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Effect of Capping Materials and Procedures on the Measured Compressive Strength of High-Strength Concrete

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ABSTRACT: The effect of end conditions and testing procedures on the measured strength of 100- by 200-mm (4- by 8-in.) concrete cylinders were evaluated. Concretes representing three strength levels: 50, 75, and 120 MPa (7000, 11 000, and 17 000 psi) were prepared. Cylinder end conditions included grinding and capping with two types of sulfur mortar and cement paste. Effect of thickness of capping material was also evaluated.

Cement paste caps produced, on average, 1% higher strengths than ground ends, regardless of concrete strength level and cap thickness. Cylinders capped with sulfur mortar 2 h prior to testing produced 2 to 5% lower strengths than the ground condition. Capping cylinders with sulfur mortar seven days prior to testing produced strengths equivalent to the ground condition, except with thick caps of sulfur mortar on the 120 MPa (17 000 psi) concrete, in which case lower strengths were observed. No significant difference between sulfur mortars was evident, even though one was advertised for use with high-strength concrete.

KEYWORDS: compressive strength tests, capping methods, grinding surface ends, cement paste caps, sulfur mortar caps, high-strength concrete, cap thickness

Increasingly, concrete with compressive strength exceeding 70 MPa (10 000 psi) is being produced and used on a commercial basis. The validity of traditional procedures of testing concrete strength, for quality control or acceptance purposes, of high-strength concrete has been a subject of several recent research studies [1-3]. Richardson [4] and Carino et al. [3], among others, have provided extensive reviews of the literature regarding the variables that influence the determination of compressive strength of conventional and high-strength concrete. This report discusses a portion of a larger study [3] on methods of testing for compressive strength of high-strength and very high-strength concrete. The primary objective in this investigation was to determine the effect of end preparation of test cylinders on measured strength. All cylinders used in this study were 100 by 200 mm (4 by 8 in.) in dimension. Three concrete mixtures were designed to obtain strength levels of 50, 75, and 120 MPa (7000, 11 000, and 17 000 psi). In the ensuing discussion, these are referred to as the 7K, 11K, and 17K concrete mixtures, respectively. Test cylinder ends

were either ground or capped. Capping materials included neat cement paste and two proprietary sulfur mortar capping compounds. Additionally, the capping materials were each used at two thicknesses. This amounted to seven end conditions of cylinders for each strength level.

Experimental Program

Materials

The portland cement used in this study conformed to the Specification for Portland Cement (ASTM C 150) Type I. Additionally, the 17K concrete mixture incorporated a dry-densified form of silica fume. Class C fly ash, water reducing admixture, and high range water-reducing admixture (HRWRA). The characteristics of the cementitious materials are given in Table 1. The characteristics

TABLE 1a—Characteristics of cementitious materials (Series 222C).

Chemical Composition	Cement %	Fly Ash %	Silica Fume %
CaO	64.5	30.2	0.42
SiO ₂	21.2	30.5	97.20
Al ₂ O ₃	4.9	18.5	0.35
Fe ₂ O ₃	3.6	6.3	0.22
MgO	1.0	6.3	0.85
SO ₃	2.3	3.6	...
LOI	1.4	0.4	1.72
Insoluble Residue	0.2	...	...
Na ₂ O eq.	0.2	1.9	0.68
Carbon	...	...	1.59
Compounds, Bogue			
C ₁ S	57		
C ₂ S	18		
C ₃ A	7		

TABLE 1b—Description of ingredients (Series 222C).

Material	Lot Number	Description
Portland cement	7335	ASTM C 150, Type I
Fly ash	7008	ASTM C 618, ² Class C
Silica fume	7338A	dry densified
Water reducer	7344	ASTM C 494, ² Type A
HRWRA	7343	ASTM C 494, ² Type F

²ASTM C 618, Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete; ASTM C 494, Specification for Chemical Admixtures for Concrete.

