Determination of Transport Properties of Lightweight Aggregate Concrete for Service Life Modeling

Expanded Shale, Clay, and Slate Institute (ESCSI)

TCG Project Number: 16059
January 27, 2017

Addendum Prepared for:

Norlite

February 3, 2017

Prepared by:

Tourney Consulting Group, LLC
3401 Midlink Drive
Kalamazoo, MI 49048 USA
(269)384-9980 Phone
(269)384-9981 Fax

WWW.TOURNEYCONSULTING.COM

February 2, 2017

Mr. William H. Wolfe
Senior Engineer
Norlite
P.O. Box 694
Cohoes, NY 12407

Re: Determination of Transport Properties of Lightweight Aggregate Concrete for Service Life Modeling—Norlite Performance
TCG Project Number: 16059

Dear Bill:

TCG has completed its study for the Expanded Shale, Clay, and Slate Institute (ESCSI) to determine the effects of lightweight (LW) coarse and fine aggregates on the transport properties of concrete. The transport properties are used in several service life programs including STADUIM®, Life 365™ and analysis according to fib Bulletin 34. Specified required design service lives of 75 years or more is becoming very common, and the use of lightweight aggregates can offer several benefits. Determining how they affect the service life for typical mixtures utilized in these structures will lead to early consideration of lightweight aggregates in the design process.

Modeling the performance of a bridge deck in the Detroit area, with the transport properties determined for use in Life 365™ or STADIUM®, was performed.

Results are presented for Norlite coarse LW aggregates.

Supplementary cementitious materials (SCMs), corrosion inhibitors, or corrosion resistant reinforcing bars were not considered so that the pure effect of lightweight aggregates could be demonstrated. In combination with any of these it is anticipated that the lightweight aggregates would show even a better performance enhancement.

Experimental Program:

The program is based on comparing the different aggregates for a specific mixture design frequently used in structures which need to meet a service life greater than or equal to 75 years. It was decided to use only ordinary portland cement (OPC) for the cementitious component so that changes in properties are only related to the change in aggregates. The concretes were air-entrained to be representative of applications where freezing and thawing are a concern.

Table 1 shows the testing conducted for NORLITE LW aggregate (S) and a control mixture (C).

Table 1 Test Program per Mixture Design

Tests	Per Mix	Notes
Plastic Properties (slump, air setting time)	1	For each Mix
Compressive St.	3	1, 28, 90 days
STADIUM Transp. (IDC, MTC, ASTM 642 porosity)	2	28 and 90 days
ASTM C1760 Bulk Conductiivty	2	28, 90 days
NT Build 492 Non Steady State Diffusion Coeff.	1	28 days
ASTM C1556 Bulk Diffusion	1	28 days
ASTM C1585 Capillary Absorption	1	28 and 90 days

Description of Transport Tests

STADIUM® modeling software utilizes two transport properties, the first is the Ionic Diffusion Coefficient (IDC) which represents the movement of chloride and other ions through the capillaries. The second is the Moisture Transfer Coefficient (MTC) which models chloride ingress when the concrete is not 100% saturated, which is unique to STADIUM and highly relevant when conducting service life analysis. Note that the STADIUM modeling program is the only one that accounts for the movements of multiple species in the concrete as well as for chemical reactions and binding reactions. This allows for a prediction of the chloride-to-hydroxide levels, which is important for comparing mixtures with SCMs.

The ASTM C1760 Bulk Conductivity test is directly related to the ASTM C1202 Rapid Chloride Permeability, but is non-destructive as it is conducted for a short time and doesn't subject the specimens to heating. The bulk conductivity is used to monitor the change in permeability over time as it is directly related to the diffusion coefficients.

The NT Build 492 provides a relatively rapid (1 to 2 days) indication of chloride ingress. It adjusts for increases in conductivity that is not related to chloride ingress. The results are used in the fib service life analysis.
The ASTM C1516 Bulk Diffusion is used to calculate the apparent diffusion coefficient for chloride ingress and can be used in Life 365 or the fib service life analysis.

ASTM C1585 Capillary Absorption is used to predict the surface concentration of chloride when the concrete is not water-saturated. It can be used in Life 365 and the fib service life analysis. This is of primary use when there is wetting and drying of the surface. In Life 365 the time to reaching the maximum surface concentration is decreased or increased compared to a control concrete based upon the ratio of the absorption values.

