Pergamon

Cement and Concrete Research 32 (2002) 1545–1550

CEMENT AND CONCRETE RESEARCH

Effects of end conditions on compressive strength and static elastic modulus of very high strength concrete

Mehmet Gesoğlu, Erhan Güneyisi, Turan Özturan*

Department of Civil Engineering, Boğaziçi University, 80815, Bebek, İstanbul, Turkey

Received 18 April 2001; accepted 15 April 2002

Abstract

The use of bonded and unbonded caps in testing very high strength concrete cylinders has been investigated experimentally. A hundred and ninety-two concrete cylinder specimens of 150-mm diameter and 300-mm height were cast and tested using packing with softboard, neat cement paste, neoprene pad and sulfur mortar. The design strength level of 75–100 MPa was achieved using water-cementitious material ratios of 0.22, 0.26 and 0.31. The results of the study were compared considering compressive strength and static elastic moduli values. A two-way analysis of variance was performed at a .01 level of significance in order to compare the effect of end conditions. It was found that the overall mean compressive strengths of specimens capped with neat cement paste, neoprene pad sulfur mortar were not significantly different. The packed specimens exhibited a significant difference from the others. On the other hand, there was no statistical difference in the static elastic moduli values when different capping types were used. Several modulus prediction equations were also examined. Experimental values were consistently higher than the predicted values.

Keywords: Capping type; Compressive strength; Elastic moduli; High-performance concrete

1. Introduction

As the application of high strength concrete has increased in the construction of high-rise buildings, bridges, offshore structures, etc., more care has been needed in applying standard testing procedures, developed for normal strength concrete, to high strength concrete. Previous studies have indicated that the end conditions of the specimens and properties of the materials used for the end preparations have significant effects on the measured strengths [1–5]. Current ASTM standards for testing of concrete cylinders require that the end of compression test specimens be plane to within 0.05 mm. Otherwise, the cylinders need to be capped according to ASTM C617-94 [6], or they may be sawed or ground to meet that tolerance. Alternatively, unbonded caps can be used according to ASTM C1231-93 [7] for concrete strength < 50 MPa.

The use of unbonded capping systems gives comparable results to those of traditional sulfur based caps [3,8]. Carrasquillo and Carrasquillo [3] used neoprene pads in steel caps and polyurethane pads with aluminum caps. Specimens capped with neoprene and polyurethane pads had strengths, which were, on the average, 1% and 3% higher than sulfur-capped specimens, respectively. In the study of Crouch and Pearson [1], an experimental program was developed to assess the difference in static elastic modulus between sulfur mortar and neoprene pad capping methods. The results showed that neoprene pad capping had similar results to sulfur capping in regard to modulus of elasticity, and no practical significance is thought to exist. Richardson [2] compared the compressive strengths of concrete cylinders capped with neoprene pad restrained by aluminum caps to compressive strengths of cylinders capped with the traditional sulfur mortar compound. It was found that although neoprene caps gave significantly different results from the sulfur caps for several testing variables, the results were not significantly different from the mean of the sulfur-capped specimens when proper ASTM procedures were followed for molding and testing cylindrical specimens.

* Corresponding author. Tel.: +90-212-3581540 to 1450; fax: +90-212-2872457.

E-mail address: ozturan@boun.edu.tr (T. Özturan).

0008-8846/02/$ – see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0008-8846(02)00826-8

Table 1
Aggregate properties

	Fine aggregate	Coarse	Aggregate
Sieve size (mm)	Sand	No. I	No. II
31.5	100	100	100
16	100	66.0	2.20
8	100	23.5	0.80
4	97.6	0.60	0.10
2	75.8	0.30	0.10
1	62.6	0.20	0.10
0.5	43.2	0.20	0.10
0.25	9.0	0.20	0.10
Fineness modulus	2.55	5.09	5.97
Specific gravity	2.55	2.92	2.91
Absorption (%)	0.8	0.66	0.60