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of the fine and coarse aggregates used in the concrete mixtures are given in Table 2.

Test Procedures

Table 3 summarizes the variables in the test series, and number of 100 by 200 mm (4 by 8 in.) cylinders made.

The composition and properties of the three concrete mixtures used are given in Table 4. Concretes were mixed in 0.064-m³ (2.25 ft³) batches in a 0.1-m³ (3.5 ft³) revolving drum mixer. The 3-3-2 mixing sequence, as specified in the Practice for Making and Curing Concrete Test Specimens in the Laboratory (ASTM C 192), was used to mix the 7K and 11K concrete batches. Based on prior experience with mixtures with high cementitious content, the mixing procedure outlined in ASTM C 192 was modified as follows.

1. The coarse aggregate, silica fume, and some of the mixing water was mixed for 5 mins.
2. The damp fine aggregate was batched followed by cement, fly ash, and water. Water reducer was batched on the fine aggregate.

TABLE 2—Characteristics of aggregates (Series 222C).

Coarse Aggregate		Lot No. 7336, Traprock, Mannassas, VA	
Absorption		0.9 %	
Bulk dry Sp.Gr.		2.90	
Dry Rodded Unit Weight		1719 kg/m ³ (107 lb/ft ³)	
Gradation, Percent Passing			
Sieve, mm	7K & 11 K	17K	
19.0 (3/4 in.)	100%	--	
12.5 (1/2 in.)	63%	--	
9.5 (3/8 in.)	39%	100%	
4.75 (No. 4)	0%	0%	
Fine Aggregate		7K & 11 K	17K
Lot No.		7390	7336
Description	Natural Sand	Crushed Traprock (washed)	
Absorption	0.81 %	0.91 %	
Bulk dry Sp.Gr.	2.59	2.90	
Fineness Modulus	2.60	3.72	
Gradation, Percent Passing			
Sieve	7K & 11 K	17K	
9.5 mm (3/8 in.)	100.0	100.0	
4.75 mm (No. 4)	98.3	100.0	
2.36 mm (No. 8)	85.6	59.2	
1.18 mm (No. 16)	72.6	33.4	
600 μm (No. 30)	55.6	20.1	
300 μm (No. 50)	22.0	11.1	
150 μm (No. 100)	5.4	3.8	
75 μm (No. 200)	1.2	1.3	

3. Concrete was mixed and HRWRA was added in small increments until the desired consistency was obtained. After all the ingredients were in the mixer, the 3-3-2 mixing sequence was followed.

The gravimetric air content of the 17K batches was relatively high at 4.5 to 5% (Table 4). The increased entrapped air content of these batches was also evident in the densities of the hardened cylinders. This concrete mixture tended to be extremely cohesive due to the high admixture and cementitious materials content. The tendency of these mixtures to entrap air, when mixed in a laboratory drum mixer, has been consistently observed.

As noted in Table 3, thirty-two 100- by 200-mm (4 by 8 in.) cylinders were molded from each concrete batch. Batches for the three strength levels in Round A were mixed on the same day. The batches in Round B were mixed on the next day. Two operators filled molds in three layers and two other operators consolidated concrete in the cylinders with a 10-mm (3/8 in.) rod. The first layer in all the molds was filled prior to filling the second layer. The sequence in which individual molds were filled was randomized in an attempt to reduce variability between specimens.

The molded cylinders were transferred to a curing tank and submerged in 21°C (70°F) water for the initial curing period. The cylinder molds for the 7K and 11K concretes were stripped after 24 h. Due to the relatively large doses of chemical admixtures in the 17K concrete batch, the removal of the molds was delayed to 48 h. Often, high-performance concretes with increased admixture contents will tend to set slowly and removal of molds should be postponed to after two days or later.