Concrete Plastic and Mechanical Properties

Table 2 shows the concrete proportions, plastic and mechanical properties. Information on the materials used are in the appendix.

Table 2 Concrete Mixture Proportions and Plastic and Mechanical Properties

Description	ID	
	NC	C
Mix Date:	**7/26**	**8/3**
Lafarge Alpena Type I lb/yd3	658	658
Agg.Resource Midway Pit Natural Fine Agg SSD lb/yd3	1568	1294
Bay Aggregates Cedarville Pit Limestone Coarse Agg. #67 SSD lb/yd3	150	1800
Lightweight Coarse SSD lb/yd3	862	------
Total Water lb/yd3	------	243
Designed Air %	6.5	6.0
Designed Plastic Density lbs/ft3	123.3	148.0
Water/Cement Ratio	0.37	0.37
Admixtures		
BASF Master Air AE100 oz/cwt	0.2	0.5
BASF Glenuim 7500 (HRWR) oz/cwt	5.2	4.4
Physical Properties		
Slump, in.	2.75	4.00
Air % as tested (Volumetric)	7.00	7.10
Density lb/ft3 (Agg. Loose Drained)	56.1	------
Density lb/ft3 Plastic (Concrete)	**125.7**	**146.2**
Density lb/ft3 Oven Dry (Concrete)	115.7	142.1
Density lb/ft3 Equilibrium Air Dry (Concrete)	122.3	147.3
No. of Days to Reach Equilirium (avg 2)	112	56
Compressive Strength		
1 Day Strength psi (3 each)	3650	3310
28 Day Strength psi (3 each)	6420	5470
90 Day Strength psi (3 each)	7200	5950

Mix Preparation Procedures

In preparation for mixing of the concrete the coarse LW aggregates were saturated by covering with water in sealed pails, and after 1 day adding water to make sure all the aggregates were submerged. The coarse LW aggregates remained submerged in water for a minimum of 7 days. Before weighing the aggregates for the mixes, they were placed covered in pails with holes on the bottom to let excess water drain off.

Concrete Testing

Compressive strengths, Table 2, are increased for the NORLITE lightweight aggregate mix versus the control. The increase in strength would be an indication of better aggregate bond and enhanced curing.

Porosity of the concrete according to ASTM C642 was determined as was the porosity of the LW coarse aggregates. The porosity of the LW fine aggregate was assumed to be the same as the coarse aggregate from the same source. The porosity of the concrete was then adjusted for the volume of porosity in the LW aggregates in a cubic yard. The volume of permeable voids in the aggregates was somewhat less than the aggregate porosity so that was taken into account in the adjustment. The data are shown in Table 3. After correcting for the voids in the aggregates the LW mixes have similar to better porosity in the paste fraction to the control mixture.

Table 3 C642 Porosity Data

Material	NC	C
ASTM C642 Volume Permeable Voids %	14.33	11.72
ASTM C642 Volume Permeable Voids in aggregate %	27.18	------
Corrected ASTM C642 Volume Permeable Voids %	8.98	11.72

The conductivity and resistivity properties are in Table 4. The surface resistivity can be correlated to the bulk conductivity at a given time. The bulk conductivity is more closely related to the strength and diffusion values which are bulk properties. The conductivity is decreasing in time indicating that the concrete permeability is decreasing. The correction gave a negative number for the HD LW aggregate so the original porosity was used, which is a conservative approach.

The bulk conductivity is related to the ASTM C1202 Coulomb values as it represents the initial reading in that test. If the specimens don't increase in temperature, then it is related to the final Coulomb value, which is typical for low permeability concretes with SCMs. Table 4 has predicted C1202 values assuming no heating. These values are more closely related to diffusion values. The surface resistivity at 28 days was converted using the relationship developed by J. Weiss et al at 28 days.

