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Correlation of strength of 75 mm diameter and 100 mm diameter cylinders for high strength concrete

Anil K. Patnaik[a,*], Indubhushan Patnaikuni[b]

[a]Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, 501E St. Joseph Street, Rapid City, SD 57701, USA
[b]Department of Civil and Geological Engineering, RMIT University, GPO Box 2476V, Melbourne, Victoria 3001, Australia

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Abstract

Results of statistical analysis of test data are presented to establish if there is a correlation between the strength of 75- and 100-mm-diameter cylinders for concrete with strength between 110 and 160 MPa. A linear regression analysis showed that strength measured on 75-mm cylinders is within 5% of the corresponding strength measured on 100-mm cylinders. A more detailed analysis of the difference between the mean strengths of the two sizes of cylinder of each group of the tests indicated that 75- and 100-mm cylinders measure the concrete strength within 4%. It is concluded that 75-mm cylinders are suitable for compressive strength testing of high strength concrete (> 100 MPa). For strength of concrete greater than 150 MPa, 75-mm cylinders are likely to measure smaller concrete strength than the corresponding 100-mm cylinders. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Even though compressive strength of most concrete cast in the construction industry until recently was below 35 MPa, the strength of concrete normally used these days in industry is creeping up to about 50 MPa. For such concretes, the use of test cylinders of 150 mm diameter and 300 mm length has been convenient and acceptable for a long time. The capacity requirements of testing facilities necessary to test concretes of strengths much greater than 50 MPa increase significantly if 150 mm diameter cylinders are used to measure compressive strength. Alternatively, the size of test cylinders can be reduced so that higher strength concrete can be tested with existing facilities, provided a correlation exists between the strengths measured on 150-mm cylinders and smaller size cylinders. Smaller cylinders have definite advantages in making, handling, curing, storing, testing, and finally disposing of crushed specimens.

The correlation between strength measured on 150 × 300-mm cylinders and that measured on 100 × 200-mm cylinders is well established and documented. For example, Day [1,2], Carino et al. [3] and others cited in Refs. [1–4] studied the strength differences with the help of statistical methods and test results, and provided good insight into this issue. Patnaik and Patnaikuni [4] later performed statistical analysis on several hundreds of test data and reported that, on average, 100-mm cylinders show about 5% higher strength compared with 150-mm cylinders. They also found that the characteristic compressive strength of concrete (important in structural applications) is overestimated by about 5% when 100-mm cylinders are used to measure mean strength along with the relevant Australian standard requirements. Some national standards such as Australian Standard AS 1012.9-1986 [5] and Canadian Standard CSA A23.1 [6] now allow the use of 100-mm cylinders in place of 150-mm cylinders for compressive strength testing. According to these standards, there is no requirement to reduce the mean strength of concrete when 100-mm cylinders are used. ASTM C 31-91 [7] requires that the standard compressive strength specimen be mainly 152 × 305 mm (6 × 12 in.) when the maximum size of the coarse aggregate does not exceed 50 mm, with other sizes permitted, if specified.

Suitability of 75 mm diameter by 150 mm long cylinders for concrete compressive strength testing was studied by Nasser and Al-Manaseer [8] and Nasser and Kenyon [9].

* Corresponding author Tel.: +1-605-394-2442; fax: +1-605-394-5171.
E-mail address: anil.patnaik@sdsmt.edu (A.K. Patnaik).

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They compared the strength measured on 75-mm cylinders with that measured on the corresponding 150-mm cylinders and concluded that the 75-mm cylinder is a suitable specimen for concrete strength testing when the maximum size of the aggregate used does not exceed 25 mm. Day and Haque [10] conducted statistical analysis of test data involving strength measured on 75- and 150-mm cylinders. Their data covered concrete strength up to about 80 MPa. They concluded from the analysis that for concrete with strength less than 50 MPa, there is a "statistical equivalence" between the strengths measured on 150-mm cylinders and that measured on 100- or 75-mm cylinders.

It is now generally accepted that it is beneficial to reduce the size of the standard cylinder. Several sets of data are reported by others for comparison of strength of 150 mm diameter cylinders with that of 100-mm cylinders for very high-strength concrete. However, test data for 100-mm cylinders and the corresponding 75-mm cylinders for concrete with strength over 100 MPa are limited. It is believed that concrete with strength much greater than 100 MPa will find use in the future. While cylindrical specimens of 100 mm diameter are currently found to be suitable for the determination of concrete strength, 75×150-mm cylinders may be useful in the future when concrete with strength greater than 100 MPa is used frequently in practice. Therefore, this investigation attempts to correlate strengths of 100- and 75-mm cylinders for very high-strength concrete.

