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ENHANCED HYDRATION AND PROPERTIES OF SPECIFIED DENSITY CONCRETE

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INTRODUCTION

Five concrete mixtures of varying densities were prepared at the University of New Brunswick on Nov. 19, 1999 to determine strength, density, and degree of cement hydration for each mixture. In addition to determining the mechanical properties, testing for density after various drying regimes was conducted to provide an insight into the degree of cement hydration when part of the normal density coarse aggregate is replaced with rotary kiln produced expanded shale, clay and slate (ESCS) structural grade low density aggregates. This testing program is a pilot investigation for a larger testing program to follow. All testing was done according to ASTM unless otherwise noted.

TESTING PROGRAM

Five air-entrained concrete mixtures of varying densities were prepared to reflect what is normal practice in a precast plant making high performance concrete. The mixtures used cement containing approximately 7% silica fume to have a cement plus silica fume content of approximately 445 kg/m^3 (750 lbs/yd^3) when using a high range water reducer. The normal density coarse aggregates were replaced with low density (ESCS) aggregates by absolute volume as follows:

Mixture	Coarse Aggregate
1	all limestone
2	1/6 ESCS + 5/6 limestone
3	1/3 ESCS + 2/3 limestone
4	2/3 ESCS + 1/3 limestone
5	all ESCS

At 18 hours and 7, 28, 90 and 122 days, 102 x 203 mm (4 x 8 in) cylinders were tested for compressive strength. Additionally, at about 24 hrs, 152 x 305 mm (6 x 12 in) cylinders were also tested for compressive strength and modulus of elasticity.

Concrete density was determined in accordance with ASTM C 567 at 7, 28 and 122 days. This entailed drying some of the cylinders in air and oven drying others. To simulate field curing of the concrete all specimens, not tested at 24 hours, were left in their molds and placed in a sealed plastic bag to prevent moisture loss until stripping on the seventh day. All subsequent curing was in lab air at 23° ± 2° C (73.5 ± 3.5 ° F) and 50 ± 5% relative humidity. When the gain or loss in mass was less than 0.3% in successive weighings 28 days apart, the equilibrium density was determined. To determine the amount of evaporable water, 152 x 305 mm (6⌀ x 12") cylinders were oven dried at 110 ± 5° C (230° ± 3.5°F) until the gain or loss in mass was not more than 0.3% in successive weighings 24 hours apart. The oven dry density was then calculated.

AGGREGATES

Moisture Content, specific gravity and grading of the aggregate used are shown in Table 1.

Table 1
Coarse Aggregate Grading (% passing by mass)

Sieve Size mm	in.	Indiana Limestone	Intermediate ESCS Agg.	Coarse ESCS Agg.
25.4	1	100	100	100
19.0	¾	81	100	100
12.5	½	45	100	83
9.5	3/8	18	97	40
5.0	#4	1.2	19	4.5
2.5	#8	0.4	8	2.5
Moisture content, %		.11	20.1	16.2
24 hour absorption, %		.68	23.3	12.0
Spec. gravity (SSD)		2.69	1.75	1.72

The fine aggregate was a natural sand from the Zealand pit near Fredericton, N.B. with a specific gravity of 2.63 and a 24-hour absorption of 1.00%.

CEMENT

The cement used was a low alkali silica fume cement (meeting CSA Type 10E-SF low alk) which would be similar to an ASTM Type 1 cement to which 7% silica fume has been added.

ADMIXTURES

All mixtures had 1 liter of Master Builders Rheobuild-1000 (non-regulated) superplasticizer added per 100 kg of cement plus silica fume. In addition Master Builders (MBVR) vinsol resin air entraining agent was added to the mixture to obtain the required air content. Both admixtures were diluted in local tap water prior to being added to the mixture.

TABLE 4 CALCULATED AND MEASURED MODULUS OF ELASTICITY AT AGES SHOWN								
Mixture	Age	Density Kg/m^3 (lb/ft^3)	F'_c MPa (psi)	($x10^6$) E_{calc} (ACI 318)	($x10^6$) E_{calc} (c=25)	E (x10) MSRD	E_{calc}/E_{MSRD} (ACI 318)	E_{calc}/E_{MSRD} (c=25)
1	1	2408 (150)	27.6 (4010)	26.4 (3.83)	–	26.6 (3.85)	0.99	–
	90	2344 (147)	56.6 (8210)	36.4 (5.27)	–	32.4 (4.70)	1.12	–
2	1	2260 (141)	24.7 (3580)	22.8 (3.30)	–	23.5 (3.40)	0.97	–
	90	2229 (139)	57.9 (8390)	34.2 (4.95)	–	30.0 (4.35)	1.14	–
3	1	2173 (136)	21.6 (3130)	20.2 (2.93)	–	20.6 (2.99)	0.98	–
	90	2115 (132)	56.1 (8130)	31.1 (4.51)	23.7 (3.43)	23.6 (3.42)	1.32	1.00
4	1	2020 (126)	15.3 (2220)	15.2 (2.20)	–	15.7 (2.27)	0.97	–
	90	1923 (120)	52.8 (7650)	26.2 (3.80)	19.9 (2.89)	21.0 (3.05)	1.25	0.95
5	1	1893 (118)	20.1 (2920)	15.7 (2.28)	–	14.9 (2.16)	1.06	–
	90	1789 (112)	56.4 (8180)	24.4 (3.54)	18.6 (2.69)	18.9 (2.74)	1.29	0.98