Table 4 Resistivity and Conductivity Data

Transport Property	NC	C
Resistivity 4" x 8" cyl.(Avg 2)		
28 d Bulk Elect Resistivity (kΩ-cm) 4 Pin	7.7	9.4
28 days Coulombs 4 Pin FM 5-578	2365	1941
90 d Bulk Elect Resistivity (kΩ-cm) 4 Pin	8.5	10.9
28 d Bulk Elect Conductivity (mS/m) C1760	13.3	9.5
28 d STDev (mS/m) C1760	0.15	0.378
28 days Coulombs C1760	2410	1726
90 d Bulk Electrical Conductivity (mS/m)	9.9	6.7
90 d STDev (mS/m) C1760	0.020	0.345
90 days Coulombs	1803	1212

Table 5 provides the transport properties that can be used in Life 365™ and other models that don't directly address chloride bonding, movement of other ions, and chemical reactions that occur in the concrete over time. These properties are the ASTM C1556 Bulk Diffusion Coefficient or the NT Build 418 Non-Steady State Diffusion Coefficient, and the ASTM C1585 Absorption.

The NT Build 492 and ASTM C1556 values follow the same trend, but the ASTM bulk diffusion values are lower. This is related to the 35 days of additional ponding for the ASTM specimens in the NaCl solution as well as the NT Build 492 being a non-steady-state value. In a few cases NT Build 492 was conducted at 90 days and the values were still higher than those of C1556 at a combined 63 days of moisture (28-days fog room and 35-days ponding), so it appears that NT Build 492 might provide too high a value, but this can be correlated to C1556, as are the ASTM C1202 or C1760 test results.

Table 5 Transport Properties for Use in Life 365™

Transport Property	NC	C
Nordtest NT Build 492 (E-12 m2/s) 28-d	9.8	14.7
Diffusion ASTM C1556 (E-12 m2/s) 28-d	3.85	1.75
Cs (ppm)	9915	12841
Cs (ppm) Adjusted for porosity	6213	12841
ASTM C1585 Intitial Absorption (28 Day)	14.33	11.72
ASTM C1585 Secondary Absorption (28 Days)	0.0005	0.0008
ASTM C1585 Intitial Absorption (90 Day)	0.0003	0.0004
ASTM C1585 Secondary Absorption (90 Days)	0.0004	0.0006

The NT Build 492 test method has one advantage over other accelerated test methods in that it cancels out the effects of higher conductivity which would be present if salts, or porous lightweight aggregates were present. It shows that the non-steady state diffusion coefficient is lowered when LW aggregates are used. The chloride front is not as deep for the same potential/current range as chlorides are filling the aggregates and not penetrating as far.

The calculated surface concentration (C_s) is higher for the LW concretes as would be expected given the porous aggregate present. A C_s value adjusted for the aggregate porosity is shown. The values are based upon mass of concrete, so as LW concrete has a lower unit weight, actual chloride content in mass/unit volume are lowered. The porosities and mass corrections will be accounted for in the Life 365 modeling.

The ASTM C1585 Absorption data show that NORLITE LW concrete has lower absorption than NW concrete of the same design. This is in contrast to the higher porosity. The specimens are conditioned in an 85% RH environment at elevated temperature versus above the boiling point of water. The results indicate that at 85% RH that the pores in the aggregates do not absorb moisture quickly. The 85% RH value was chosen for the ASTM method as it results in internal RH values for concretes that are similar to those exposed to environments with deicing or marine salts. Thus, in applications where corrosion is an issue, these tests show that there is a significant reduction in absorption with LW aggregate. This will be accounted for in the Life 365 modeling by increasing the time to reach the maximum chloride concentration at the surface.

The STADIUM transport properties are in Table 6.

Table 6 STADIUM® Transport Data

Transport Property	NC	C
IDC at 28 days (10^{-11} m^2/s)	15.65	14.28
IDC 90 days (10^{-11} m^2/s)	10.66	9.75
MTC at 28 days (10^{-22} m^2)	60.65	10.00
MTC at 90 days (10^{-22} m^2)	46.12	8.68

The MTC values are very high for the LW aggregate concrete. This would normally indicate that they will have much higher sorption propertied than the control, which is not a good property in wetting and drying applications as in bridge and parking decks, or airborne exposures. This was in contrast to the ASTM C1585 absorption data. SIMCO (STADIUM developers) was contacted and this was discussed. The conclusion was that drying at 50% RH might not be representative of the field conditions, and that at higher relative humidity it is harder for water to absorb back into the LW concrete. As noted earlier this is due to more difficulty in reabsorption of water into the lightweight aggregate. It is clear that significantly less water is being absorbed than is indicated by the MTC values. The MTC value for the control mixture will be multiplied by the ratio of the initial absorption of the LW mix to the control mixture to provide a modified MTC for the LW mixture. In most cases as can be seen in Table 9 the LW will have a modified MTC that is equal to lower than that of the control mixture.