Outlined are the findings of an investigation in which test data were developed for concrete strengths between 110 and 160 MPa. The comparison is based on the measured strengths of 100-mm cylinders (instead of 150-mm cylinders) as the 100-mm cylinder has gained acceptance as a standard specimen size in Australia and elsewhere. In other words, concrete strength measured on 150 and 100 mm diameter cylinders is being considered equivalent. This may be debatable [1–4], but that aspect is outside the scope of this paper.

2. Requirements for strength equivalence

In order to investigate the effect of reducing the diameter of test cylinders from 100 mm to 75 mm for measuring concrete strength, one is faced with the following major questions:

(i) Will the strength measured by using 75 mm diameter cylinders be equal (within practical limits) to that measured by using 100 mm diameter cylinders for the same batch of concrete, and identical conditions and age?
(ii) What is the error in making an assumption that the concrete strengths measured on the two sizes of cylinder are equivalent?
(iii) Is the variability of concrete strength measured on the two sizes of cylinder the same?

This paper aims at providing some answers to these questions with the help of test data of 142 cylinders of 75 mm diameter and 122 cylinders of 100 mm diameter. The details of the analysis of the test results are presented below.

3. Experimental program

The complete details of the experimental program were published elsewhere [11–18].

3.1. Materials

The variation of mix ingredients from batch to batch was minimized by using materials from the same production batch.

3.1.1. Binder

The binder consisted of normal portland cement (NPC) and silica fume. The fineness of NPC and silica fume were 365 and 24000 m^2/kg, respectively, as determined by the laser granulometry method. Only one brand of NPC Type A conforming to Australian Standard AS1315-1973 was used.

3.1.2. Fine aggregate

The fine aggregate was washed Lyndhurst medium sand with a fineness modulus of 3.55.

3.1.3. Coarse aggregate

The coarse aggregate was crushed older basalt from Kilmore. Extensive testing of very high-strength concrete at RMIT University established that a maximum size of aggregate of 7 mm is the optimum size for very high-strength concrete [15]. Therefore, the maximum nominal size of the coarse aggregate used was 7 mm.

3.1.4. Superplasticizer

Commercially available sodium naphthalene sulfonate formaldehyde condensate superplasticizer having 42% solids content was used. The superplasticizer dosage varied between 1.3% and 3.6% of the mass of the cementitious material.

3.1.5. Silica fume

The silica fume was densified microsilica from Barrack, Western Australia. The details of the chemical analysis are given elsewhere [18].

3.2. Mixture proportions

Suitable mixture proportions for each group of tests consisting of 75- and 100-mm cylinders were based on the guidelines suggested elsewhere [11–18]. The mixture proportions used for one cubic meter of concrete are given in Table 1.

Table 1
Mixture proportions

Data group	W/B ratio	Water (kg/m^3)	Cement (kg/m^3)	CSF (kg/m^3)	Binder content (kg/m^3)	CSF dosage %	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Fine aggregate to total aggregate ratio (%)	Superplasticizer (kg/m^3)	Superplasticizer dosage (%)	Slump (mm)
R36A	0.23	128.8	560	0	560	0	1291	553	30	20.2	3.6	35
R36B	0.23	128.8	560	0	560	0	1295	555	30	20.2	3.6	45
R37A	0.23	128.8	504	56	560	10	1289	552	30	8.4	1.5	190
R37B	0.23	128.8	504	56	560	10	1289	552	30	8.4	1.5	180
R43	0.23	128.8	504	56	560	10	1289	552	30	8.4	1.5	180
R44	0.23	128.8	504	56	560	10	1289	552	30	8.4	1.5	180
R45	0.23	128.8	504	56	560	10	1289	552	30	8.4	1.5	170

3.3. Casting and curing of concrete cylinders

All the fine and coarse aggregates were oven-dried to moisture content of zero percent. Concrete ingredients were mixed in a horizontal pan mixer with a capacity of 0.08 m^3. Concrete was mixed for 28 cylinders or more in a batch. The same batch was used to make both sizes of all the cylinders of a particular group. Test cylinders were compacted in two layers in steel molds with a 200 Hz frequency vibrating table in sets of 28 at a time (it is a common local practice to use steel molds for concrete cylinders). Temperature in the laboratory at the time of casting was between 16 to 22 °C. The cylinders were demolded the day after casting and were cured in lime-saturated water at 20 °C until the day before testing. The curing tanks were equipped with water circulation and temperature control systems.