Note: Modulus of Elasticity in GPa and (psi x 10^6)

The results shown in Table 4 indicate that the ACI formula ($E_c=33W^{1.5}\sqrt{F'_c}$) is reasonably accurate for all concrete mixtures at the moderate (<4000 psi) strength levels developed at one day. The well documented over estimation of the modulus for concrete with strengths above 5000 psi was also confirmed for strength levels of 8000 psi but is more extreme for mixtures in which the substitution of lightweight coarse aggregate is above 1/3 of the limestone coarse aggregate. ACI 213 "The Guide For Structural Lightweight Aggregate", suggests modifying the coefficient 33 to 31 and 29 for 5000 and 6000 psi lightweight concrete. Calculated moduli using a coefficient of 25 for 8000 psi strength levels with equilibrium densities of 132 lb/ft^3 and lower provides reasonable correlation with measured results.

DENSITY OF CONCRETE (ASTM C 567)

OVEN DRY: Two 152 x 305 mm (6 x 12 in) cylinders from each mixture were tested according to ASTM C 567 Standard Test Method for Determining Density for Structural Lightweight Concrete with the exception that cylinders were moist cured for seven days then dried in laboratory air until time of oven drying. In section 8.3 of this standard the following equation is given for calculating O_m, the measured oven-dry density.

O_m (kg/m^3) = (D x 997) / (F-G)
O_m = measured oven-dry density
D = mass of oven-dry cylinder (kg).
F = mass of saturated surface-dry cylinders (kg). Measured at 7 days.
G = apparent mass of suspended-immersed cylinder (kg). Measured at 7 days.

Values of oven dry density are shown in Table 5.

TABLE 5 DETERMINATION OF CONCRETE DENSITY AT VARIOUS AGES (units in kg/m³ (lb/ft³))									
No.	Fresh Density	Total Water (Dry Materials)	Oven Dried Density @ Age in (days) (1)				Concrete Density after drying in lab air at age 122 days		
			7		28				
			102mm 4x8	152mm 6x12	152mm 6x12		102mm 4x8	152mm 6x12	ASTM 567 (2)
1	2408 (150.5)	195(2213)	2290 (143.1)	2296 (143.5)	2280 (142.5)	2294 (143.4)	2377 (148.5)	2384 (149.0)	2344 (146.5)
2	2260 (141.3)	206(2054)	2150 (134.4)	2165 (135.3)	2168 (135.5)	2184 (136.5)	2261 (141.3)	2269 (141.8)	2229 (139.3)
3	2173 (135.8)	244(1929)	2007 (125.4)	2033 (127.1)	2034 (127.1)	2068 (129.3)	2139 (133.7)	2155 (134.7)	2115 (132.2)
4	2020 (126.3)	292(1728)	1810 (113.1)	1820 (113.8)	1865 (116.6)	1893 (118.3)	1954 (122.1)	1963 (122.7)	1923 (120.2)
5	1893 (118.3)	293(1600)	1685 (105.3)	1685 (105.3)	1734 (108.4)	1760 (110.0)	1822 (113.9)	1839 (114.3)	1789 (111.8)

Notes: (1) Oven dried density @ age in days after moist curing for 7 days and then stored in laboratory air until the time of test.
(2) ASTM C 567 indicates that concrete density obtained from 152 x 304 mm (6 x 12) cylinders will average 40 kg/m³ (2.5 lb/ft³) higher than densities obtained from 14L (0.5 ft³) buckets.

DRYING IN AIR: At 7 days specimens from all mixtures were stripped and weighed. Those not needed for modulus of elasticity and compressive strength were exposed to laboratory air at 23 ± 2 °C and 50 ± 5% relative humidity until the change in mass was less than 0.5% in successive 28 day measurements. The recorded mass was used to determine the equilibrium density in accordance with section 8.2 of ASTM C 567.