Service Life Analysis

Service life analysis was performed for using Life 365 and STADIUM. The Life 365 and STADIUM follow the basic guidelines in fib which is more of a guide. A bridge deck subjected to deicing salts in Detroit was modeled. Typically, a less permeable mixture containing SCMs would be used, but to just show the effects of the LW aggregates the straight OPC concrete mixes at a low w/c were used.

<u>Life 365™ Service Life Analysis</u>

The default values in the Life 365 program for a Detroit urban bridge deck were used for the temperature data. Concrete cover was chosen to be 3 inches as SCMs were not in the mixture and additional corrosion protection was not added. The 28-day ASTM C1556 Bulk Diffusion values in Table 6 were used versus the default values in Life 365 and they were lower. The default rate of chloride ingress was modified for the LW mixes by multiplying the years of buildup for the control by the ratio of the control ASTM C1585 Primary Absorption to the LW Primary Absorption at 90 days. Life 365 doesn't directly address porosity which would lead to higher actual chloride concentrations at all levels, but since this chloride is in the porous aggregates and not the paste, it does not contribute to corrosion, so a correction is not needed for modeling corrosion performance.

Note that NT Build 492 non-steady state diffusion values (shown in Table 6) are two to four times higher than the ASTM C1556 bulk diffusion values. They were not used as they would have given service life results that are too low for the control mixture, based on experience, even with a longer hydration time. However, the NT Build 492 does adjust for the effects of porosity in the aggregates in which chloride enters, but is not bound. Thus the ratio of the NT Build 492 values for the LW aggregate and LW fine mixtures vs. the NT Build 492 values for the control mixture will be used to determine the effective bulk diffusion coefficients for the LW mixtures. The bulk diffusion of the control mixture will be multiplied by this ratio. Values converted to units of in^2/s are given in Table 9.

The diffusion coefficient will decrease in time due to continued cement hydration. The m parameter as defined below is used to develop the relationship of the diffusion coefficient to time. The m values were determined by comparing the ASTM C1760 Bulk Conductivity values at 28 and 90 days and fitting it to the equation:

$$\kappa_{90} = \kappa_{28}(t_{28}/t_{90})^{m},$$

Where κ_t is the conductivity at time *t*, and m is the aging (hydration) coefficient. As the conductivity is directly related to the diffusion coefficient, the m value calculated describes how the diffusion coefficient will decrease in time according to the equation: $D_t = D_{28}(28/t)^m$, where D_t is the diffusion coefficient at time *t*. The default value for m in Life 365 is 0.2 for portland cement. Since only portland cement is present the diffusion coefficient was assumed to become constant after one year based on OPC mixes evaluated in other studies. Longer curing times with could be used to determine if hydration continues for longer periods with lightweight aggregates.

The last correction that needs to be made for Life 365 is to adjust the corrosion threshold levels. Life 365 assumes all the concretes are at the same unit weight. That is not the case so one needs to multiply the chloride threshold level, C_t by the unit weight of the control concrete divided by that of the lightweight concrete. The air dry unit weights were used.

The service life analysis as shown above, requires that a mixture with NW aggregates of the same mixture design as the LW aggregate mixtures be produced so that the effects of the aggregate porosity can be addressed. Table 7 shows the parameters as described above.

Table 7 Parameters Used in the Life 365™ Modeling.

Transport Property	**NC**	**C**
Diffusion ASTM C1556 (E-9 in^2/s) 28-d	4	6
m	0.25	0.30
Hydration Time (Years)	1	1
Maximum Surface Concentration (% mass)	0.85	0.85
Years to Maximum	9.3	6.2
Chloride Threshold (% mass)	0.06	0.05

Service life was defined as 6 years after the onset of corrosion as in Life 365. The resulting service lives are shown in Table 8. Curves for chloride as a function of depth at corrosion initiation (3-inch level) and the concentration at 3-inches are shown in Appendix 2. Note that Life 365 does not adjust for the unit weight so the chloride threshold values on mass of concrete would be higher than shown, hence the increased threshold level. The chloride in the LW aggregates is not included in the total chloride so the actual chloride contents by mass of concrete will be higher than shown in the figures in Appendix 2. The ratio of the porosity before correction to after correction would be related to the total chloride in the concrete.