The plastic molds were stripped with a commercially available stripping tool. The tool is essentially a 330-mm (13 in.) screwdriver type device with a 6.4-mm (1/4 in.) cutting blade at a right angle to the driver blade. To our knowledge, the potential damage to cylinders cast in plastic molds, caused by a stripping tool, and its effect on measured strength has not been investigated.

Demolded cylinders were assigned random numbers from 1 to 32 that determined the end preparation that would be applied in the experiment. The cylinders were subsequently cured in a moist room at 23°C (73°F).

At an age of three days, the density of the hardened concrete cylinders was determined by weighing in air and immersed in water. Test cylinders with significantly different densities (exceeding ± 2 standard deviations about the average) were replaced with one of the three extra cylinders made for that purpose. This was done to ensure that the specimens used in the study were alike and the within batch variability of the strength results was small enough so as to detect significant effects of the cylinder end preparation on measured strength.

TABLE 3—Summary of test variables and number of specimens (Series 222C).

Concrete Strength, MPa (psi)	End Condition		Batches, rounds	Number of Cylinders	
	Material	Thickness, mm (in.)		per Condition	per Batch
50 (7000)	Grinding	...	A	3	32 ^a
75 (11 000)	Cement Paste	1.6, 6.4, (1/16, 1/4 in.)	B		
120 (17 000)	Sulfur 1	1.6, 4.8, (1/16, 3/16 in.)			
	Sulfur 2	1.6, 4.8, (1/16, 3/16 in.)			

^a21 cylinders for 7 end conditions, 8 cylinders to check strength trends (2 at each of 4 ages). Three extra cylinders were made to replace specimens with low or high density, prior to capping.

TABLE 4—Composition and properties of concrete (Series 222C).

Ingredient, kg/m ³	7K Batch		11K Batch		17K Batch	
	A	B	A	B	A	B
Cement	323 (545)	...	451 (760)	...	534 (900)	...
Silica fume	...	...	...	...	59 (100)	...
Fly ash	...	...	...	...	89 (150)	...
Coarse aggregate	1128 (1900)	...	1093 (1842)	...	885 (1491)	...
Fine aggregate	877 (1477)	...	763 (1286)	...	815 (1374)	...
Water	161 (272)	...	172 (289)	...	164 (276)	...
Water-reducing, mL/kg cement (fl.oz./cwt)	...	...	...	...	3.3 (5)	...
HRWRA, mL/kg cem (fl.oz./cwt) W-C or W/(C + P)	0.50	...	0.38	...	32.5 (50)	0.24
Properties/Round	A	B	A	B	A	B
Slump, mm (in.)	80 (3.25)	75 (3.0)	145 (5.75)	145 (5.75)	17 (62)	17 (63)
Temperature, °C (°F)	16 (60)	17 (63)	16 (60)	17 (62)	2502 (156.2)	2488 (155.3)
Unit wt, kg/m ³ (lb/yd ³)	2462 (153.7)	2472 (154.3)	2493 (155.6)	2493 (155.6)	4.4	5.0
Gravimetric air, %	1.8	1.4	1.5	1.5	...	...
Average cylinder density at three days, kg/m ³ (lb/yd ³)	2490 (155.4)	2493 (155.6)	2522 (157.4)	2517 (157.1)	2538 (158.4)	2538 (158.4)

TABLE 5—Compressive strength of neat cement paste cubes (Series 222C) (W-C ratio 0.32).

	1 day	7 day	14 day	28 day
Cube 1, MPa	32.6	81.4	95.3	102.4
Cube 2, MPa	33.0	85.3	101.7	107.7
Average, MPa (psi)	32.8 (4750)	83.4 (12 090)	98.5 (14 290)	105.1 (15 240)

TABLE 6—Compressive strength of sulfur mortar cubes (Series 222C).