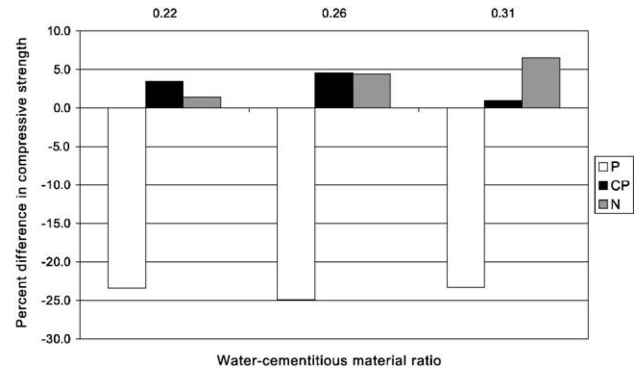

Fig. 1. Average percent difference with respect to the compressive strength of sulfur-capped specimens.

Table 2
Mix design for 1 m^3 concrete

Water/cement ratio (w/c)	0.25	0.30	0.35
Water/cementitious material ratio (w/cm)	0.22	0.26	0.31
Type I Portland cement (kg)	550	500	450
Water (kg)	138	150	158
Crushed limestone no. I (kg)	626	635	669
Crushed limestone no. II (kg)	716	727	766
Sand (kg)	388	394	415
Silica fume (%)	15	15	15
High-range water-reducing admixture (%)	4	3	2
Typical slump (cm)	10 ± 2	12 ± 2	12 ± 2

The main objective of the study presented here is to investigate the effects of capping concrete cylinder specimens with neat cement paste, neoprene pad, sulfur and packing with softboard on both compressive strength and static modulus of elasticity of concretes with strength varying from 75 to 100 MPa. The test results were evaluated statistically through two-factor analysis (two-way ANOVA) at a .01 level of significance and a regression model was proposed in regard to compressive strength and modulus of elasticity for three capping types.

2. Experimental details

Tests were performed on large number of specimens belonging to three different concretes with water-cementitious material ratios of 0.22, 0.26 and 0.31. Cylinder test specimens with 150-mm diameter and 300-mm height had four different end conditions such as packing with softboard, neat cement paste capping, neoprene pad capping and traditional sulfur capping. Specimens were tested for compressive strength and static modulus of elasticity. The end conditions of the specimens conformed to the requirements of ASTM C617-94 for bonded and ASTM C1231-93 for unbonded capping systems.

Same materials were used for all concrete batches. Type I Portland cement and commercial grade silica fume were

Table 3
Data from compressive strength test (in MPa)

		Packing			Cement paste			Neoprene			Sulfur		
W/CM	Batch no.	Ave.	S.D.	Range	Ave.	S.D.	Range	Ave.	S.D.	Range	Ave.	S.D.	Range
0.22	1	77.2	9.4	14.9	92.9	7.3	11.7	91.1	7.3	11.6	90.3	5.5	8.8
	2	71.5	6.3	10.1	94	7.5	11.9	96.7	12.4	19.7	95.2	4.1	3.8
	3	66.5	8.6	13.7	97.7	10.1	16.0	99.7	9.2	14.7	92.2	2.3	4.4
	4	70.7	17.3	27.5	102	5.3	8.5	91.2	11.8	18.7	97.6	2.3	3.7
	Ave.	71.5	10.4	16.5	96.7	7.5	12.0	94.7	10.2	16.2	93.8	3.9	5.2
0.26	1	61.8	16.7	26.5	93.7	5.0	7.9	83.8	11.2	17.9	87.5	4.7	7.4
	2	68.9	8.8	14.0	86.2	7.6	12.0	87.1	5.5	8.8	87.2	2.7	11.6
	3	59.1	7.2	11.5	87.9	2.7	4.2	93.2	5.3	8.4	80.4	3.4	9.1
	4	62.2	6.2	9.9	82.7	8.6	13.7	85.1	12.6	20.1	86.5	4.0	6.3
	Ave.	63	9.7	15.5	87.6	5.9	9.5	87.3	8.7	13.8	85.4	3.7	8.6
0.31	1	75.8	5.6	8.9	79.1	6.3	10.1	86.9	6.6	10.5	83.9	2.3	8.9
	2	67.7	7.5	11.9	85.3	3.5	5.6	90.7	4.5	7.2	80.9	2.7	4.3
	3	53.6	8.5	13.6	86.6	3.3	5.3	89.5	6.9	10.9	84.5	2.6	4.1
	4	57.9	9.1	14.4	85.5	4.6	7.3	87.8	5.4	8.6	85.7	6.4	10.1
	Ave.	63.7	7.7	12.2	84.1	4.4	7.1	88.7	5.8	9.3	83.8	3.5	6.9