Table 8 Life 365™ Predictions of Service Life (6 years after corrosion initiation)

Concrete	NC	C
Service Life (years)	41	30

The Life 365 analysis is showing an 37% improvement for the NORLITE LW coarse aggregate mixture. A conservative approach of one year for hydration to continue was used, if it continued longer then the service lives would be higher.

STADIUM Modeling

The IDC and MTC values in Table 6 were used in the STADIUM analysis. The porosity was adjusted to reflect the pastes porosity. As in the Life 365 analysis the threshold values are raised to reflect the lower unit weight of the concrete. Table 9 shows the parameters used in the STADIUM modeling.

Table 9 Parameters Used in STADIUM Modeling

Transport Property	NC	C
IDC at 28 days (10^{-11} m^2/s)	15.65	14.28
Hydration parameter- a	0.38	0.39
Hydration parameter- α (1/s)	0.0040	0.0004
Corrected MTC (10^{-22} m^2)	6.7	10.0
Porosity (%)	8.98	11.72
Maximum chloride at surface mM/L	1000	1000
Chloride Threshold (ppm)	638	500

The hydration parameter “a” is the fraction of the 28-day IDC value that will be reached at the end of hydration (ultimate IDC). The hydration parameter “α” relates to the time to reach the ultimate IDC value with higher values corresponding to less time. Note that the porosity needed to be raised to 10% to conduct the STADIUM run.

The times to spalling and cracking (initiation plus six years for propagation), are shown in Table 10, and the chloride profiles as a function of time are in Figure 1. Note that actual chloride contents in the concrete would be higher as the chloride in the lightweight aggregate is not considered.

Table 10 STADIUM Predictions of Service Life (6 years after corrosion initiation)

Concrete	NC	C
Service Life (years)	42	34

The service life in STADIUM is approximately 7% higher.

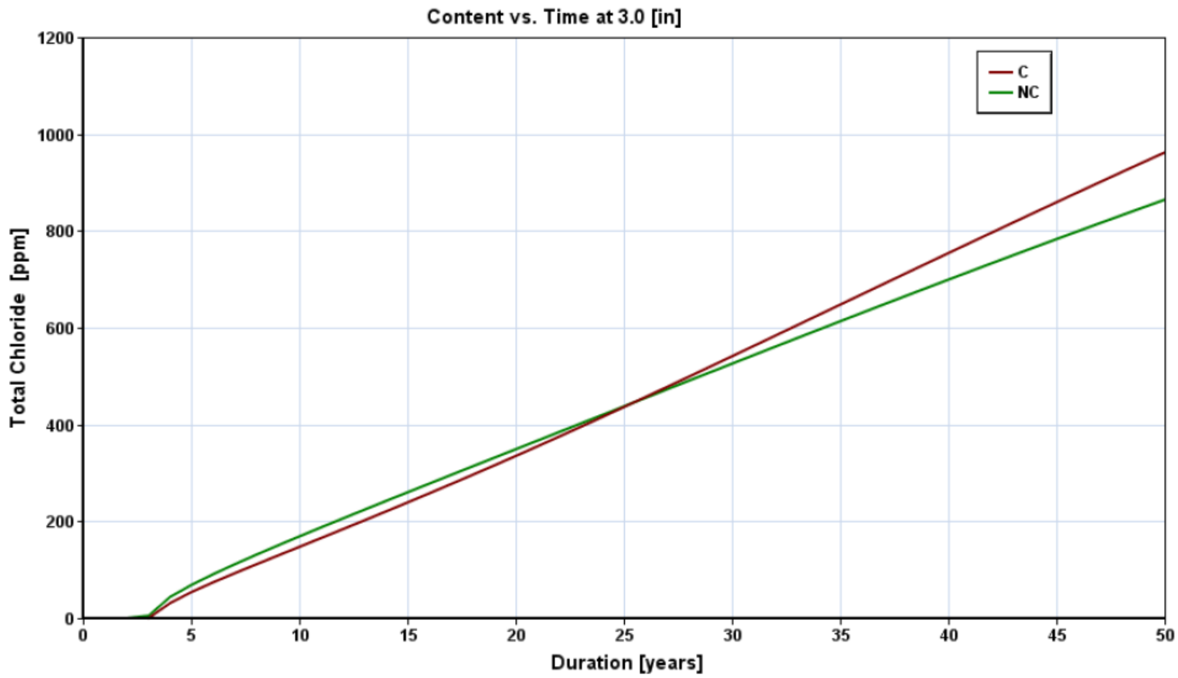


Figure 1 STADIUM curves at 3-inches of cove for Control and NORLITE LW aggregate mixtures for a bridge deck exposure in Detroit, MI.