	Sulfur SM1, Lot 7269				
	2 h	6 h	1 day	7 days	28 days
Cube 1, MPa	46.7	47.9	49.6	84.5	85.2
Cube 2, MPa	47.5	47.6	49.7	78.1	84.3
Average, MPa (psi)	47.1 (6833)	47.8 (6930)	49.7 (7205)	81.3 (11 788)	84.7 (12 288)
	Sulfur SM2, Lot 7368				
	2 h	6 h	1 day	7 days	28 days
Cube 1, MPa	64.3	65.7	81.7	92.2	90.5
Cube 2, MPa	61.5	67.9	81.0	89.7	...
Average, MPa (psi)	62.9 (9125)	66.8 (9688)	81.4 (11 800)	91.0 (13 195)	90.5 (13 125)

Cylinder End Preparation

Grinding—Grinding was done on a Blanchard cylindrical grinder at the National Institute of Standards and Technology (NIST). This machine is typically used to grind engine blocks, cylinder heads, and other large surfaces, where the flatness requirement is about 0.05 mm (0.002 in). It leaves a swirl pattern on metal but worked well on concrete cylinders. Cylinders were transported to NIST, immersed in saturated lime water, and the ends were ground when the specimens were 18 days of age. The ends of cylinders designated for cement paste or sulfur caps were not ground.

Cement Paste Caps—Preliminary mixtures of cement paste were prepared at 0.36 and 0.32 W-C ratios. The pastes were mixed in a mortar mixer and were remixed at periodic intervals for approximately 3 h. It was decided to use cement paste at a 0.32 W-C ratio. The 0.36 W-C ratio paste at 3 h was somewhat too stiff to leave streaks in the cap. Six 50-mm cubes were prepared from the 0.32 W-C ratio cement paste. Table 5

summarizes the age-strength data of the cement paste. Cement, Lot 7335, used for the concrete batches, was used for the cement paste caps.

To provide a template for capping, a 100-mm (4 in.) deep, vertically sliced top of a 100-mm (4 in.) diameter plastic cylinder mold was used as a sleeve to wrap around one end of the cylinder and it was held snugly in place with a 100-mm (4 in.) hose clamp. The protrusion of the mold above the top of the cylinder was adjusted, using spacers, to either 1.6 or 6.4 mm ($1/16$ or $1/4$ in.) to receive the paste for the cap. A mound of paste was placed on the top surface of the cylinder to be capped and a plane machined steel plate was slowly lowered until paste escaped over the top of the mold. The plate was carefully oiled to minimize adhesion. At 24 h, a light tap on the edge of the plate parallel to the plane of the cap was sufficient to release the plate from the hardened cement paste cap. The top end was capped seven days before testing and the bottom end six days before testing.

Sulfur Caps—Two commercially available sulfur mortars were used. Sulfur SM1 was a regular type typically used for testing

TABLE 7—Effect of capping on strength (Series 222C).