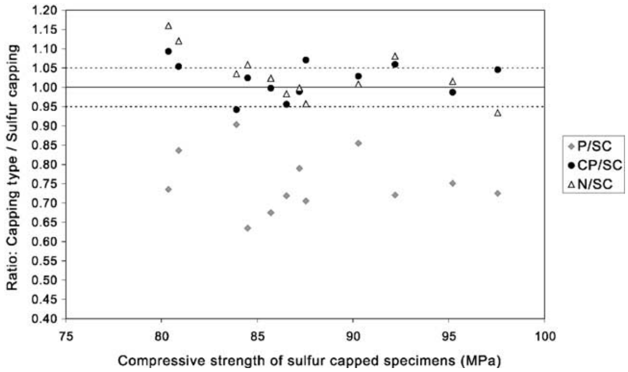

Fig. 2. Ratio of compressive strength test results obtained from cylinders tested using different capping types to that of sulfur capped specimens, plotted vs. compressive strength of specimens tested using sulfur mortar.

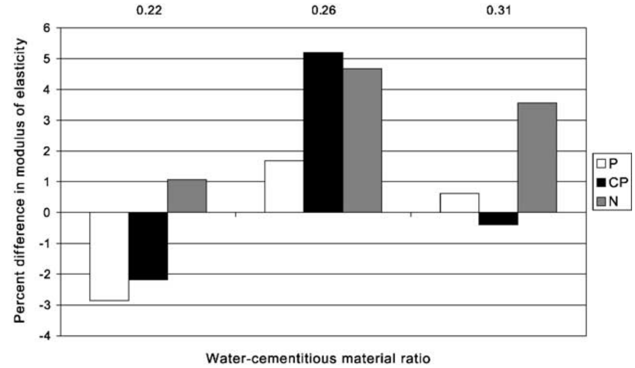

Fig. 3. Average percent difference with respect to the static elastic modulus of sulfur-capped specimens.

used together with natural river sand and crushed limestone having a maximum particle size of 32 mm. Both aggregates were obtained from local sources. Aggregate gradation is given in Table 1.

Twelve batches of concrete were produced. Each batch was mixed as per ASTM C192 in a power-driven revolving pan mixer. A high-range water-reducing admixture was used to achieve the specified slump at each water-cementitious material ratio. The details of mix proportions for 1 m^3 of concrete are given in Table 2. Sixteen cylinder specimens were cast from each batch and four of them were selected randomly for each capping type. Thus, totally 192 specimens were tested. Test specimens were demoulded 24 h after casting and then water cured for 7 days. Afterwards, the specimens were kept in a curing room at a temperature of 21 ± 1 °C and at relative humidity of $60 \pm 5\%$ until the time of testing. Specimens were tested at the age of 28 days. Capping the specimens with cement paste was done at the end of the water-curing period while the other types of capping were applied just prior to testing.

