven-dry density; E_m = measured equilibrium density; E_c = calculated equilibrium density.

the fresh density and the 4 by 8 in cylinders for the equilibrium density. Another factor that affected the oven-dry density measurements is the use of the 0.5% change in mass to terminate the measurements; oven drying ended when the change of mass was not more than 0.5%. It took 2 to 6 months to dry the samples. A smaller value for the change in mass may be needed to obtain meaningful results.

ASTM C567 (ASTM, 2005) calculates oven-dry density based on the mixture quantities, aggregate moisture contents, and the concrete batch volume. The data collected from the 14 batches indicate a fair correlation between measurements of actual samples and calculations of the oven-dry density from the mixture information, as indicated by the R^2 value of 0.44 shown in Table 6. The measured equilibrium density did not correlate well with the calculated equilibrium density; R^2 was 0.33. However, the measured equilibrium density was highly correlated with that calculated from the measured oven-dry density as shown in Table 6 and Figure 1; R^2 was 0.95. Thus, densities calculated using the mass of ingredients from mixture designs did not correlate well with the equilibrium density measured from actual concrete samples. The data suggest fair correlations between fresh density and measured equilibrium density, as shown in Table 6; R^2 was 0.53. The fresh density was typically greater than the equilibrium density, which occurs because of moisture loss in exposed concrete (Holm and Ries, 2006).

Table 6. Regression Analysis for Densities

x	y	R^2	Standard Error
O_c	O_m	0.44	3.420
O_m	Fresh density	0.49	1.583
O_c	E_m	0.33	3.294
E_m	Fresh density	0.53	1.516
E_m	E_c (using O_m)	0.95	1.047
E_m	E_c (using O_c)	0.33	2.238

O_c = calculated oven-dry density, O_m = measured oven-dry density; E_m = measured equilibrium density; E_c = calculated equilibrium density.

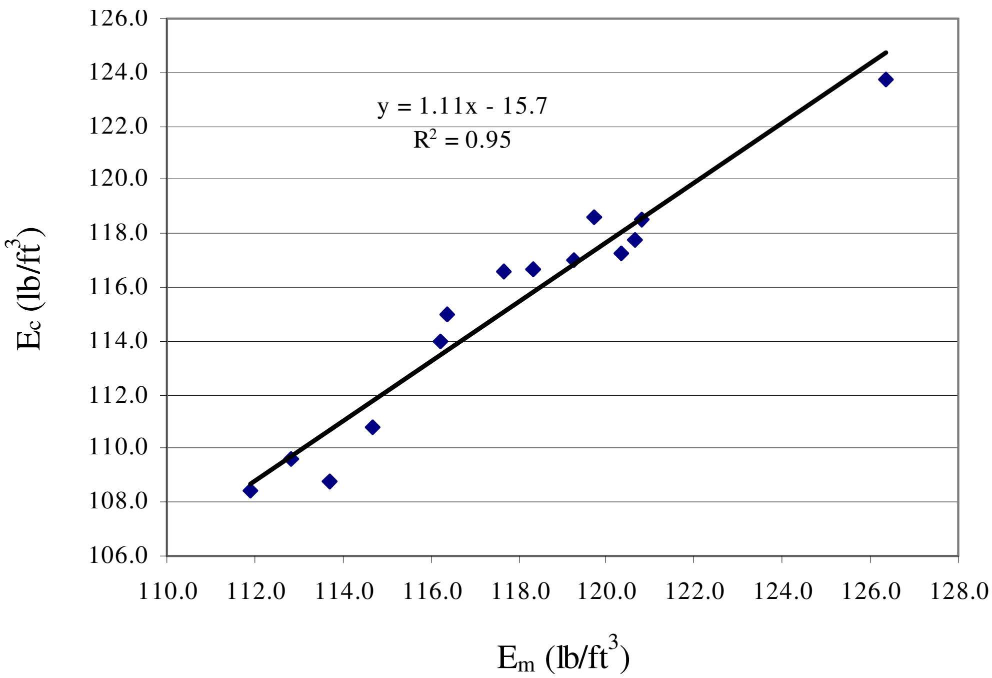

Figure 1. Measured Equilibrium Density (E_m) Versus Calculated Equilibrium Density ($E_c = O_m + 3$ lb/ft^3 where O_m = measured oven-dry density)

Hardened Concrete Properties

Strength and Elastic Modulus

The compressive strengths are given in Table 7, the elastic moduli in Table 8, and the splitting tensile strengths in Table 9. The relationships between strength and elastic modulus for different curing conditions were analyzed statistically using the paired *t*-test and are presented in Table 10. The highest 28-day compressive strengths were achieved by specimens that were moist cured followed by those subjected to steam plus air; the differences in averages were not found to be significant. However, the differences in the average compressive strength between the specimens with the lowest average, i.e., steam plus moist-cured specimens, and the other two, i.e., exposed to moist environment or steam plus air, were significant.

