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Evaluation of ASTM Standard Consolidation Requirements for Preparing High-Strength Concrete Cylinders

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Synopsis: An experimental study was designed to accomplish the following: 1) Compare densities and strengths of cylinders prepared by vibration or rodding following current ASTM C 31 and C 192 requirements for the number of layers; 2) investigate whether the experience of the operator affects cylinder strength when vibration and rodding are used to consolidate the specimens; and 3) compare the strengths of 100 mm x 200 mm rodded cylinders prepared by using two or three layers with the strengths of 150 mm x 300 mm rodded cylinders.

Two experiments were designed: 1) a half-fraction, factorial design with the following factors: cement content, slump, cylinder size, consolidation method, and operator; and 2) a comparative design to compare the strengths of 100 mm diameter cylinders rodded using two or three layers with the strengths of 150 mm diameter cylinders. The following summarizes the observations from the first experiment:

Overall, the 100 mm cylinders (three layers) were 1.5 % stronger than the 150 mm cylinders. However, due to a significant interaction effect between *size* and *cement content*; there was a 3.4 % difference at the high cement content and no statistically significant difference at the low cement content.

The rodded cylinders were, on average, 4.2 % stronger than the vibrated cylinders. There was a significant interaction effect between *method* and *size*; therefore, the rodded 100 mm cylinders were 7.4 % stronger than the vibrated 100 mm cylinders, but there was no difference between the 150 mm cylinders prepared by the two methods. Also, the rodded 100 mm cylinders were 4.6 % stronger than the rodded 150 mm cylinders, but the vibrated 150 mm cylinders were 1.6 % stronger than the vibrated 100 mm cylinders.

The was no significant effect due to operator experience.

There was no significant interaction between *slump* and *method*.

There was no significant interaction between *cement content* and *method*.

In the second experiment it was found that the strength differences between 100 mm and 150 mm rodded cylinders were reduced by one-half when two layers, instead of three, were used to cast the 100 mm cylinders.

Keywords: Building technology; compressive strength; consolidation; cylinders; density; experimental design; high-strength concrete; segregation; statistical analysis

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INTRODUCTION

Current ASTM Standard Practices C 31/C 31M and C 192/C 192M require that concrete specimens made with mixtures having slumps greater than 75 mm must not be consolidated by vibration. The apparent reason for the restriction is to avoid the possibility of segregation in high-slump concretes due to settling of the coarse aggregate particles and excessive bleeding. However, the use of high-strength concrete, made with high cement contents, raises the question of whether this restriction is necessary. Mixtures with high cement contents tend to be cohesive. When high slump is obtained by using flow-enhancing admixtures there is less tendency for segregation compared with high-slump concrete without these admixtures. Allowing technicians to vibrate these high-slump concretes could reduce the time to mold standard test specimens compared with rodding.

The same standards specify three layers when rodding is used to consolidate 100 mm x 200 mm cylinders[1]. A recent study comparing the strengths of 100 mm x 200 mm cylinders with those of 150 mm x 300 mm cylinders of high-strength concrete showed that the smaller cylinders were denser (Carino, et al. 1994). The 100 mm cylinders were prepared by rodding using three layers. It was also found that the 100 mm cylinders were stronger, and it was surmised that this higher strength may be related to higher density. Perhaps only two layers are sufficient to prepare 100 mm diameter cylinders.

[1]For simplicity, cylinders are identified as 100 mm x 200 mm and 150 mm x 300 mm instead of the exact metric equivalents of their actual dimensions which are 4 x 8 in. and 6 x 12 in.

Objectives

The two factors mentioned in the above introduction provided the motivation for the experiments conducted. The objectives of the study include the following:

- Compare compressive strengths of cylinders prepared by vibration with those prepared by rodding.
- Investigate whether the experience of the operator affects the resulting cylinder compressive strength depending on whether vibration or rodding is used to consolidate the specimens.
- Compare the compressive strength of 100 mm x 200 mm cylinders when prepared by rodding using two versus three layers.

Before describing the experimental design and discussing the results, a brief historical review is presented on the subject of consolidation of standard test specimens.

BACKGROUND

The 1917 report of the ACI Committee on Specifications and Methods of Test for Concrete Materials, chaired by Sanford E. Thompson, was one of the earliest reports in the United States on the subject of preparing standard test specimens (ACI 1917). Based on tests in various laboratories, the authors of the report offered the following tentative recommendations:

- The shape for the test specimen should be a cylinder with a height of twice its diameter. *"The diameter should not be less than 6 in. except with very fine stone when 4 in. may be adopted."*
- The diameter should be at least four times the maximum size of the coarse aggregate particles.
- The strength of cubes or cylinders having a length equal to the diameter can be converted approximately to the strength of a standard cylinder by multiplying by 0.73.
- *"For field tests of concrete in actual construction, concrete should be taken from the loose mass after it is dumped from the barrow or other receptacle and before it is tamped or otherwise compacted."*
- Field test specimens should be embedded in moist sand near the structure until shipped to the laboratory. The specimens should be packed during shipment to retain moisture.

It is interesting to see how many of these recommendations have been carried over to modern standards for preparing test specimens. The 1917 report, however, did not mention the method of compaction.