E_m (kg/m³) = (A x 997) / (B – C)
E_m = measured equilibrium density, kg/m³
A = mass of cylinder as dried, kg
B = mass of saturated surface-dry cylinders, kg
C = apparent mass of suspended-immersed cylinder, kg

Concrete densities were calculated by assuming that the values of B and C were equal to values of F and G which are given in Table 5. The value of A was obtained by subtracting from F (the saturated surface dry weight at 7 days) the average loss of mass of all similar sized cylinders during the air drying period.

TABLE 6 DETERMINATION OF THE EFFECTIVE W/B RATIO								
Mixture No.	Cement	Water Net	Water Total	W/B (Net)	Water Loss Air Drying @ 122	Water Loss Oven Drying @ 122	Non Evaporable Water	Effective W/B
1	470	186	195	.40	16	94	85	.18
2	454	179	206	.39	26	99	81	.18
3	446	200	244	.45	39	119	86	.19
4	438	215	292	.49	65	130	97	.22
5	438	181	293	.41	63	129	101	.23

Note: All cement and water quantities are reported in kg/m³

The amount of total water in each mixture is shown below:

For Mix 1 155 + 798 x .0485 + 985 x .0011 =195
For Mix 2 171 + 751 x .021 + 90 x .201 + 794 x .0011 = 206
For Mix 3 192 + 736 x .021 + 176 x .201 + 623 x .0011 = 244
For Mix 4 207 + 723 x .021 +346 x . 201 +306 x .0011 = 292
For Mix 5 152 + 744 x .0485 + 559 x .188 = 293

The chemically combined water (i.e. non-evaporable water) was determined at various ages by subtracting from the total water in the mixture, the difference between the fresh density and the oven dry mass. The results are shown in Table 6.

Despite a limited number of specimens, the results in Table 6 show that concretes incorporating lightweight aggregates containing high levels of absorbed water develop a higher non-evaporable water content indicating a substantially improved degree of hydration.

MOISTURE LOSS – DRYING IN AIR

The moisture loss due to drying in air is shown in Table 6. The moisture loss between the time of mixing, and before oven drying was arrived at by subtracting from the fresh density, the density of the concrete as determined on cylinders that were stripped at 7 days. To minimize errors in determining length, the ends of the cylinders were ground prior to measuring their length. Cylinders were weighed to the nearest gram and their diameter and length were measured at the four quadrants to the nearest 0.001 in.

ASTM C 567 suggests that for commercial concretes at usual strength levels (< 4000 psi, < 28 MPa) equilibrium density normally reached in about 120 days could be approximated by an increase of 3 lb/ft³ (50 kg/m³) above oven dry density. However, this investigation shows that equilibrium density was not reached in 122 days using concrete incorporating high volumes of cement and high quality pozzolans that developed extremely low permeability. For this class of concretes a more realistic approximation of equilibrium density would be 100 kg/m³ (6 lb/ft³).

CONCLUSIONS

1. For the materials used in this investigation, it was shown that substitution by absolute volume, of 1/6, 1/3 and 2/3 of the 25-5 mm (1 in - #4) limestone with 9.5-2 mm (3/8 - #8) lightweight aggregate resulted in minimal differences in 28-day compressive strengths
2. As expected, the modulus of elasticity was reduced as the volume of lightweight aggregate was increased. Modifying the ACI 318 modulus formula coefficient form 33 to 25 for the 55 MPa (8000 psi) provided reasonable correlation with measured values.
3. Maintaining the compressive strength values while decreasing the equilibrium density resulted in improving the structural efficiency (strength/density ratio) from approximately 23 to 32.
4. The results of this investigation suggest that the partial replacement of normal density aggregate with low density (lightweight) ESCS aggregate containing absorbed water provide benefits to high performance concrete (HPC) mixtures with low water/binder (w/b) ratio's. The absorbed water provides an internal reservoir to enhanced cement hydration after initial set, significantly extending the time of curing. This process is referred to as internal curing. This is beneficial because the low permeability of low w/b ratio HPC mixtures will limit the access of external curing moisture. Absorbed water is not part of the mixing water and is not calculated as part of the w/b ratio. The enhanced degree of hydration resulting from internal curing will provide a higher quality microstructure and contribute to lower permeability and improved durability.
5. Results of this investigation suggest that the determination of oven dry and equilibrium densities following the procedures of ASTM C 567 "Standard Test Method for Determining Density of Structural Lightweight Concrete" using 152 x 304 mm (6 x 12) may be accomplished with similar precision using 102 x 203 mm (4 x 8) specimens.
6. Concretes containing high volumes of cementitous binder (that include high quality pozzolans) release moisture very slowly. In this investigation equilibrium moisture contents were not reached at 122 days.

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