For splitting tensile strength at 28 days, the same trend as with the compressive strength was observed. The moist-cured specimens had the highest average followed by the steam-cured specimens. There was no statistical difference between the steam-cured specimens exposed to air or moist curing; however, between these and the moist-cured specimens there was a statistical difference. The elastic modulus results at 28 days indicated that the highest value was attained when the specimen was exposed to steam and moist curing, closely followed by the moist-cured specimens. The difference was not significant; but the difference between these and the specimens exposed to steam plus air was significant.

Cylinders that were steam cured for 90 days (16 hours, air cured for 6 days, and then placed outside for 83 days) had lower compressive strength and elastic modulus values when compared to cylinders moist cured for 90 days. The differences in compressive strengths and elastic moduli were significant.

The data show that when there is no statistically significant difference in compressive strength, there is a significant difference in splitting tensile strength and elastic modulus as indicated in Table 11.

Table 7. Compressive Strength (psi)

Mix No.	w/cm	Curing Method[a] A	B	C	D	E	F	G
1	0.43	3580	5090	4720	4920	5890	5960	---
2	0.43	4120	5360	5120	6080	6510	5790	---
3	0.43	4060	5810	5690	6940	7690	6430	---
4	0.35	3980	5490	5140	7120	7650	6240	---
5	0.43	4300	5970	5240	3600	7070	6400	---
6	0.35	6090	7630	7310	7830	9110	8080	---
7	0.43	4180	5150	4900	5710	6485	5630	---
8	0.43	3000	4080	3900	4260	5040	4180	---
9	0.39	4730	6670	6555	7170	---	---	7450
10	0.39	4770	6090	5870	6070	---	---	6230
11	0.39	4360	5070	5190	5990	---	---	5630
12	0.39	5090	6690	6380	7320	---	---	7280
13	0.39	3500	4540	4380	4570	---	---	4910
14	0.39	3460	5790	5460	5630	---	---	5990

w/cm = water–cementitious material ratio.
[a]A = 16-hr steam; B = 16-hr steam / 27-day air; C = 16-hr steam / 27-day moist; D = 28-day moist; E = 90-day moist; F = 16-hr steam / 6-day air / 83-day outside; G = 16-hr steam / 27-day moist / 60-day outside.

Table 8. Elastic Modulus (10^6 psi)

Mix No.	Curing Method[a] A	B	C	D	E	F	G
1	2.43	2.63	2.81	2.47	3.22	3.00	---
2	2.67	2.62	2.81	2.47	4.18	3.32	---
3	3.01	3.29	3.78	3.92	4.42	3.82	---
4	3.02	3.01	3.02	3.07	3.99	3.43	---
5	3.69	2.99	3.23	3.40	3.78	3.52	---
6	2.92	3.44	3.61	3.99	5.18	3.94	---
7	2.94	2.93	3.13	3.26	4.49	3.46	---
8	1.88	2.08	2.35	2.33	3.03	2.36	---
9	3.75	3.31	3.95	4.10	---	---	3.66
10	3.16	3.18	3.43	3.52	---	---	3.21
11	3.01	2.62	2.81	2.47	---	---	3.14
12	3.36	3.49	3.86	3.58	---	---	3.66
13	2.06	2.37	2.52	2.64	---	---	2.35
14	2.62	2.86	3.03	2.78	---	---	2.61

[a]A = 16-hr steam; B = 16-hr steam / 27-day air; C = 16-hr steam / 27-day moist; D = 28-day moist; E = 90-day moist; F = 16-hr steam / 6-day air / 83-day outside; G = 16-hr steam / 27-day moist / 60-day outside.