In 1920, ASTM published the first standard on making and storing concrete specimens in the field (ASTM C 31-20T, 1920). The following procedure was specified for molding 6 in. x 12 in. (152 mm x 305 mm) cylinders:

> *"Test specimens shall be molded by placing the concrete in the form in layers approximately 4 in. in thickness. Each layer shall be puddled with 25 to 30 strokes with a 5/8 to 3/4 in. bar about 2 ft long, tapered slightly at the lower end."*

Thus we have the precedent of using three layers in molding the standard 150 mm x 300 mm cylinder. At that time, concrete was consolidated in the field by hand tamping, so only rodding was mentioned in the original version of ASTM C 31.

With the growing use of reinforced concrete in the 1920s, concrete members became thinner. As a result, wetter mixtures began to be used to permit consolidation by hand tamping in congested members (ACI 309, 1993). These wetter mixtures resulted in inferior concrete, and methods were sought as alternatives to hand tamping to permit consolidation of the drier mixtures. This led to the development around 1930 of vibration as a consolidation technique. Subsequently, several fundamental studies were carried out to understand the nature of the interactions between a vibrator and fresh concrete. The report of ACI Committee 309 (ACI 309, 1993) provides a review of these important studies.

As the use of vibration increased in the 1930s, questions were raised about the problem of over vibration and the benefits of revibration. In their classic paper, Tuthill and Davis (1938) provided practical guidance related to vibration. Over vibration occurs when the vibrator is left at the same location for a time longer than needed to consolidate thoroughly the concrete within the vibrator's zone of influence.

According to Tuthill and Davis (1938), vibration of fresh concrete results in two actions. First, voids are filled until the concrete, as a whole, reaches its lowest level in the forms. Then, with continued vibration, a *gravimetric separation process* begins to occur, causing the denser aggregates to settle and the mortar fraction to rise to the top surface. The mortar fraction that moves to the top will have a high water-cement ratio and result in inferior hardened properties. Thus vibration starts to become detrimental if it is continued beyond the point at which the voids are filled and large bubbles have escaped. If over vibration occurs in a cylindrical test specimen, there will be an accumulation of weaker material in the top portion that will limit the measured strength. Tuthill and Davis stated that:

> *"Vibration is generally considered to be effectively complete when considerable amounts of air ceases bubbling to the surface and when mortar begins to flush to the top, or, as it has been expressed, 'when the concrete mass appears to have "melted" to the point where the entire mix looks uniform.' Time, however, is not the only factor involved; the consistency and proportions of the mix, the type of vibrator, the condition and shape of the forms and the distance between points at which the vibrator is applied,—all may have a bearing upon whether over vibration is a continual difficulty or an occasional occurrence."*

Tuthill and Davis (1938) concluded that because of the many factors that have to be taken into account, it is difficult to write prescriptive specifications on the duration of vibration, and experience and watchfulness of field personnel are key factors in minimizing overvibration.

During the early 1940s, there appeared a series of questions in the "Job Problems and Practice" section of the *ACI Journal* dealing with overvibration and preparation of standard test specimens. In the April 1943 issue, the following question was posed: *"What maximum slump mixture* *should be permitted where concrete is to be placed by vibration?"* H.S. Meissner, chairman of the ACI committee on vibration, responded as follows (Meissner and Withey 1943):

> *"...Overvibration is more likely in a wet than a dry mix. There is therefore some limit in slump, above which vibratory methods are more liable to do more harm than good. In my opinion concrete having a slump greater than four inches can be easily, very easily, placed by spading, puddling, and rodding and that vibration would be a dangerous adjunct..."*

Prof. M.O. Withey of the University of Wisconsin stated:

> *"I think there is a danger from segregation when concrete with a slump of more than 4 in. is subjected to internal vibration."*

In the June 1943 issue of the *ACI Journal*, a question was asked about the best current practice for the consolidation of concrete cylinders by vibration (Anonymous 1943). The anonymous reply quoted the U.S. Bureau of Reclamation *Concrete Manual* (4th Ed.). It was recommended that 150 mm x 300 mm and 400 x 800 mm cylinders should be molded in two layers. Each layer should be compacted for 20 seconds with an internal vibrator of appropriate size. It was noted that in the Bureau laboratories vibrators with diameters of 25 or 29 mm were being used for 150 mm x 300 mm cylinders.

The same question about vibration of test cylinders appeared in the November 1944 issue of the *ACI Journal*. H.F. Gonnerman of the Portland Cement Association provided the following response (Gonnerman 1944):

> *"While a number of investigations have been conducted to determine the effects of vibration on concrete, we know of no specification or procedure recognized as standard for the consolidation of concrete test cylinders. The best procedure in a given case will depend on a number of factors, such as the type and properties of the vibrator, the proportions, water-cement ratio, grading, consistency, and other properties of the mix. The time of vibration should be just sufficient to consolidate thoroughly the entire mass, since continuing the vibration after consolidation has occurred is likely to produce segregation.*
> *...The mold is half-filled with concrete which is then consolidated with an internal vibrator (9,000 rpm). When consolidation of this layer is about completed and as the vibration proceeds an assistant fills the balance of the mold. The operator gradually withdraws the vibrator as consolidation takes place, care being taken to avoid leaving the vibrator in the mold too long as this will tend to give a core of mortar, particularly when the maximum size of coarse aggregate is 1 1/2 in."*

Gonnerman referred to other research studies that employed external vibration to prepare 150 mm x 300 mm cylinders. In one case, the external vibrator was operated at 3500 rpm, and a vibration period of 1 minute was used. In another study, external vibration at 3500 rpm was maintained for 1 1/4 min.