Commercially available sulfur mortar, Portland cement and neoprene pad with steel end caps were used. Data from the manufacturer indicated that the sulfur mortar had a cube compressive strength of about 45 MPa at 2 h and 58 MPa at 7 days. Sulfur mortar once used for capping was not reused in this study. Portland cement used for capping had a 7 days compressive strength of 65 MPa and an optimum consistency was obtained at a water–cement ratio of 0.33 by mass. The same set of neoprene pads was used for the entire study. Manufacturer's specifications indicated a durometer hardness of 60 for the neoprene pads. The steel end caps had an inside diameter of 160 mm. The cavity in the steel retainer had a depth of 30 mm.

The compression test was carried out by a 3000 kN capacity testing machine according to ASTM C39. Companion cylinders were tested for determining the modulus of elasticity as per ASTM C469 before they have been loaded to failure under compression. Each of these specimens was fitted with a compressometer containing a dial gage capable of measuring deformation to 0.002 mm and then loaded three times to 40% of the ultimate load of companion cylinder. The first set of readings of each

Table 4
Data from static modulus of elasticity test (in GPa)

		Packing			Cement paste			Neoprene			Sulfur		
W/CM	Batch no.	Ave.	S.D.	Range	Ave.	S.D.	Range	Ave.	S.D.	Range	Ave.	S.D.	Range
0.22	1	47.1	5.7	9.1	46.4	2.6	4.1	46.8	2.8	4.4	45.0	1.0	1.5
	2	48.0	2.4	3.8	48.3	1.7	2.7	53.2	2.4	3.9	50.8	4.8	7.6
	3	46.8	3.1	4.9	47.0	1.2	1.8	47.6	3.1	4.9	50.0	2.4	3.9
	4	47.3	2.7	4.3	48.8	2.0	3.1	49.3	0.5	0.9	49.3	1.5	2.4
	Ave.	47.3	3.5	5.5	47.6	1.9	3.0	49.2	2.2	3.5	48.8	2.4	3.8
0.26	1	45.4	4.9	7.7	50.5	6.2	9.9	45.9	2.8	4.4	48.5	5.0	8.0
	2	47.6	3.9	6.3	47.1	1.3	2.1	47.7	1.4	2.2	41.1	2.0	3.3
	3	40.9	2.8	4.4	43.0	1.3	2.1	46.2	2.8	4.4	43.2	2.5	3.9
	4	45.4	5.8	9.3	45.4	0.4	0.6	44.7	1.2	2.0	44.2	2.6	4.2
	Ave.	44.8	4.4	6.9	46.5	2.3	3.7	46.1	2.0	3.3	44.3	3.0	4.8
0.31	1	43.0	6.0	9.6	44.7	0.4	0.7	46.1	1.7	2.8	45.8	2.5	3.9
	2	48.2	2.1	3.3	45.0	2.8	4.4	48.1	4.2	6.6	44.6	0.5	0.9
	3	46.2	2.4	3.8	46.1	1.0	1.7	47.6	3.4	5.4	45.3	2.9	4.7
	4	44.5	2.7	4.4	44.3	1.4	2.2	45.4	1.6	2.6	45.1	1.8	2.9
	Ave.	45.5	3.3	5.3	45.0	1.4	2.2	46.8	2.7	4.3	45.2	1.9	3.1

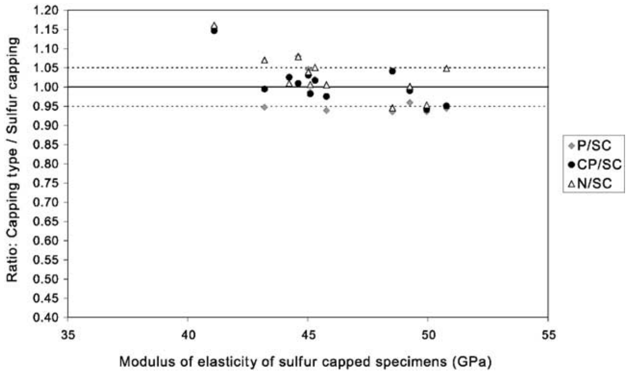

Fig. 4. Ratio of modulus of elasticity test results obtained from cylinders tested using different capping types to that of sulfur capped specimens, plotted vs. static elastic modulus of specimens tested using sulfur mortar.

cylinder was discarded and the modulus was reported as the average of the second two sets of readings. Following the third loading of each specimen, the compressometer was removed and the specimen was loaded to failure to determine the compressive strength.