The predicted times to cracking and spalling are equal to or better than the control concrete for the NORLITE lightweight mix in the STADIUM analysis.

The STADIUM conditions are the same as in the main report.

Summary and Conclusions

Transport properties of concretes with NORLITE LW aggregates were determined versus a control mixture with NW aggregates. The service life performance, of a bridge deck in the Detroit area, was determined using the transport properties determined for use in Life 365™ or STADIUM®.

The STADIUM results showed that that the service life will be slightly increased compared to the control as follows:

- For NORLITE lightweight coarse aggregate mixture by approximately 23%.

Life 365 analysis showed an increase in service life for NORLITE LW coarse aggregate mixture, to about 37%.

To address the effects of aggregate porosity, it was necessary to use several test methods and a comparison to a NW aggregate control concrete of the same mixture design and materials.

In this study, NORLITE LW aggregate concrete increased the compressive strength of concrete compared to NW concrete.

Conductivity tests can be used to determine how permeability changes in time, but higher conductivity (corresponds to higher C1202 rapid chloride permeability), or lower surface resistivity, do not necessarily indicate a higher chloride ingress rate for LW aggregate concrete.

Likewise, the loss of moisture is high in the migration drying tests conducted for STADIUM. However, the reintroduction of moisture at relative humidity found in regions where deicing salts are used, was found to be reduced using the ASTM C1585 absorption test method.

Disclaimer

The results and conclusions are based upon the materials tested and a specific mixture design, the models used, and TCG's engineering judgement. Different mixture designs and materials would be expected to follow the trends found, but validation of the transport properties is recommended, before modeling. The service life models do not address cracking and the analysis is based on repair of cracks greater than 0.004-inch in width.

Sincerely,

Tourney Consulting Group, LLC

Neal S. Berke
Vice President

CC: Vincent Wheeler

Appendix 1 LW Aggregate Properties

3/4 Aggregate

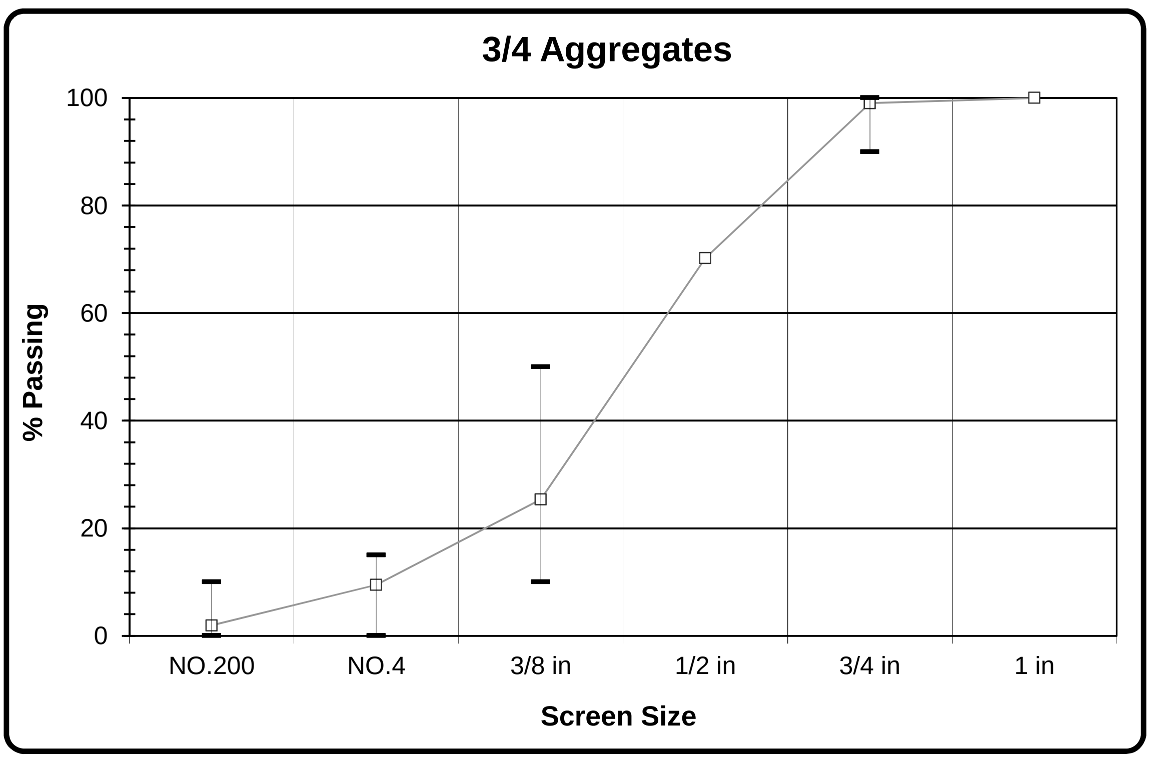
LABORATORY ANALYSIS OF LIGHTWEIGHT AGGREGATE