During the late 1950s and early 1960s, the use of low-slump concrete became more common in the construction of pavements and in manufacturing of precast, prestressed members. It was difficult to properly consolidate standard test cylinders of these low-slump concretes by rodding, as specified in the 1959 versions of ASTM C 31 and C 192. The ASTM subcommittee responsible for these standards undertook a study to provide the basis for revisions to permit vibration of low-slump concrete. Various laboratories participated in the study and compared the strengths of vibrated specimens with rodded specimens. One study involved three factors (Whitehurst and Goodwin 1963):

- Cement content (335 kg/m^3 and 445 kg/m^3)
- Slump ("No slump" = 0 mm to 5 mm, and "Low slump" = 25 mm to 50 mm)
- Consolidation method (rodding, internal vibration, and external vibration).

The internal vibrator had a diameter of 33 mm and a frequency greater than 166 Hz. External vibration was obtained by using a vibrating table operating at 58 Hz. Steel cylinder molds, 150 mm x 300 mm, were used, and 11 to 12 replicate specimens were tested for each condition. Unfortunately, the vibration times, number of penetrations, and number of layers were not reported. The resulting average compressive strength results are summarized in Fig. 1. The error bars represent the 95 % confidence limits for the averages. It can be seen that differences due to method of consolidation were most noticeable in the no-slump mixtures. For the mixture with high cement content, rodding resulted in weaker specimens for both levels of slump; whereas for the low cement content mixtures, the differences were significant only for the no-slump mixture. Note also that the variability was greater for the rodded no-slump specimens for both cement contents..

Another study involved two mixtures (Tynes 1962). One had a slump of 0 mm to 5 mm, and the other had a slump of 100 mm to 115 mm. Four consolidation methods were used to prepare 150 mm x 300 mm cylinders: (1) rodding; (2) an internal vibrator with a 19 mm diameter and a frequency of 183 Hz; (3) an internal vibrator with a 38 mm diameter and a frequency of 100 Hz; and (4) a vibrating table with a frequency of 60 Hz. The 150 mm x 300 mm cylinders were prepared in two layers, and three insertions of the vibrator were used for each layer. Five batches were made for each mixture, and three replicate specimens for each consolidation method were made from each batch. The vibration times in seconds for the bottom and top layers were as follows:

Slump, mm	Vibrating Table (EV)		Internal Vibration			
			38 mm diameter 100 Hz (IV-38)		19 mm diameter 183 Hz (IV-19)	
	Bottom	Top	Bottom	Top	Bottom	Top
100 to 115	3	6	6	8	6	8
0 to 5	10	20	12	16	12	16

Figure 2 summarizes the results of the study. The individual strengths have been normalized by dividing by the average for each concrete mixture. The average strengths produced by each consolidation method are shown as open circles. Overall, the effects of consolidation methods on the resulting strength are not large. Based on an analysis of variance (ANOVA), Tynes concluded that for the no-slump concrete, the average strengths of the cylinders prepared using the two types of internal vibrators were not statistically different. Likewise, there was no significant difference between the average strength of the rodded and externally vibrated specimens. However, there were statistically significant differences (at the 5 % level) between the average strengths of the internally vibrated cylinders and those obtained using the other two methods. In this case internal vibration produced the highest average strengths. For the high-slump concrete, there were no statistically significant differences between the average strengths of cylinders prepared by the vibration methods. On average, the rodded cylinders were 2 % to 4 % stronger than those prepared by the vibration methods, and the difference between the strengths of the rodded- and externally-vibrated cylinders was statistically significant (at the 5 % level).

Based on these and other studies in the early 1960s, modifications were made to ASTM C 31 and C 192. These changes permitted the use of vibration in preparing test specimens for concretes with slumps less than 75 mm, and it became mandatory to use vibration to prepare cylinders of no-slump concrete. However, for slumps greater than 75 mm, vibration was prohibited.

Gaynor (1968) reported on a study dealing with high-strength air-entrained concrete. Mixtures were made with different aggregates, cement contents, and air contents. The slumps of the mixtures were between 100 and 125 mm. Four nominal levels of air contents were used: 1.5 % (non air-entrained), 4.5 %, 7.5 %, and 10.5 %. For each batch, two cylinders were compacted by vibration and four cylinders were compacted by rodding. The vibrated cylinders were molded in two layers and two insertions of a 25 mm diameter vibrator were used per layer. The duration of the vibration was not reported. At 28 days, the vibrated and compacted cylinders were tested for compressive strengths. The following ratios of the vibrated-to-rodded cylinder strengths were obtained:

Nominal air content, %	Average Strength Ratio	Standard Deviation
1.5	1.01	0.02
4.5	1.04	0.02
7.5	1.08	0.03
10.5	1.11	0.04

Thus it was concluded that vibration of air-entrained concrete reduced the air content and resulted in higher cylinder strength. Limited density measurements confirmed a higher density for the vibrated cylinders.