3. Experimental results and discussion

3.1. Compressive strength

Within test ranges, standard deviations and average strengths obtained from compression tests are given in Table 3. The differences in the average strengths of concretes with various capping systems, from the specimens tested using sulfur mortar capping were − 22.3, − 22.4 and − 20.1 MPa for packing (P), 2.9, 2.2 and 0.3 MPa for cement paste capping (CP), and 0.9, 1.9 and 4.9 MPa for neoprene capping (N), respectively, for W/CM ratios of 0.22, 0.26 and 0.31. On the other hand, the mean value of strength differences P−S, CP−S and N−S obtained from 12 tests irrespective of W/CM were − 21.6, 1.8 and 2.6 MPa, respectively. It may also be observed from Table 3 that the overall mean value of standard deviations irrespective of W/CM were 9.3, 5.9, 8.2 and 3.7 MPa, respectively, for P, CP, N and S capped specimens. Figs. 1 and 2 show the percent differences [(P−S)/S, (CP−S)/S, (N−S)/S] in compressive strength for three W/CM ratios and the ratio of compressive strength of cylinders with P, CP and N capping to those of sulfur-capped specimens, respectively. It was observed that the strength of the specimens with packing was within − 25% of the companion cylinders capped with sulfur mortar. However, cement paste and neoprene capped specimens had approximately 1–5% greater strengths in comparison to that of their equivalents with sulfur mortar capping. Fig. 2 indicated that the specimens tested without capping deviated up to 40% from those tested using sulfur capping and the ratio always lied below 1.00, while this ratio for the specimens tested using cement paste and neoprene pad lied mostly above 1.00. None of the specimens capped with cement paste and neoprene had strengths < 5% and > 15% of the companion cylinders tested using sulfur capping.

3.2. Static modulus of elasticity

Results including the within test ranges associated with the standard deviations and the average ranges from static modulus of elasticity tests are given in Table 4. The differences between the averages of modulus of elasticity of packed and sulfur-capped specimens ranged from − 1.5 to 0.3 GPa. Similarly, modulus of elasticity of the specimens capped with cement paste differed − 1.2 to 2.2 GPa from sulfur-capped specimens. The deviation in the moduli for neoprene capped and sulfur-capped specimens ranged between 0.4 and 1.8 GPa. Based on experimental data in Table 4, the overall mean of standard deviations were 3.7, 1.9, 2.3 and 2.4 GPa, respectively, for P, CP, N and S capped specimens. The average percent differences in the modulus of elasticity of concretes with respect to the results of the specimens tested using sulfur mortar are given in Fig. 3. From this figure, it was seen that the percent deviation for the entire tests fell within a range of − 3% to + 5%. The ratio of static elastic modulus of cylinders tested using packing, neat cement paste and neoprene pad to those with sulfur caps was plotted in Fig. 4. It was observed that the ratios were generally within 5% of equality for all capping types as opposed to the compression test results for the packed cylinders. Thus, the capping type was less effective on the modulus of elasticity in

Table 5
Statistical test results

Dependent variable	Source of variation	Degrees of freedom	Mean square	Computed F	P level	Significance
Compressive strength	W/CM ratio	2	405.6	19.48	.000002	Yes
	Capping type	3	1607.1	77.20	.000000	Yes
	Interaction	6	9.2	0.44	.846735	No
	Error	36				
Modulus of elasticity	W/CM ratio	2	39.2	8.91	.00072	Yes
	Capping type	3	5.41	1.23	.31293	No
	Interaction	6	2.52	0.57	.74913	No
	Error	36	4.4			

comparison to the compressive strength since the data was obtained up to 40% of the ultimate compressive strength.