Condition Date Tested	Batch 7K Strength, MPa (psi)			Batch 11K Strength, MPa (psi)			Batch 17K Strength, MPa (psi)		
	A	B	Average	A	B	Average	A	B	Average
	03/29	03/30		04/07	04/08		06/01	06/02	
Ground	49.90	48.42		78.2	74.3		x	116.1	
	49.19	49.13		76.6	75.9		113.5	118.3	
	48.53	48.21		75.7	74.7		112.8	113.4	
Average	49.2	48.6	48.9 (7092)	76.8	75.0	75.9 (11008)	113.1	116.0	114.6 (16618)
% of Ground			100.0%			100.0%			100.0%
Cement Paste 1.6 mm thick (1/16 in.)	49.76	47.92		77.1	75.6		122.1	113.0	
	49.13	50.07		77.4	77.4		116.5	109.9	
	49.38	48.88		76.4	75.2		121.7	111.7	
Average	49.4	49.0	49.2 (7135)	77.0	76.0	76.5 (11094)	120.1	111.6	115.8 (16802)
% of Ground			100.6%			100.8%			101.1%
Cement Paste 6.4 mm thick (1/4 in.)	51.55	49.80		75.2	77.9		x	116.8	
	49.73	48.80		76.2	75.8		112.4	115.2	
	49.05	49.16		x	76.8		115.4	113.5	
Average	50.1	49.3	49.7 (7206)	75.7	76.8	76.3 (11061)	114.0	115.2	114.6 (16622)
% of Ground			101.6%			100.5%			100.0%
Sulfur SM1 1.6 mm thick (1/16 in.)	47.95	49.51		77.2	76.5		120.4	114.1	
	48.99	47.17		77.6	77.9		115.9	114.7	
	46.67	47.00		76.4	75.1		116.0	117.1	
Average	47.9	47.9	47.9 (6945)	77.1	76.5	76.8 (11136)	117.5	115.3	116.4 (16884)
% of Ground			97.9%			101.2%			101.6%
Sulfur SM1 4.8 mm thick (3/16 in.)	44.82	47.06		73.3	76.6		103.7	113.8	
	45.65	47.11		75.2	77.8		107.5	113.5	
	41.59	47.60		76.9	74.8		111.9	110.7	
Average	44.0	47.3	45.6 (6620)	75.1	76.4	75.8 (10989)	107.7	112.7	110.2 (15986)
% of Ground			93.3%			99.8%			96.2%
Sulfur SM2 1.6 mm thick (1/16 in.)	47.28	45.80		73.9	76.7		118.0	115.9	
	48.61	47.48		73.9	76.9		120.2	118.0	
	48.98	47.27		76.0	76.1		116.9	117.7	
Average	48.3	46.9	47.6 (6900)	74.6	76.5	75.6 (10957)	118.4	117.2	117.8 (17089)
% of Ground			97.3%			99.5%			102.8%
Sulfur SM2 4.8 mm thick (3/16 in.)	48.86	45.86		74.5	78.2		x	113.4	
	47.24	47.44		77.6	73.2		104.7	112.2	
	44.55	45.42		76.9	77.3		112.4	114.0	
Average	46.9	46.2	46.6 (6753)	76.3	76.2	76.3 (11061)	108.6	113.2	110.9 (16089)
% of Ground			95.2%			100.5%			96.8%
Average	48.0	47.9	47.9 (6950)	76.1	76.2	76.2 (11045)	114.6	114.5	114.5 (16612)
Number	21	21		20	21		18	21	
Std. Dev. ¹	2.27	1.31	1.85 (269)	1.38	1.34	1.36 (198)	5.34	2.35	4.01 (582)
Coef Var, %	4.72%	2.74%	3.87%	1.82%	1.76%	1.79%	4.66%	2.05%	3.50%
Max	51.6	50.1		78.2	78.2		122.1	118.4	
Min	41.6	45.4		73.3	73.2		103.7	109.9	
(Avg. - 3 SD)	41.2	43.9		71.9	72.2		98.6	107.4	

x - Outliers

¹ Standard deviation of all 18 to 21 cylinders tested.

1 MPa = 145.0 psi

TABLE 8—Within-test coefficient of variation (Series 222C).

Concrete Batch	Round, %		Average, %
	A	B	
7K	2.92%	1.88%	2.46%
11K	1.61%	1.90%	1.76%
17K	2.72%	1.44%	2.17%
Average			2.13%

normal-strength concrete. Sulfur SM2 was advertised as a high-strength sulfur mortar for use when testing high-strength concrete. Age-strength data for 50-mm (2 in.) cubes of the sulfur mortars are given in Table 6.

The desired cap thickness was obtained by attaching a stop around the cylinder that allowed the specimen to be lowered into the molten sulfur to a predetermined position. A few 6.4-mm ($1/4$ in.) voids at the interface of the cylinder and the cap were formed as the sulfur hardened. These voids in the capping material only occurred with the thick caps and were observed after the specimens were tested. The 7K concrete cylinders were capped 2 h prior to testing, to represent what is thought to be normal practice. The 11K and 17K concrete cylinders were capped seven days prior to testing for strength.