Table 9. Splitting Tensile Strength (psi)

Mix No.	Curing Method[a]						
	A	B	C	D	E	F	G
1	---	565	555	535	570	570	---
2	---	560	500	540	630	535	---
3	---	610	600	625	705	645	---
4	---	570	545	635	650	590	---
5	---	585	560	660	605	590	---
6	---	655	660	665	755	645	---
7	---	535	540	530	580	570	---
8	---	440	435	480	545	445	---
9	595	605	575	605	---	---	635
10	455	550	535	555	---	---	550
11	435	515	550	590	---	---	615
12	510	625	615	670	---	---	605
13	385	460	500	515	---	---	495
14	425	525	515	590	---	---	535

[a]A = 16-hr steam; B = 16-hr steam / 27-day air; C = 16-hr steam / 27-day moist; D = 28-day moist; E = 90-day moist; F = 16-hr steam /6-day air /83-day outside; G = 16-hr steam / 27-day moist / 60-day outside.

Table 10. Paired *t*-Test Results for Different Curing Methods

Property	Variable 1		Variable 2		df	u	$\lvert X_d \rvert$	Significant Difference?
	Cure[a]	Avg.	Cure[a]	Avg.				
Compressive Strength (psi)	B	5674	C	5418	13	108.0	255.4	Yes
	B	5674	D	5944	13	530.6	270.0	No
	C	5418	D	5944	13	462.2	525.4	Yes
Elastic Modulus (10^6 psi)	B	2.92	C	3.17	13	0.091	0.251	Yes
	B	2.92	D	3.14	13	0.177	0.227	Yes
	C	3.17	D	3.14	13	0.137	0.024	No
Splitting Tensile Strength (psi)	B	557	C	549	13	14.6	8.2	No
	B	557	D	585	13	20.8	28.2	Yes
	C	549	D	585	13	20.3	36.4	Yes
Compressive Strength (psi)	E	6931	F	6088	7	375.2	842.9	Yes
Elastic Modulus (10^6 psi)	E	4.03	F	3.36	7	0.298	0.678	Yes

df = degrees of freedom; $u = t_{1-\alpha}\, s_d / \mathrm{sqrt}(n)$ where α = significance level of test, n = number of tests, and s_d=standard deviation; X_d = average of differences.
[a]B = 16-hr steam / 27-day air; C = 16-hr steam / 27-day moist; D = 28-day moist; E = 90-day moist; F = 16-hr steam / 6-day air / 83-day outside.

Table 11. Summary of Significant Differences From Paired *t*-Test

Curing Method[a]	Compressive Strength	Splitting Tensile Strength	Elastic Modulus
B compared to C	Yes	No	Yes
B compared to D	No	Yes	Yes
C compared to D	Yes	Yes	No

[a]B = 16-hr steam / 27-day air; C = 16-hr steam / 27-day moist; D = 28-day moist.

Rapid Chloride Permeability and Surface Resistivity

The permeability results for the 14 batches are summarized in Table 12 and plotted in Figure 2. Figure 2 shows the high variability and low correlation between RCP and SR, which was attributed mainly to the different aggregate sources. The plot also includes the best-fit equation provided by a Florida study (Kessler et al., 2008). The values were mainly on one side of the Florida curve.

Table 12. Rapid Chloride Permeability and Surface Resistivity

Mix No.	Cylinder No.	Curing Method[a]	Permeability (coulombs)	Surface Resistivity (kOhm-cm)
1	1290	A	1443	21.9
2	1317	A	1160	21.9
5	1710	A	1463	24.4
6	1738	A	1329	23.5
7	1810	A	1469	21.6
8	1837	A	1205	21.1
9	2637	B	3858	19.0
	2659	C	1887	56.0
	2660	D	1256	40.1
	2661	A	1079	48.8
10	2665	B	3619	15.3
	2686	C	1809	45.3
	2687	D	1569	31.2
	2688	A	1282	41.1
11	2692	B	4471	13.8
	2713	C	2504	41.6
	2714	D	1884	28.1
	2715	A	1351	37.9
12	2748	B	4095	----
	2769	C	1810	47.5
	2770	D	1405	30.9
	2771	A	1205	33.5
13	2775	B	3590	----
	2796	C	1778	56.2
	2797	D	1398	37.1
	2798	A	1103	37.4
14	2803	B	4156	----
	2824	C	2168	39.8
	2825	D	1737	22.5
	2826	A	1458	23.9

[a]A = moist accelerated cure (1 wk at room temperature, 3 wks at 100°F); B = 16-hr steam; C = 16-hr steam / 27-day air; D = 16-hr steam / 27-day moist.