3.3. Analysis of variance

TA two-way analysis of variance was performed statistically to investigate the influence of capping type on both compressive strength and static elastic modulus. Capping type and W/CM ratio were selected as factors, whereas the compressive strength and the modulus of elasticity were dependent variables. It was considered that the case of four replications of the specimen end treatment combinations are determined by three levels of factor W/CM ratio and four levels of factor capping types.

The following hypotheses were tested using a .01 level of significance: (1) $H_0{}'$: there is no difference in the mean compressive strength (or modulus of elasticity) when different W/CM ratios are used; (2) $H_0{}''$: there is no difference in the mean compressive strength (or modulus of elasticity) of the concrete specimens having four different capping types; (3) H_0: there is no interaction between the different W/CM ratios and the different capping types.

Results obtained from statistical analysis were shown in Table 5. From the table, the interactions for both compressive strength and static elastic modulus were insignificant. Capping type and W/CM ratio individually had significant effects on the compressive strength. However, the capping type had no effect on the modulus of elasticity whereas the effect of W/CM ratio was pretty significant. After finding out that the capping type significantly influenced the compressive strength of concrete specimens, a statistical paired t-test was applied to each individual strength level obtained from different capping types at a .01 level of significance. Packed specimens exhibited a significant difference from the others and there was no statistically significant difference between sulfur mortar, cement paste and neoprene-capped specimens, as shown in Table 6.

3.4. Correlation between static elastic modulus and compressive strength

Static elastic moduli and compressive strengths of concrete cylinder specimens capped with neat cement paste, neoprene pad and sulfur mortar were plotted to observe this correlation. These three capping types were selected since the variance analysis results indicated that there was no statistical difference between them. A linear regression analysis applied to the test data gave the below equation:

$$E = 5.536\sqrt{f_c} - 5.552 \quad (1)$$

where the static elastic modulus (E) is in GPa and the compressive strength (f_c) is in MPa. The Pearson correlation coefficient was .72, the analysis of variance F-statistics showed that this relationship is significant at a .01 level.

Data from this experimental study and several relations for predicting modulus of elasticity from compressive strength such as Eq. (1) of this study, ACI Building Code relation [9], relations proposed by Carrasquillo et al. [10], Shah and Ahmad [11] and Oluokun et al. [12] were all shown in Fig. 5. Experimentally determined static elastic modulus values were generally higher than the predicted values at 75–100 MPa design strength levels. Fig. 5 indicated that static elastic moduli within this range agreed reasonably well (within 4% and 7%) with the predicted values from the ACI 318-89, and Oluokun, Burdette and Dietherage, respectively. However, the agreement of the test results with the Carrasquillo et al. and Shah and Ahmad prediction relations were only within 18% and 20%, respectively.

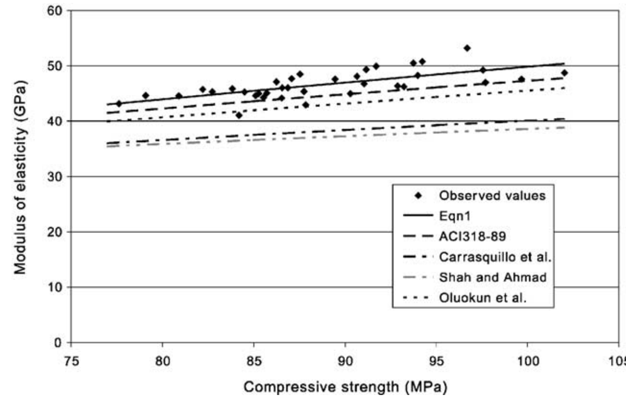

Fig. 5. The plot of compressive strength vs. static elastic modulus.