Strength Tests—The rate of strength development of concretes was monitored by testing extra cylinders prepared for the purpose. It was decided to test a concrete batch when the strength was approximately at the desired level. The 7K, 11K, and 17K batches were tested at ages of 28, 37, and 92 days, respectively.

Prior to testing, the dimensions of the cylinders were measured. The planeness of the top and bottom surfaces of the ground ends and caps were measured to 0.0025 mm (0.0001 in.), using a device assembled at NIST. No cap or ground end was out of plane by more than 0.0225 mm (0.0009 in.). The testing machine capacity was 1334 kN, (300 000 lb) and the loading rate was within the prescribed requirements of the Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM C 39).

Discussion of Test Results

Principal Results

Table 7 is a summary of test results after elimination of four cylinder tests that were considered outliers. The outliers are discussed further in a later section. The table includes individual cylinder strengths, and averages and standard deviations of end conditions, batches, and replicate rounds. The relative strengths of each condition are compared to the ground condition (100%) for each concrete strength level.

Since three cylinders represent a test result for each end condition, a within-test coefficient of variation can be calculated for each of the seven end conditions in the six batches of concrete. The seven within-test coefficients of variation for a concrete batch were pooled to obtain an "average" within-test coefficient of variation for each concrete batch. These values are given in Table 8 and are different from the coefficient of variation for 21 cylinders in the batch given in Table 7. An average within-test (from three cylinders with the same end condition) coefficient of variation for different conditions and strength levels is 2.13%.

Since the average strengths for each condition in Table 7 are the result of averaging results from either five or six cylinder

values, differences of about 2% from the ground end condition are statistically significant differences, at $\alpha = 0.05$. The following observations can be made.

1. Neat cement paste caps tended to give strengths about 0.5 to 1.6% higher than grinding, but this is not of either practical nor statistical significance. No significant effect of cap thickness, with cement paste, was evident.
2. For the 7K concrete cylinders, which were capped with sulfur 2 to 4 h before testing, strengths were reduced 2 to 3% with thin caps and 5 to 7% with thicker caps. The 2 h 50-mm (2 in.) cube strengths for sulfur mortars SM1 and SM2 were 47.1 and 62.9 MPa (6833 and 9125 psi), respectively, compared to the concrete strength of 48 MPa (6950 psi).
3. When sulfur caps were applied seven days before testing, and cap thickness was at 1.6 mm ($1/16$ in.) (thin caps), both capping materials performed quite well on both 11K and 17K concretes. In fact, they tended to give somewhat higher strengths than ground ends. However, this is of doubtful statistical significance. The relative difference between the two sulfur mortars was not statistically significant for either thin or thick caps.
4. Among the cylinders that were capped with sulfur seven days prior to testing, 3 to 4% lower strengths were observed only with 4.8-mm- ($3/16$ in.) thick caps on 17K concrete. At seven days age, 50-mm (2 in.) cube strengths for sulfur mortars SM1 and SM2 were 81.3 MPa (11 788 psi) and 91.0 MPa (13 195 psi), respectively, compared to the average concrete strength of 115 MPa (16 600 psi).

What Does Cube Strength of Capping Material Indicate?

Results of this study show that the compressive strength of 50-mm (2 in.) cubes of capping materials is not very useful in determining whether the capping material will perform adequately when testing concrete. For instance, the cement paste used for capping had a seven-day cube strength of 83.4 MPa (12 090 psi). Both cap thicknesses performed as well as the ground condition on all the strength levels up to 115 MPa (16 600 psi).

For sulfur mortar cubes, the rate of cooling differs through the depth of the cube. This difference probably results in a different microstructure between the surface and the interior and possibly effects the strength of the cube. The microstructure of a cube is possibly different from that of a thin sulfur cap.