3.4. Preparation and testing of cylinders

The rough ends of all the cylinders were cut with a diamond saw to maintain a height to diameter ratio of 1.97. A belt sander was used to remove the lime that was deposited from the lime-saturated curing water on the two end surfaces of the cylinders. Both the ends of the cylinders were ground to a smooth finish using a mechanical sander and capped with commercially available high strength sulfur capping material the day before testing. All the cylinders of each group (75- and 100-mm cylinders) were tested on the same day. The cylinders were tested with a 2000 kN capacity Shimadzu RH200 testing machine. The precision of the machine conformed to Grade A as defined in AS2193-1978 [19]. The cylinders were loaded uniformly at 20 MPa per minute as per AS1012.9-1986 [5].

4. Results and discussion

4.1. Simple linear regression analysis of mean strengths

A summary of the cylinder test results is shown in Table 2. Each data group consists of two mean values of strength, one value corresponds to 75-mm cylinders and the other corresponds to 100-mm cylinders. A scatter diagram of the mean strengths of the two sizes of cylinders is shown in Fig. 1. The test data from Day [1,2] and Gonnerman [20] are also included in the figure. As evident in the figure, there are no relevant test data for concrete with strength between about 50 and 110 MPa. The figure also shows a line of equality (solid line) with a slope of 1.0 and two other lines with slopes of 0.95 and 1.05. Note that the average values of test data of this study are within the lines with slopes of 0.95 and 1.05, indicating that the mean strengths of concrete measured with the two sizes of cylinder are within 5%. An equation of best fit was developed by linear regression of all

Table 2
Test results for 75- and 100-mm cylinders

Data group	Age (days)	75 × 150-mm cylinders				100 × 200-mm cylinders			
		Number of cylinders (n_{75})	Mean strength (MPa)	Standard deviation (MPa)	Coefficient of variation (%)	Number of cylinders (n_{100})	Mean strength (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
R36A	91	24	130.2	2.7	2.0	12	127.5	3.0	2.4
R36B	91	25	132.3	3.4	2.6	25	128.7	3.1	2.4
R37A	91	12	157.5	1.6	1.0	12	162.1	2.6	1.6
R37B	91	7	155.5	1.8	1.2	10	157.9	2.8	1.8
R43-7D	7	12	112.8	0.8	0.7	12	108.4	2.1	1.9
R43-28D	28	12	141.8	3.2	2.2	12	141.2	4.4	3.1
R44-56D	56	12	148.9	1.4	0.7	13	149.8	5.8	3.9
R44-91D	91	13	155.9	3.2	2.0	13	158.0	5.6	3.5
R45-180D	180	25	152.8	6.4	4.2	13	152.0	9.0	5.9

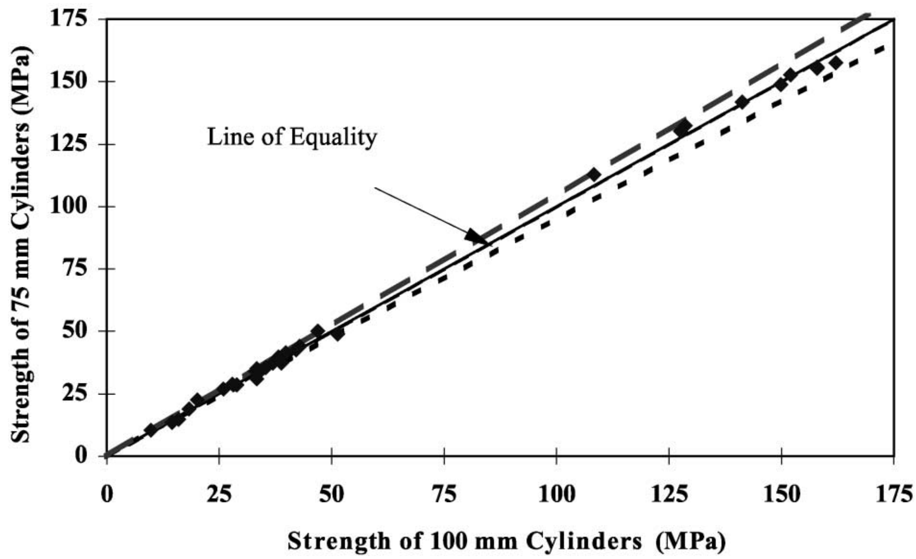

Fig. 1. Scatterplot of strength of 75- and 100-mm cylinders.