DATE SAMPLED:	July 12, 2016
TIME SAMPLED:	3:00:00 PM
TRANSPORTER:	Tourney
LAB FILE ID#:	160713f

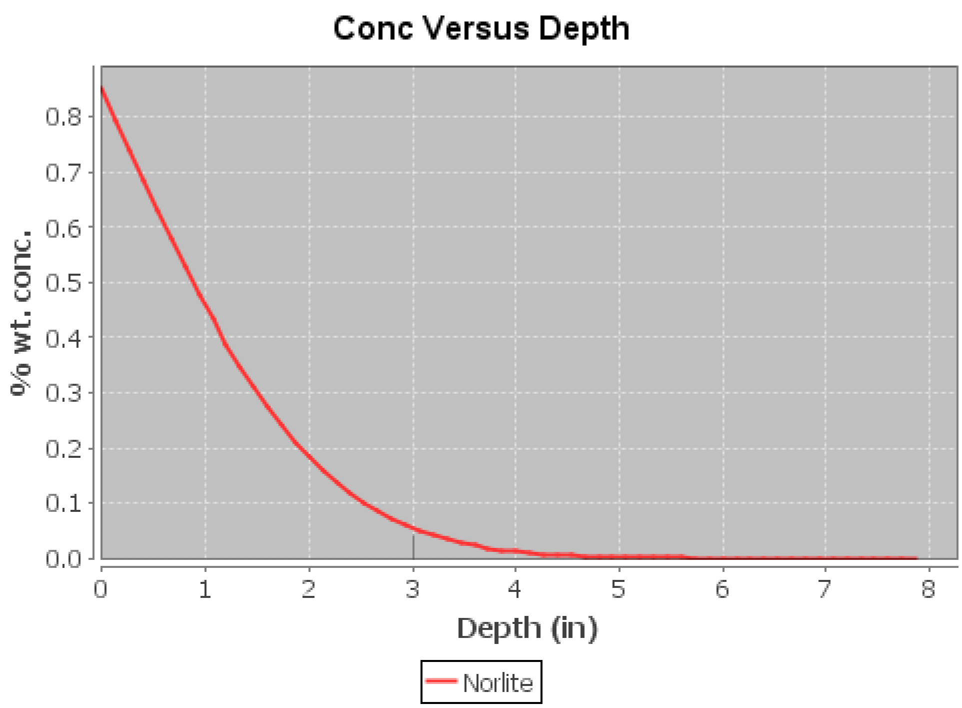
SIEVE SIZE	WT.	% RETAINED	% PASSING	CUM% RETAINED	ASTM C330-04	NORLITE LIMITS	MOISTURE	
1	0.0	0.0	**100.0**	**0.0**	100	100	WET WT.	1000.0
3/4	8.0	1.0	**99.0**	**1.0**	90-100	90-100	DRY WT.	820.0
1/2	236.0	28.8	**70.2**	**29.8**	-	-		
3/8	368.0	44.9	**25.4**	**74.6**	10-50	10-50	**% MOISTURE**	**21.95**
NO. 4	130.0	15.9	**9.5**	**90.5**	0-15	0-15		
NO.200	62.0	7.6	**2.0**	**98.0**	0-10	0-10		
PAN	16.0	2.0						
TOTAL	820.0							