In 1986, a field study was carried out by Texas Highway Department to compare the strengths of cylinders prepared by vibration and rodding (Perkins 1986). The program involved 15 different concrete mixtures typical of those used in prestressed and precast concrete. The slumps varied between 65 mm and 190 mm, and water-reducing admixtures were used to achieve the high slumps. Both 100 mm and 150 mm diameter cylinders were cast in steel molds. The cylinders were rodded in three layers according to ASTM C 31. Two layers were used for the vibrated 150 mm cylinders, and the vibrator was inserted at three points of each layer. The vibrator had a diameter of 22 mm. The vibrator was maintained in the concrete until the layer "became relatively smooth," and time of insertion varied between 3 s and 5 s. For the 100 mm diameter cylinders, two layers were used with one vibrator insertion per layer. The duration of insertion was also 3 s to 5 s. After vibration of each layer, the molds were tapped 5 times with a rubber mallet. Four cylinders were made for each combination of size and consolidation method. At 7 days and 28 days, two replicate cylinders were tested. Figure 3 shows the average strength of the replicate cylinders. We did an analysis of variance of Perkins' data and found no statistically significant difference between the vibrated and rodded cylinders. However, there was a significant interaction effect between the size and method. The vibrated 100 mm diameter cylinders were 0.7 % weaker than the rodded cylinders, a difference that is not statistically significant. The vibrated 150 mm cylinders were 1.3 % stronger than the rodded cylinders, which is a statistically significant difference at the 5 % level. An analysis of the effect of size showed that the rodded 100 mm diameter cylinders were 2 % stronger than the rodded 150 mm diameter cylinders. For the vibrated cylinders there was no difference due to size.

In comparing the results of these various investigations, it is noted that the Texas study used shorter vibration times than reported by Tynes. This could explain why the Texas study showed smaller differences between rodded and vibrated specimens. Thus the available evidence does not appear to support the prohibition of vibration to mold specimens of concrete with slumps greater than 75 mm. The present study intended to gain further insight into the relationships between the cylinder compressive strength and the consolidation method.

Current ASTM Requirements

ASTM Practices C 31/C 31/M and C 192/C 192M provide procedures for preparing standard test specimens in the field and in the laboratory, respectively. The following excerpt from ASTM C 31/C 31M (ASTM C 31/C 31M 1995) deals with the vibration procedure:

> "*Maintain uniform time period for duration of vibration for the particular kind of concrete, vibrator, and specimen mold involved. The duration of the vibration required will depend upon workability of the concrete and the effectiveness of the vibrator. Usually sufficient vibration has been applied as soon as the surface of the concrete has become relatively smooth. Continue vibration only long enough to achieve proper consolidation of the concrete. Overvibration may cause segregation. Fill the molds and vibrate in the required number of approximately equal layers. Place all concrete for each layer in the mold before starting vibration of that layer. In compacting the specimen, the vibrator shall not be allowed to rest on the bottom or sides of the mold. Carefully withdraw the vibrator in such a manner that no air pockets are left in the specimen. When placing the final layer, avoid overfilling by more than 1/4 in. [6 mm].*"

For the vibration of cylinders, the following additional procedure is given:

> "*Use three insertions of the vibrator at different points for each layer. Allow the vibrator to penetrate through the layer being vibrated, and into the layer below, approximately 1 in. [25 mm]. After each layer is vibrated, tap the outsides of the mold lightly 10 to 15 times with the mallet, to close any holes that remain and to release any large air bubbles that may have been trapped. Use an open hand to tap light-gage single-use molds which are susceptible to damage if tapped with a mallet*."

Similar requirements are given in C 192/C 192M (ASTM C 192/C 192M 1995). The diameter of the internal vibrator shall be no more than 1/4 of the cylinder diameter. However, C 192/C 192M prohibits vibration of 100 mm diameter cylinders.

EXPERIMENTAL PROCEDURE

Scope

As mentioned in the introduction, the present study was designed to examine the effects of different consolidation methods on the resulting compressive strengths of cylinders. It was also desired to establish whether the effects of consolidation method depended on other factors. Factorial experiments were designed and the following factors (and their settings) were investigated:

- Slump (<75 mm or > 75 mm)
- Cement content (normal or high)
- Cylinder diameter (100 mm or 150 mm)
- Method of consolidation (rodding or vibration)
- Operator (B = experienced or A = novice)
- Number of layers for rodded 100 mm x 200 mm cylinders (2 or 3)

Concrete Mixtures

Four concrete mixtures were used. The proportions and fresh concrete properties are shown in Table 1. The coarse aggregate was a crushed traprock of 12.5 mm maximum size, and the fine aggregate was washed natural sand. Type I cement and densified silica fume were used. All mixtures were air entrained. Mixture 1 (NL) had a normal cement content and low slump. Mixture 2 (NH) had a normal cement content and high slump. Mixture 3 (HL) had a high cement content and low slump. Mixture 4 (HH) had a high cement content and high slump.