the data points shown in the figure. The following equations best describe the test data:

$$S_{75} = 0.994\ S_{100} + 0.67 \quad \text{for the line of best fit,}$$
$$S_{100} = 1.006\ S_{75} - 0.67 \quad \text{for the line of best fit.} \tag{1}$$

An assumption that the strengths measured with the two sizes of cylinder is equal will lead to the following equation:

$$S_{75} = S_{100} \quad \text{for the line of equality} \tag{2}$$

where S_{75} is the mean strength of 75 mm diameter cylinders in MPa; S_{100} is the mean strength of 100 mm diameter cylinders in MPa.

The line of best fit (Eq. (1)) has a standard error of 2 MPa and a coefficient of determination of .998. The standard errors for the y-intercept and the slope of Eq. (1) are 0.56 MPa and 0.007. The equation is valid for concrete strengths between 20 and 50 MPa and between 110 and 160 MPa.

For all practical purposes, Eqs. (1) and (2) are similar.

If the data of this study is exclusively considered in a regression analysis, the equation of best fit for concrete strength between 110 and 160 MPa is as follows:

$$S_{75} = 0.85\ S_{100} + 21.7 \quad \text{for the line of best fit,}$$
$$S_{100} = 1.177\ S_{75} - 25.5 \quad \text{for the line of best fit.} \tag{3}$$

Eq. (3) is better suited for concrete strengths between 110 and 160 MPa.

The accuracy of the simple linear regression analysis depends on the assumption that the standard deviation of the error variable is constant no matter what the strength of the concrete is [21]. This assumption is not necessarily valid for strengths measured on concrete cylinders. Therefore, the

Table 3
Summary of data analysis

Data group	Grand mean strength (MPa)	Sample size ($n_{75}+n_{100}$)	Residual $S_{75}-S_{100}$ (MPa)	Pooled S.D. (MPa)	t statistic	t critical	Hypothesis test result	95% CI estimator of residual (MPa) UCL	LCL	Larger of UCL and LCL as % strength
1	2	3	4	5	6	7	8	9	10	11
R36A	129.3	36	2.6	2.8	2.584	2.086	Reject	4.7	0.6	3.7
R36B	130.5	50	3.6	3.3	3.892	2.012	Reject	5.5	1.7	4.2
R37A	159.8	24	− 4.6	2.2	5.167	2.101	Reject	− 2.7	− 6.4	4.0
R37B	156.4	17	− 2.4	2.5	2.118	2.131	Do not reject	0.2	− 5.0	3.2
R43-7D	110.6	24	4.5	1.6	6.962	2.145	Reject	5.8	3.1	5.4
R43-28D	141.5	24	0.6	3.8	0.374	2.086	Do not reject	3.4	− 2.3	2.4
R44-56D	149.4	25	− 0.9	4.2	0.574	2.160	Do not reject	2.7	− 4.6	3.1
R44-91D	157.0	26	− 2.0	4.6	1.132	2.093	Do not reject	1.7	− 5.8	3.7
R45-180D	152.5	38	0.8	7.3	0.285	2.093	Do not reject	6.0	− 4.5	4.0
							Average	3.0	− 2.6	3.7

differences between S_{75} and S_{100} were further investigated by using a detailed statistical analysis.

4.2. Detailed statistical analysis

The results given in the previous section are based on the analysis of mean strengths in a global sense. The following outlines the results of the analysis of each of the nine groups (see Table 2) individually with due consideration of variation within each population. The test data of other researchers were not included in the detailed statistical analysis because the required details for analysis are not reported in the referred papers.