Correlation Between Rapid Chloride Permeability and Surface Resistivity

As discussed previously, two additional batches (see Table 13) with lightweight coarse aggregate from a single source, North Carolina, were cured differently to achieve a variation in permeability values and were tested for RCP and SR. The 28-day compressive strength of the mixture with fly ash was 5,190 psi, and that of the mixture with slag cement was 7,460 psi. The RCP and SR values are shown in Figure 3; as may be seen, the correlation was high ($R^2 = 0.97$). Again, the values were on one side of the curve developed in the Florida study (Kessler et al., 2008). As displayed in Figure 2, there is a wide scatter in data obtained from different aggregate sources and the values are different from those in the Florida study. This indicates the influence of aggregates from different sources on the results.

Table 13. Permeability Data From the Two Batches

Curing Condition	Age (days)	Concrete with Fly Ash RCP (coulombs)	Concrete with Fly Ash SR (kOhm-cm)	Concrete with Slag Cement RCP (coulombs)	Concrete with Slag Cement SR (kOhm-cm)
Moist cure (MC)	28	2912	15.14	1353	30.31
MC 1 wk 73 °F + 3 wk 100 °F	28	298	70.01	614	41.59
MC 2 wk 73 °F + 2 wk 100 °F	28	548	50.62	688	39.42
MC 3 wk 73 °F + 1 wk 100 °F	28	1190	25.74	960	30.29
MC	36	2187	18.80	----	----

RCP = rapid chloride permeability; SR = surface resistivity.

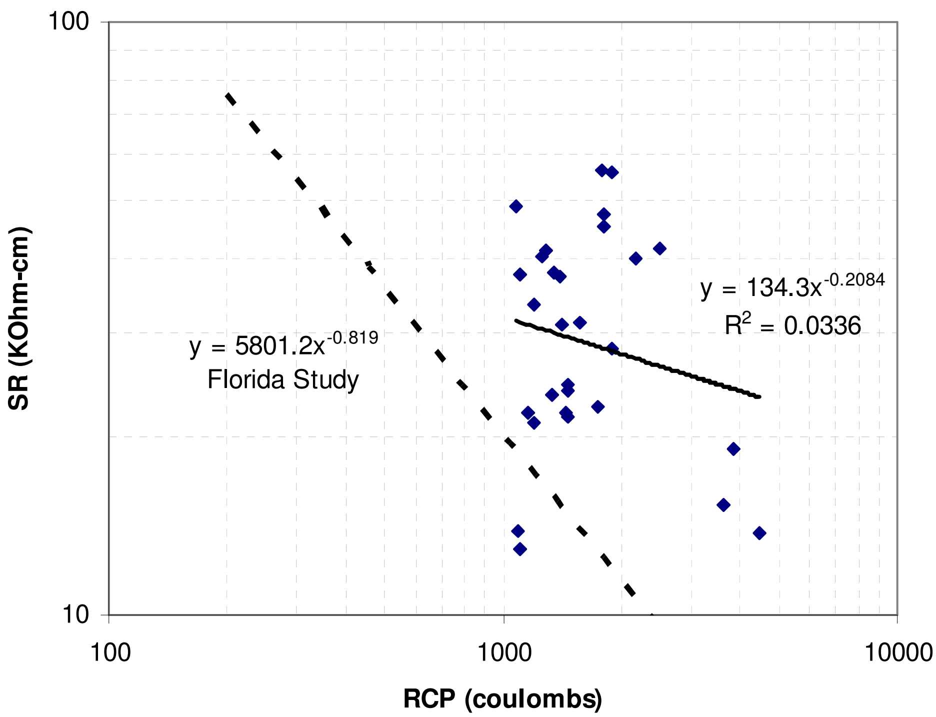

Figure 2. Rapid Chloride Permeability (RCP) Versus Surface Resistivity (SR) for Initial 14 Batches. The best fit (trend line) from the Florida study (Kessler et al., 2008) is also displayed.