Design of Experiment

This study included two experiments: a *consolidation* experiment and a *layers* experiment. The *consolidation experiment* was designed to compare cylinder strengths of specimens prepared by rodding or vibration. A half-fraction, factorial experiment was used with a high and low setting of five factors: *cement content*, *slump*, *cylinder size*, *consolidation method*, and *operator*. The generator for the design was chosen so that the factor *operator* was confounded with the 4-factor interaction (*cement content*slump*size*method*). See a textbook on experiment design for additional explanation, such as Box, Hunter, and Hunter (1978). A half-fraction factorial design permits measuring the effects of the main factors and the two-factor interactions, under the assumption that all three-factor and four-factor interactions are negligible. Since there are 5 factors, the half-fraction factorial experiment has 16 runs, that is, 16 distinct combinations of the factors. These are shown in Table 2. Three replicate specimens were prepared for each run, for a total of 48 individual tests. An extra vibrated cylinder was molded for subsequent cutting to examine aggregate distribution in the hardened specimens. To make the experiment more practical to run, the experimental runs were divided into *blocks* determined by the four batches of concrete to be mixed. Two batches were run each day. Blocking the experiment this way confounds the effects of cement content, slump, and their interaction with differences between days and batches. However, since the effects of cement content and slump are well known, the ability to estimate those effects is not important to us. As mentioned earlier, the effects of primary interest are consolidation method, cylinder size, operator, and interactions of these factors with all of the other factors.

The *layers experiment* was designed to compare the strengths of 100 mm diameter cylinders prepared by rodding using two layers with the strengths of 100 mm cylinders rodded in three layers and of 150 mm cylinders rodded in three layers. The three *size-consolidation* conditions are called the factor *group*. The lower portion of Table 2 shows the experiment design. Note that four of the runs from the *consolidation experiment* are also used in the *layers experiment*. This means that the strength data were used in the analyses of both experiments. For this part of the experiment, only the experienced operator (B) was involved. Thus the fixed factors in the *layers experiment* are *group*, *cement content*, and *slump*. The blocking of the *layers experiment* was similar to blocking of the *consolidation experiment*.

Procedure

As described above, specimens for the normal cement content mixtures [1 (NL) and 2 (NH)] were cast on one day, and specimens for the high cement content mixtures [3 (HL) and 4 (HH)] were cast on the following day. The plastic molds were labeled and placed in random order on the floor where they would be filled. The experienced operator (B) gave instructions to the novice operator (A) on how to fill, consolidate, and strike off the cylinders. Each operator filled all the molds with the first layer, which was subsequently consolidated, before filling the remaining layers. The internal vibrator had a shaft diameter of 27 mm and a frequency of 133 Hz measured in air[2]. The

[2]According to ASTM requirements, the diameter of the vibrator must be less than 1/4 of the cylinder diameter. Thus the vibrator is about 2 mm larger in diameter than permitted. It was assumed that this minor difference would not have a significant effect on the results.

consolidation requirements in ASTM C 31 were used for the *consolidation experiment*; that is, the 100 mm and 150 mm cylinders were rodded in three layers (25 strokes per layer) and vibrated in two layers. Current vibration requirements in C 31 and C 192 specify three insertions of the vibrator per layer. It was believed that this would be excessive for the 100 mm cylinders. Thus these were vibrated using one insertion per layer. The vibrator was inserted slowly, maintained for one second, and then slowly extracted. In the *layers experiment*, all specimens were rodded in approximately equal layers. Each plastic mold was struck lightly 10 times with a rubber mallet after each layer had been consolidated. After the cylinders had been struck off, they were carefully picked up and submerged in a water tank in the moist room. The water tank was used to moderate temperature differences between the cylinders. One day after casting, the cylinders were removed from their molds, and their masses were measured in air and under water to obtain their densities. The cylinders were stored in a moist room until the day they were capped with a sulfur capping compound.

One week before compression testing, the cylinders were capped with a sulfur capping compound. The heights of the cylinders were measured before and after capping both ends. These heights were used to estimate the average cap thicknesses. An effort was made to produce thin caps, and the average cap thickness based on the length measurements was 2.6 mm with a standard deviation of 0.5 mm. After being capped, the cylinders were returned to the moist room until the time of testing.

The cylinders were tested at an age of 28 days. The order of testing was randomized. The cylinders were loaded in a 4.45-MN capacity, manually-operated testing machine. The stress rate during the linear portion of the stress-strain curve was about 0.25 MPa/s.

Data Transformation and Analysis

As in a previous study (Carino et al. 1994), the compressive-strength values were converted by taking their natural logarithms. This was done to better satisfy the assumption that the within-test standard deviation is constant over the strength level. In addition, the transformed values were adjusted by subtracting the average transformed value of each mixture. This adjustment causes the factors cement content and slump to have zero effect in the data analysis, but it allows for interaction of these factors with the other factors. The values of adjusted transformed strength are approximately equal to fractional strength differences, for example, a value of 0.02 represents a difference of approximately 2 % between the strengths at the high and low levels of the factor.

Commercial software was used to carry out data analysis to identify which factors and interactions had statistically significant effects on measured cylinder strength. For the *consolidation experiment*, analyses were done using both the "regression analysis" and the "general linear model" capabilities of the software. The results are identical with respect to identifying the significant factors, but regression analysis gives directly the main effects and the two-factor interactions. On the other hand, the general linear model portion of the software allows for examination of differences between means.

In a balanced factorial experiment with two levels for each factor, such as was used here, an *effect* is the difference in the average of all the results at the high setting minus the average of all the results at the low setting. For example, the effect of cylinder size is the average of all the 150 mm cylinder results minus the average of all the 100 mm cylinder results. Because logarithms of strengths are used, the value of an effect is approximately a fractional difference. For example, if an effect has a value of 0.02, the average of the results at the high setting are about 2 % greater than the results at the low setting. If the effect has a negative value, it means the average at the high setting is smaller than the average at the low setting.