The difference between the mean strengths measured on the two sizes of cylinder of each of the nine groups was studied (Analysis of Residual or test for differences between means) in order to accept or reject the statistical equivalence of the two strengths. The "Residual" R (or "difference" between mean strengths) is defined as:

$$R = S_{75} - S_{100}. \tag{4}$$

From the above equation it is possible to consider that the two average strengths, S_{75} and S_{100}, are statistically equivalent if R is not statistically different from zero. The null hypothesis to be tested is, $S_{75} - S_{100} = 0$. Note that the "difference" between mean strengths defined in Eq. (4) will be referred to as "Residual" in the rest of this paper.

The results of the test of the above hypothesis at the 95% confidence level are summarized in Table 3 and plotted in Fig. 2. The mean strength (column 2) and sample size (column 3) given in the table refer to the grand mean strength and total number of cylinders, respectively, of the entire population (75- and 100-mm cylinders) for the particular group. The grand mean strength was used to plot the results in Fig. 2. Each "Residual" is the difference in the mean strengths ($S_{75} - S_{100}$) measured on the two sizes of cylinders in a particular group. The table also shows the values of the pooled standard deviation for all the cylinders of the group, and the values of t statistic and t critical for each group. The rejection region is defined by t critical. An individual group would fail to satisfy the null hypothesis that $S_{75} - S_{100} = 0$ at the 95% confidence level if the t statistic is greater than t critical.

The 95% confidence interval (CI) estimator of residual ($S_{75} - S_{100}$) was calculated for each group, and is shown in Table 3 and plotted in Fig. 2. Column 9 of Table 3 shows the upper confidence limit (UCL) of the residual, and column 10 shows the lower confidence limit (LCL) of the residual. Column 11 of the table shows larger absolute value of UCL and LCL of the corresponding group expressed as a percentage of the mean strength of the corresponding 100-mm cylinders given in Table 2.

For example, the residual for a group (say R43-28D) is statistically estimated to be between -2.3 and 3.4 MPa at 95% confidence level. For this group, the residual measured with the two sizes of cylinders can be between -2.3 and 3.4 MPa, the maximum possible absolute difference being 3.4 MPa (2.4%) compared to mean strength of 141.2 MPa. For practical applications, this percentage may be considered to be an "error" in assuming that the concrete strengths measured on the two sizes of cylinders are equal. The average of this "error" for the nine groups shown in Table 3 is 3.7%. Therefore, average "error" in assuming that the concrete strengths measured on the two sizes of cylinders are equal is expected to be less than 4%.

Data shown in Table 3 and in Fig. 2 indicate that four out of the nine data groups failed to satisfy the hypothesis at the 95% confidence level. Furthermore, out of the four groups that failed the test, three groups are expected to have residuals greater than zero, i.e., $S_{75} - S_{100} \geq 0$. This means that 75-mm cylinders indicate higher strengths compared with 100-mm cylinders (nonconservative). For these groups,

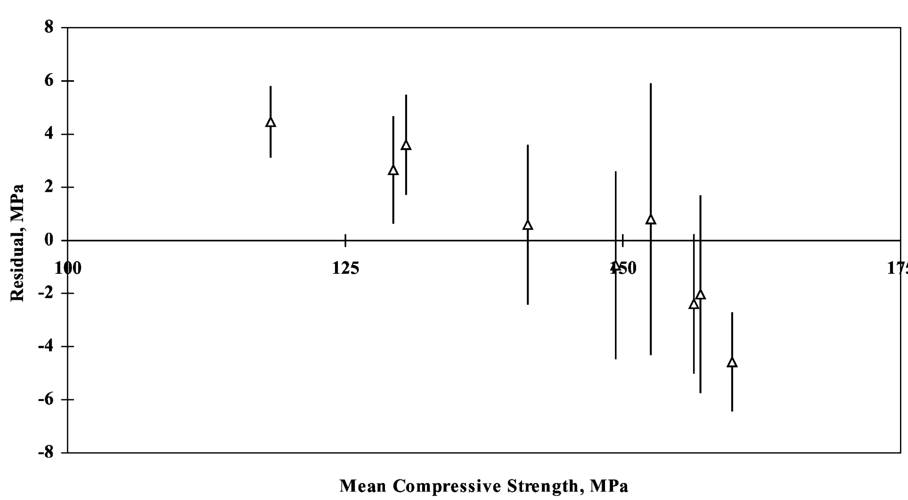

Fig. 2. Plot of residual with error bars (at 95% CI) for different compressive strengths.