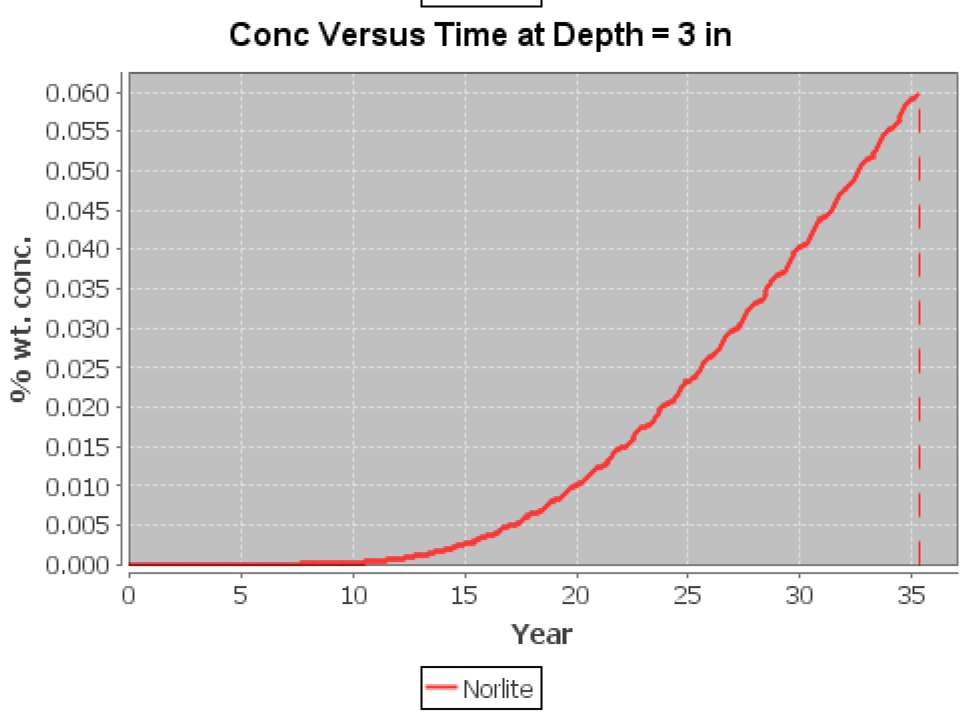
UNIT WEIGHT = MOIST lbs./cu.ft.: 53.01

FM= **6.19**
Target FM= 7.08



Appendix 2 Life 365™ Results


Conc Versus Depth
% wt. conc.
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8
Depth (in)
Norlite


Conc Versus Time at Depth = 3 in
% wt. conc.
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
5
10
15
20
25
30
35
Year
Norlite

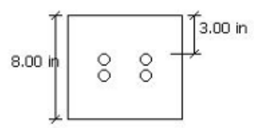
Life-365 v2.2 - Concrete Mixes and Service Lives

Project: Norlite

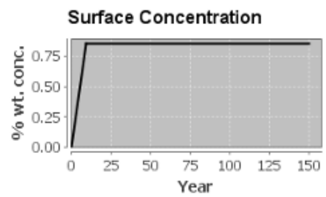
Description: Detroit Bridge Deck

Analyst: Analyst

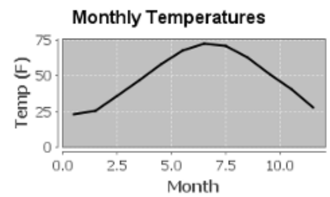
Date: 01/18/2017



slabs and walls (1-D)
Outer dim: 8in; clear cover: 3in



Max surface: 0.850 % wt. conc.
Years to buildup: 9.3



Loc: user-defined
Type: user-defined

Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
Norlite	yes	n/a	n/a	n/a		Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
Norlite	-> 4.00E-9 in*in/sec	-> 0.25	-> 0.06 % wt. conc.	35.2 yrs	-> 6 yrs	**41.2 yrs**

"->" indicates that the user has directly specified this value; "+" indicates the service life exceeds the study period.