Table 6
Paired t-test results

Capping types	Number of sample	$t_{computed}$	P level	Significance
P–CP	12	8.227	.000	Yes
P–N	12	9.683	.000	Yes
P–S	12	8.286	.000	Yes
CP–N	12	0.328	.746	No
CP–S	12	0.737	.469	No
N–S	12	1.263	.220	No

4. Conclusions

Based on the results obtained from this study, the following conclusions may be drawn.

(1) The use of neat cement paste and neoprene pad capping systems yielded average compressive strengths about 1–5% higher than those obtained using sulfur mortar capping, irrespective of W/CM. The use of packing in compression tests, on the other hand, resulted in a great difference of −25% from sulfur-capped specimens.

(2) The use of packing, neat cement paste and neoprene pad capping systems gave average static elastic moduli within 5% of those obtained using sulfur mortar.

(3) Based on the analysis of variance results, the overall mean compressive strength of concrete specimens capped with neat cement paste, neoprene pad and sulfur mortar were not significantly different. The packed specimens only exhibited a significant difference from the others. On the other hand, there was no statistical difference in the static elastic moduli when different capping types were used.

(4) The largest standard deviations in compressive strength belonged to the packed and neoprene pad capped specimens. However, the overall standard deviations in elastic moduli were not significantly different for all capping types.

(5) Experimentally determined static elastic modulus values were consistently higher than those predicted by the relations proposed in the literature for a compressive strength range of 75–100 MPa.

(6) Use of neoprene pad capping systems demonstrated significant practical advantages over neat cement paste and sulfur mortar capping, including reduced cost, time savings and a safer working environment.

Acknowledgments

The authors wish to express their thanks to Mr. İlyas Gültekin for his invaluable assistance during the laboratory phase of the study.

References

[1] L.K. Crouch, J.B. Pearson, Neoprene capping for static modulus of elasticity testing, ACI Mater. J. 92 (6) (1995) 643–648.

[2] D.N. Richardson, Effects of testing variables on the comparison of neoprene pad and sulfur mortar-capped concrete test cylinders, ACI Mater. J. 87 (5) (1990) 489–495.

[3] P.M. Carrasquillo, R.L. Carrasquillo, Effect of using unbonded capping systems on the compressive strength of concrete cylinders, ACI Mater. J. 85 (17) (1988) 141–147.

[4] W. Vichit-Vadakan, N.J. Carino, G.M. Mullings, Effect of elastic modulus of capping material on measured strength of high strength concrete cylinders, Cem., Concr., Aggregates 20 (2) (1998) 227–234.

[5] C.L. Lobo, G.M. Mullings, R.D. Gynor, Effects of capping materials and procedures on the compressive strength of 100 × 200 mm (4 × 8 in.) high strength concrete cylinders, Cem., Concr., Aggregates 16 (2) (1994) 173–180.

[6] ASTM C617-94, Standard practice for capping cylindrical concrete specimens, Annual Book of ASTM Standards, V. 04.02, May 1994, pp. 290–293.

[7] ASTM C1231-93, Standard practice for use of unbonded caps in determination of compressive strength of hardened concrete cylinders, Annual Book of ASTM Standards, V. 04.02, July 1993, pp. 628–630.

[8] Ç. Özyıldırım, Neoprene pads for capping concrete cylinders, Cem., Concr., Aggregates 7 (1) (1985) 25–28.

[9] ACI Committee 318, Building Code Requirements for Reinforced Concrete (ACI 318-89), American Concrete Institute, Detroit, 1989.

[10] R.L. Carrasquillo, A.H. Nilson, F.O. Slate, Properties of high-strength concrete subjected to short-term loads, ACI J. Proc. 78 (3) (1981) 171–178 (May–June).

[11] S.P. Shah, S.H. Ahmad, Structural properties of high-strength concrete and its implementations for precast prestressed concrete, PCI J. 30 (6) (1985) 92–119.

[12] F.A. Oluokun, E.G. Burdette, J.H. Deatherage, Elastic modulus, Poisson's ratio, and compressive strength relationships at early ages, ACI Mater. J. 88 (1) (1991) 3–10.