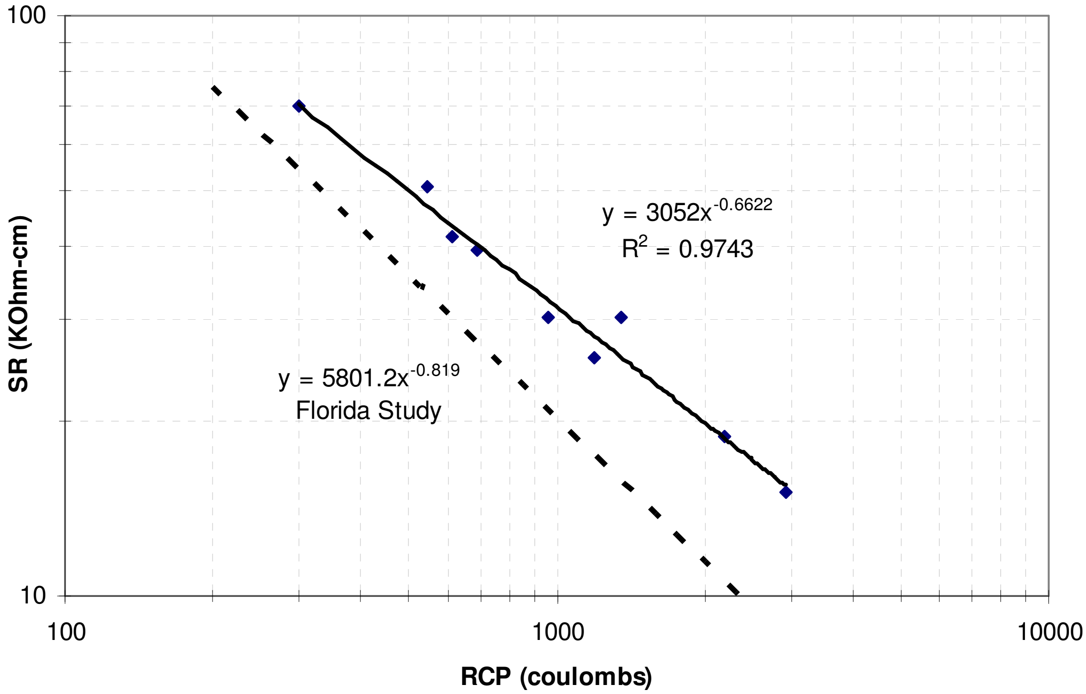

Figure 3. Correlation Between Rapid Chloride Permeability (RCP) and Surface Resistivity (SR) for the Two Batches

CONCLUSIONS

- The measured equilibrium density from LWC cylinders did not correlate well with the calculated equilibrium density from the mixture input.
- The correlation between the fresh density and measured equilibrium density of the LWC was fair ($R^2 = 0.53$).
- Compressive strength was highest for moist-cured LWC specimens followed by those exposed to steam and air. When there was no significant difference in the compressive strength of specimens subjected to different curing conditions, there was a significant difference in splitting tensile strength and elastic modulus.
- The LWCs had a higher elastic modulus when moist cured versus being exposed to steam and air.
- For a given lightweight aggregate source, a satisfactory correlation was found between rapid chloride permeability and surface resistivity ($R^2 = 0.97$).

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RECOMMENDATIONS

1. *VDOT's Materials Division and Structure and Bridge Division should specify and use fresh concrete density rather than the equilibrium density for dead load computations during the design of LWC.* Fresh concrete density is required for acceptance testing during placement. It is much easier to determine, correlates with the equilibrium density, and is conservative when design dead loads are computed.

2. *VDOT's Materials Division and Structure and Bridge Division should specify the curing condition for specimens used to determine the compressive strength, splitting tensile strength, and elastic modulus of LWC since for a given compressive strength, splitting tensile and elastic modulus values are dependent on the curing conditions.*

3. *VDOT's Materials Division and Structure and Bridge Division should use the SR value in screening or accepting LWC for permeability after AASHTO adopts its use.* The correlation between SR and RCP was very good for a given source of material, and the SR test is much easier and faster.

BENEFITS AND IMPLEMENTATION PROSPECTS

Understanding the density, splitting tensile strength, and elastic modulus for different curing conditions for LWC would permit more accurate design assumptions. A better understanding of the properties will allow for maximizing material properties and ensuring a consistent safety factor. Determining permeability through the use of the SR test would enable a large number of tests in a short period of time. This would yield better control of permeability, which is essential for longevity. The knowledge acquired would lead to optimum designs that will be cost-effective because of longer life and minimal interruption to the traveling public. Another advantage of using LWC is the reduced weight, which allows widening of bridges without having to reinforce or add substructure elements such as piles, which reduces both the cost and the environmental impact.

LWC is expected to be durable in bridge decks because of the reduced amount of cracking attributed to the modulus compatibility between the paste and the lightweight aggregates and to internal curing. The increased durability of LWC leads to a longer lasting material that will reduce future maintenance and repair costs, thus enabling the "get-in, get-out, and stay-out" consistent with the federal goals.

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