For the *layers experiment*, there were three levels for the method of consolidation. Since this was not amenable to regression analysis, only the general linear model was used to analyze the results. The analysis software permitted an *analysis of variance* to establish which factors had statistically significant effects and a *post-hoc test* (Scheffé method) was used to examine the significance of strength differences for various combinations of factors.

RESULTS AND DISCUSSION

Density

In order to examine whether the consolidation methods affected the densities of the cylinders, an analysis was performed on the densities measured after removing the molds. Table 3 shows the measured densities for each cylinder from the 24 runs. The ID numbers indicate the following (from left to right):

- N and H indicate normal or high cement content [N = –1, H = +1],
- L and H indicate low or high slump [L = –1, H = +1],
- R and V indicate rodding or vibration [R = –1, V = +1],
- The numbers 2 or 3 indicate the number of layers, and
- B and A indicate the operator [B = experienced = –1 , A = novice = +1].

The "–1" and "+1" indicate the "low" and "high" setting of the factors that were used for the values of the independent variables in the regression analysis.

To simplify comparisons of the effects of consolidation methods and to investigate interactions among the factors, the individual densities were normalized by dividing by the average for each mixture. These average values are shown at the bottom of Table 3. The resulting density ratios were used in subsequent data analyses.

Table 4 shows the results of the data analysis for the runs belonging to the *consolidation experiment*. The linear regression approach was used; and, as mentioned above, the values of the independent variables (the factors and the two-factor interactions) were taken as "–1" or "+1" depending on the factor settings. The numbers in the column labeled "Coefficient" are one-half the values of the effects, that is, one-half the difference between the average density ratios at the high and low settings. The column labeled "Probability" gives the likelihood of the value of the coefficient due to solely random effects. A value of probability less than 0.01 is usually interpreted to mean that the effect is highly significant (statistically), that is, there is a low probability that the measured difference is due to chance.

Examination of the values in Table 4 shows that there were no main effects, that is, the factors *size, method* and *operator* did not have statistically significant effects on density. However, there were significant two-factor interactions: namely, *size*method* and *method*operator*. Figures 4 and 5 help to illustrate the meaning of these two-factor interactions.

Figure 4 is a two-way table to explain the *size*method* interaction effect. The number within the circles are the average density ratios for the different combinations of cylinder size and consolidation method. The numbers between the circles are the differences between the average values, and they represent the size of the effect. The "**" symbol signifies highly significant effects, that is, a probability level less than 0.01, and the "*" symbol signifies a probability level less than 0.05 that the effect is due to chance. It can be seen that for the rodded cylinders, the density ratio of the 100 mm cylinders is 0.004 greater than for the 150 mm cylinders. Likewise, for the 100 mm cylinders, the rodded specimens had a density ratio that is 0.004 greater than the vibrated specimens

Figure 5 helps to explain the *method*operator* interaction effect. It can be seen that the rodded cylinders prepared by operator A (inexperienced) are slightly denser than the vibrated cylinders and denser than the rodded cylinders produced by operator B.

In summary, analysis of the densities revealed that the rodded, 100 mm cylinders were the most dense. Since there is a correlation between specimen density and compressive strength, it is anticipated that the rodded 100 mm cylinders will be strongest.

Strength

Consolidation Experiment—Table 5 shows the compressive strengths and adjusted transformed strengths (subtracting overall mean of each mixture) for each specimen in the *consolidation experiment*. The ID designations are as described above, with the addition of a replicate number at the end of each designation.

Figures 6 and 7 show the cylinder strength and adjusted transformed strength, respectively, versus the run number. These figures show that one of the results for Run 11 had an abnormally low value. Examination of the cylinder after testing did not reveal an obvious cause of the low strength. However, it was judged to be an outlier and that result was not used in subsequent analyses.

The adjusted transformed strengths were analyzed using multi-variate, linear regression. Table 6 shows the results of the analysis. The “coefficient” column gives one-half the values of the effects, for example, the value -0.0075 for the variable *size* means that, overall, the 150 mm cylinders are about 1.5 % weaker than the 100 mm cylinders. The main effects and the two-factor effects that are statistically significant (probability less than 0.05) are shown with shading in the “variable” column. A review of Table 6 reveals that *cylinder size* and *consolidation method* have statistically significant effects on cylinder strength. The *cement content* and *slump* have no effect because, as explained, adjusted transformed strengths, instead of the measured strength values, are used in the analysis. The factor *operator* does **not** have a statistically significant effect. On average, the cylinders made by the inexperienced operator are 0.8 % weaker than those made by the experienced operator ($2 \times -0.0042 \times 100$ %) which is not statistically significant for this data set.

As mentioned, *on average*, the 100 mm cylinders are 1.5 % stronger than the 100 mm cylinders. However, the two-factor interaction *cement-content*size* also has a statistically significant effect. This means that, in this experiment, the effect of cylinder size depends on the cement content. Figure 8 helps to explain the situation. The numbers within the circles are the average transformed strengths for the four combinations of *cement content* and *cylinder size*. It can be seen that for the normal cement content there is no significant difference between the strengths of the 150 mm and 100 mm diameter cylinders. However, for the high cement content, the 100 mm cylinders are 3.4 % stronger. Thus it appears that when cylinders are made according to current standards, size appears to have a significant influence on strength at the high cement content, that is, for higher-strength concrete.