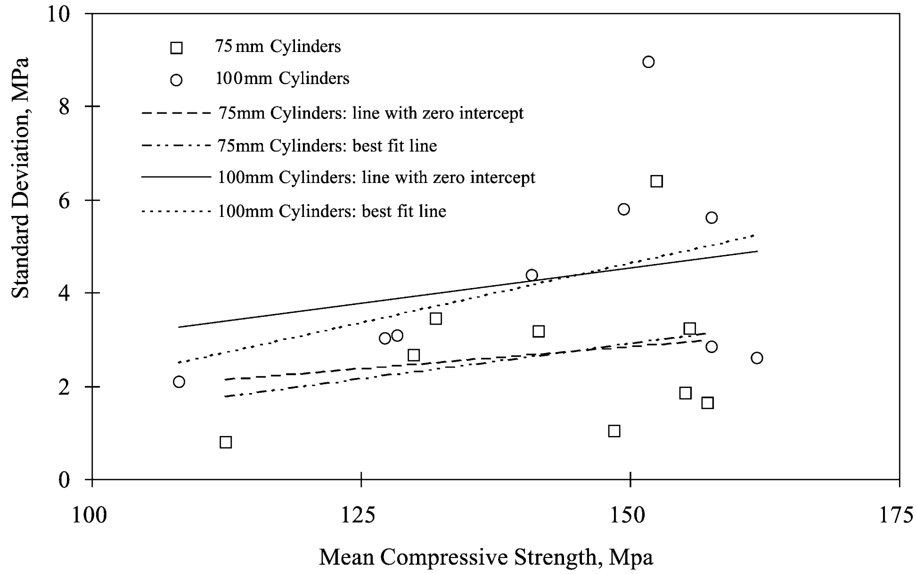

Fig. 3. Variation of standard deviation of strength with concrete strength.

the difference between S_{75} and S_{100} is likely to be up to 5.8 MPa or 5.4% of the concrete strength of the corresponding 100-mm cylinders. The fourth group that failed the test has a residual less than zero, i.e., $S_{75} - S_{100} \leq 0$, which means that 75-mm cylinders indicate lower strengths compared with 100-mm cylinders (conservative). For this group, the difference between S_{75} and S_{100} is up to -6.4 MPa or -4% of the concrete strength of the corresponding 100-mm cylinders. The other five data groups passed the hypothesis test, i.e., for these five data groups S_{75} is not statistically different from S_{100} at 95% confidence level.

The results of the analysis are also shown in Fig. 2. The figure shows the points corresponding to the "Residual" values for the nine data groups and the associated error bar for each data group of "Residual" at 95% confidence level. If the error bar touches the $R = 0$ line, then the hypothesis cannot be rejected at 95% confidence level. Fig. 2 also shows an obvious trend for R that decreases as strength increases, suggesting that for strength of concrete greater than 150 MPa S_{75} may be smaller than S_{100}.

4.3. Other results

The coefficient of variation of strength of 100-mm cylinders was found to be greater than that of 75-mm cylinders. This decrease in coefficient of variation for smaller size cylinders is in agreement with the observations in some of the earlier studies by others [22]. Fig. 3 shows the variation of standard deviation of strength with concrete strength. The figure also shows the lines developed from a linear regression analysis. The data are widely scattered about both the line of best fit and the line with zero intercept for both the sizes of cylinder. The present test results are inadequate to conclusively establish an expression for variation of standard deviation with concrete strength for the two sizes of cylinder.

5. Concluding comments

Compressive strengths were measured using 75- and 100-mm cylinders from the same concrete batch and concrete strength between 110 and 160 MPa. A linear regression analysis of the test data showed that strength measured on 75-mm cylinders is within 5% of the corresponding strength measured on 100-mm cylinders. A comparison of mean strengths using the *t* test indicated that 75- and 100-mm cylinders measure the concrete strength within 4%. This is encouraging as the use of 75-mm cylinders is particularly beneficial for compressive strength testing of concrete with strength greater than 100 MPa. This study demonstrates that 75×150-mm cylinders may be used for compressive strength testing of concrete with strength greater than 100 MPa.

The differences between the strengths measured with the two sizes of cylinder appear to be related to the strength of the concrete. For strength of concrete greater than 150 MPa, S_{75} may be smaller than S_{100}.

The results presented in this paper are for tests using concrete with maximum size of coarse aggregate of 7 mm. These results are believed to be also applicable to other aggregate sizes, but further tests are required to confirm this.

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