The sulfur mortars achieved 2 h cube strengths of 47.1 and 62.9 MPa (6830 and 9130 psi), respectively, compared to the strength of the 7K concrete at about 48 MPa (6950 psi). However, the measured strength of the 7K concrete cylinders capped with sulfur at 2 h was lower compared to cylinders with ground ends, regardless of the type or thickness of the sulfur caps.

At seven days, the two sulfur mortars had cube strengths of 81.3 and 91.0 MPa (11 790 and 13 200 psi), respectively. Measured cylinder strengths of 76 (11 000 psi) and 115 MPa (16 950 psi) capped with sulfur mortar were not less than the ground condition, except with 4.8-mm ($3/16$ in.) thick caps on the 115 MPa (16 600 psi) concrete.

Although the failure mechanism is not clear, it appears that if cylinders are capped six or seven days before testing, both the sulfur mortars were adequate to test concrete strengths up to 115 MPa (16 600 psi), provided the caps are very thin. To ensure the cap thickness is uniformly maintained at less than 3.2 mm, ($1/8$ in.) (as required in ASTM C 39), will require that the cylinder ends are relatively smooth before capping. From these tests, it

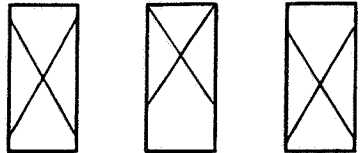
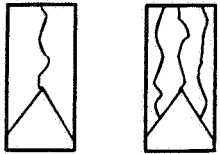
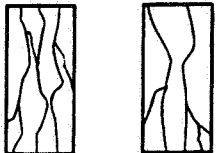
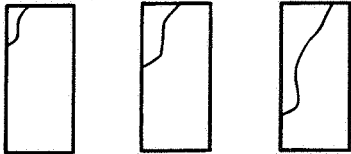
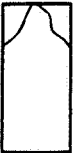

TABLE 9—Outliers in Round A, 17K concrete batch (Series 222C).

Condition	Cyl. No.	Break Type	Planeness,* 0.0025 mm		Specific Gravity	Strength, MPa	Within-Test Std dev.	Outlier
			top	bot				
Ground	1	1	9	8	2.544	x	0.54	97.4
	2	1	2	5	2.539	113.6		
	3	1	6	4	2.537	112.8		
					2.5399	113.2		
Cement Paste 1.6 mm thick	4	1	6	9	2.545	122.1	3.11	
	5	1	4	5	2.534	116.6		
	6	1	9	8	2.535	121.8		
					2.5382	120.2		
Cement Paste 6.4 mm thick	7	6	5	6	2.537	x	2.13	98.4
	8	1	5	8	2.541	112.5		
	9	1	9	7	2.535	115.5		
					2.5375	114.0		
Sulfur 1 1.6 mm thick	10	2	6	9	2.541	120.5	2.57	
	11	3	6	4	2.535	116.0		
	12	3	3	3	2.535	116.1		
					2.5371	117.5		
Sulfur 1 4.8 mm thick	13	5	9	6	2.545	103.7	4.12	
	14	5	2	3	2.533	107.6		
	15	5	5	5	2.542	112.0		
					2.5398	107.7		
Sulfur 2 1.6 mm thick	30	1	4	6	2.540	118.1	1.69	
	17	2	6	4	2.546	120.3		
	18	1	6	5	2.547	117.0		
					2.5443	118.5		
Sulfur 2 4.8 mm thick	19	3	4	5	2.543	x	5.44	94.2
	20	3	5	4	2.534	104.8		
	21	3	4	9	2.538	112.5		
					2.5382	108.7		
Avg. No.			5.47	5.85		114.6	3.12	
Std Dev						18		
Coef. Var., %						5.34		
Max						4.7%		
Min						2.7%		
Avg. - 3 std Dev						122.1		
						103.7		
						98.6		

1 MPa = 145.0 psi

*Max deviation out of plane, average of three directions on capped or ground ends

TABLE 10—Description of cylinder break types (Series 222C).