Table 6 also shows that, *on average*, the consolidation method had a statistically significant effect. Specifically, vibration resulted in 4.3 % lower strength ($2 \times -0.0214 \times 100$ %) than rodding. There is, however, also a statistically significant *size*method* interaction effect. Figure 9 illustrates the significance of this interaction. For the 150 mm cylinders, there is no statistically significant difference in strength between vibrated and rodded specimens. On the other hand, for the 100 mm cylinders, the rodded specimens are 7.4 % stronger. Recall that the 100 mm cylinders in the *consolidation experiment* were rodded using three layers, as is required by current ASTM standards. For rodded specimens, the 100 mm cylinders are 4.6 % stronger than the 150 mm cylinders. For the vibrated specimens, the 150 mm cylinders are 1.6 % stronger. The vibrated 100 mm cylinders are the weakest (as indicated by the lowest average adjusted transformed strength of –0.029). Recall that the 150 mm cylinders had three insertions of the vibrator per layer compared with one insertion for the 100 mm cylinders. To repeat, the ASTM requirement of three vibrator insertions per layer was not followed for the 100 mm cylinders because it was believed to be excessive for the smaller specimens.

Discussing the effects not found significant is important also. For example, the interaction *cement content*method* is not statistically significant. This means that the effect of the consolidation method on strength does not depend on the cement content. There is also no significant *slump*method* interaction, which means that the effect of consolidation does not depend on the slump of the concrete. This is very important because it does not support the current ASTM restriction against vibration of mixtures with slump greater than 75 mm. Recall that the vibration time was kept short in this study. Finally, the factor *operator* and all two-factor interactions that included this factor have no statistically significant effects. This shows that special skill is not required to consolidate specimens properly. In particular, cylinder preparation using vibration rather than rodding does not appear to require special operator skill, provided the operator is instructed on proper procedures.

Layers Experiment—Table 7 shows the cylinder strengths and the adjusted transformed strengths for the *layers experiment*. The three different *groups* are identified as follows:

- R3-100 = 100 mm cylinders rodded using 3 layers,
- R2-100 = 100 mm cylinders rodded using 2 layers, and
- R3-150 = 150 mm cylinders rodded using 3 layers.

Figure 10 shows the individual adjusted transformed strengths arranged according to the three groups. This figure shows that, on average, the 100 mm cylinders that were rodded using three layers are 3 % stronger than the 150 mm cylinders. This compares with the difference of 4.6 % obtained in the *consolidation experiment* (Fig. 9).

The results of the experiment were analyzed using the *general linear model* approach. This approach incorporates *analysis of variance* to establish whether there are statistically significant differences among the means corresponding to different factor combinations. Table 8 shows the results of the analysis of variance, and the factor combinations having statistically significant effects are shown with shading. Thus the effect of *group* is statistically significant, as are the interactions *cement content*group* and *slump*group*. Thus the effect of *group* depends on the other two factors.

To examine the results further, Table 9 shows the average adjusted transformed strengths for each of the 12 combinations of the three factors: *group, cement content*, and *slump*. Each number is the average of three replicate test specimens. The computer program computed the differences among all possible combinations of the 12 average values, and assigned a probability level based on the Scheffé method of multiple comparisons. Table 10 lists the differences between groups within each mixture that were statistically significant. These differences are also shown graphically in Fig. 11, which shows the individual results grouped by mixture and *group*.

Figure 10 shows that, on average, group R3-100 cylinders are strongest, group R3-150 are weakest, and group R2-100 are midway between the two. However, Fig. 11, shows that this pattern is not consistent within each mixture, and this is the reason for the statistically significant two-factor interactions as shown in Table 8. These results appear to show that the differences between *groups* are more pronounced in the high cement content mixtures. However, even in the case (NL) where the average strength of the R2-100 cylinders differs from the strength of the

R3-150 cylinders more than the strength of R3-100 cylinders, the effect is no worse than in the case (HL) where the strength of R3-100 cylinders differs most from the strength of R3-150 cylinders. This fact, combined with the main effect that shows the R2-100 cylinders to be more similar to the R3-150 cylinders than the R3-100 cylinders, on average, suggest that 2-layer consolidation is preferable to 3-layer consolidation for rodded 100 mm cylinders.

Evidence of Segregation

As mentioned, concrete specimens made of high-slump mixtures are not permitted to be vibrated to avoid the possibility of segregation by settlement of coarse aggregate and rise of water. To examine whether settlement of coarse aggregate occurred in the vibrated high-slump mixtures, cylinders were cut longitudinally. The cut surfaces were examined visually for evidence of segregation. Figure 12 shows the cross-sections of 100 mm cylinders from the high-slump mixtures and Fig. 13 shows cross-sections of the cylinders from the low-slump mixtures. Evidence of segregation is noted, but it is not of the type addressed by the ASTM restriction. There are mortar-rich pockets in the centers of the cylinders, which are more pronounced in the low-slump mixtures. Apparently, when the vibrator is withdrawn, the coarse aggregate particles do not flow readily back to their original positions resulting in a non-uniform distribution of coarse aggregate particles. Perhaps this problem could have been reduced in this study if the vibrator had been withdrawn more slowly.