Designation	Break Type	Description
1		Two cones, reasonably well formed, with no fractures through the cap larger than 1 inch
2		One well-formed cone with no significant break through that cap. The other end has major breaks through the cap and a poor or no significant cone is formed.
3		No well-formed cones and major fractures through both caps or ends
4		Side breaks at top or bottom
5		Similar to No. 4, but pointed. If apex of cone is 1 or 2 inches from end, then classify it as No. 2
6		Diagonal break with no significant fracture through the cap. Tap with hammer to be sure this is not a No. 1 type break

appears that sulfur caps on concrete cylinders at a 48 MPa (6950 psi) strength level should be applied at a period that exceeds 2 to 4 h before testing.

Additional tests are needed to more accurately determine the required characteristics of sulfur capping materials to assure proper test results.

Why Were There Outliers?

Table 9 provides data for individual cylinders, made from Batch A of the 17K concrete. In this group of 21 cylinders, three cylinders were considered outliers. The criteria used was to calculate the standard deviation of the 21 cylinder strengths and disregard those that differed from the average by more than three standard deviations. Other statistical tests and criteria would suggest similar treatment.

When this criteria was applied to the five other batches of concrete, only one additional cylinder result was discarded. The outliers are the three values in the far right column of Table 9. The cylinder densities were normal. Except for the ground cylinder 1, the planeness of the capped surface was normal and there was no systematic effect of planeness on measured strength in any given group.

The type of break was rated with a number ranging from 1 to 6 (Table 10).³ Generally, a higher number indicates fractures through the ends of the cylinders. Cylinder 7 (an outlier) had the most unusual fracture. Cylinders 13 to 15 tended to have higher numerical break types and had marginally lower strengths. Generally, thick sulfur mortar caps tended to have more unusual breaks and lower strength on this 17K concrete batch.

The inevitable question is whether significantly low cylinder strengths or outliers can be expected when testing high-strength concrete? Does testing high-strength concrete need additional attention to detail and are tolerances of procedures outlined in the test methods adequate? Perhaps the 17K batch in this study set slowly and was damaged when these cylinders were stripped with the tool discussed earlier. Tests are needed to determine if this is possible.

³National Ready Mix Concrete Association (NRMCA) Joint Research Lab Series J159B, Tests of Neoprene Capping Procedures, 1982)

Conclusions

1. Capping the ends of test cylinders with neat cement paste caps, with a 50-mm cube strength of 85 MPa (12 000 psi), resulted in measured strengths equal to cylinders with ground ends for concrete with strengths up to 120 MPa (17 000 psi). This was true for cap thicknesses of 1.6 and 6.4 mm ($1/16$ or $1/4$ in.).
2. Two types of sulfur mortar caps applied 2 to 4 h before testing resulted in lower measured strengths for 50 MPa (7000 psi) concrete. The reduction in strength was 2 to 3% with 1.6-mm- ($1/16$ in.) thick caps and 5 to 7% with 4.8-mm- ($3/16$ in.) thick caps. Cube strengths of the sulfur mortars at 2 h were not significantly lower than the strength of the concrete tested.
3. When these two sulfur mortars were applied six or seven days before testing on 75 MPa (11 000 psi) concrete, both performed satisfactorily at both cap thicknesses. On 120 MPa (17 000 psi) concrete, sulfur-cap thickness at 4.8 mm ($3/16$ in.), which exceeds ASTM C 39 requirements of 3.2 mm ($1/8$ in.), resulted in lower measured strengths. The 50-mm (2 in.) cube strengths of the Sulfur Mortars 1 and 2, at seven days, were 81.3 and 91.0 MPa, (11 800 and 13 200 psi), respectively.
4. There was no significant difference between the two sulfur-capping materials when applied six to seven days prior to testing.

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