SUMMARY

Consolidation Experiment

This experiment was designed to determine whether the consolidation method (rodding or vibration) used to prepare standard test specimens affects the cylinder strength. Cylinders were rodded in three layers and vibrated in two layers, according to current requirements in C 31 and C 192. Four mixtures were used that included different cement contents and different slumps. In addition, the influence of operator experience was also studied. Based on statistical analysis of the half-fraction factorial experiment, the following observations were made:

- Overall, the 100 mm cylinders were 1.5 % stronger than the 150 mm cylinders. However, because of a significant interaction effect of *size*cement content*, the difference was 3.4 % at the high cement content, and there was no significant difference at the low cement content.
- Overall, the rodded cylinders were 4.2 % stronger than the vibrated cylinders, but there was a significant interaction effect of *method*size*. As a result, the rodded 100 mm cylinders were 7.4 % stronger than the vibrated 100 mm cylinders, but there was no significant difference between the rodded and vibrated 150 mm cylinders. The vibrated 100 mm cylinders were the weakest. In the *consolidation experiment*, the 100 mm diameter cylinders were rodded using three layers.
- The experience of the operator did not affect the resulting strengths. However, the novice

operator had been instructed on the proper techniques by a highly experienced operator.

- There was no significant interaction between *slump* and *method*. Thus there was no support for the current ASTM restriction against vibrating high-slump mixtures.
- There was no significant interaction between *cement content* and *method*.

These results do not support the current restriction against vibration of mixtures with slumps greater than 75 mm. In addition, the observed differences between the strengths of 100 mm and 150 mm cylinders may be caused by the current requirements of rodding 100 mm cylinders using three layers.

Layers Experiment

This experiment was designed to determine whether the differences between the strengths of rodded 100 mm and 150 mm cylinders could be reduced by using two layers for the 100 mm cylinders. Based on statistical analysis of the data, the following observations were made:

- On average, the 100 mm cylinders rodded in three layers (group R3-100) were 3 % stronger than the 150 mm cylinders (group R3-150), but the difference was reduced to 1.5 % for 100 mm cylinders rodded using two layers (group R2-100).
- There were significant interactions of the factor *group* with *cement content* and *slump*. It appeared that the high cement content mixtures were more sensitive to the details of the consolidation method than the normal cement content mixtures.

Recommendations

Based on the findings of this study, the following recommendations are made:

- The restriction against using vibration to prepare test specimens of high-slump concretes should be removed because there is insufficient evidence to suggest that vibration will cause settlement of the aggregate in the cylinder molds. However, the vibration procedures in ASTM C 31 and C 192 should be revised to include a time limit on the duration of vibration when high-slump concretes are used. Based on experience, a duration of 5 seconds per insertion may be sufficient.
- Studies should be conducted to determine whether the mortar pockets observed in this study can be reduced by proper vibration techniques.
- The consolidation procedures in ASTM C 31 and C 192 should be modified so that only two layers are used when using rodding to prepare 100 mm diameter cylinders.

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TABLE 1—MIXTURE PROPORTIONS (per m^3) AND FRESH CONCRETE PROPERTIES

	Mixture 1 (NL)	Mixture 2 (NH)	Mixture 3 (HL)	Mixture 4 (HH)
Cement, kg	272	264	479	448
Silica fume (SF), kg	0	0	39	36
Cement + SF, kg	272	264	518	484
Coarse aggregate, kg	1100	1069	963	900
Fine Aggregate, kg	861	809	784	733
Water, kg	149	164	159	151
Air entraining agent, L	0.09	0.06	0.34	0.32
HRWR, L	0	0	7.33	11.54
w/c	0.55	0.62	0.31	0.31
Batch size, m^3	0.075	0.092	0.087	0.078
Slump, mm	32	171	89	248
Temperature, ˚C	24	24	26	26
Fresh density, kg/m^3	2383	2306	2422	2266
Air content (Press.), %	5.0	6.2	4.2	8.4
Air content (Grav.), %	5.9	7.7	4.3	10.4

TABLE 2—EXPERIMENT DESIGN

Run No.	Day	Cement Content	Slump	Size, mm	Method	Layers	Operator
Consolidation Experiment							
1		Low	Low	100	Rod	3	A
2		Low	Low	100	Vibrate	2	B
3		Low	Low	150	Rod	3	B
4	1	Low	Low	150	Vibrate	2	A
5		Low	High	100	Rod	3	B
6		Low	High	100	Vibrate	2	A
7		Low	High	150	Rod	3	A
8		Low	High	150	Vibrate	2	B
9		High	Low	100	Rod	3	B
10		High	Low	100	Vibrate	2	A
11		High	Low	150	Rod	3	A
12	2	High	Low	150	Vibrate	2	B
13		High	High	100	Rod	3	A
14		High	High	100	Vibrate	2	B
15		High	High	150	Rod	3	B
16		High	High	150	Vibrate	2	A
Layers Experiment							
17		Low	Low	100	Rod	3	B
18		Low	Low	100	Rod	2	B
3	1	Low	Low	150	Rod	3	B
5		Low	High	100	Rod	3	B
19		Low	High	100	Rod	2	B
23		Low	High	150	Rod	3	B
9		High	Low	100	Rod	3	B
20		High	Low	100	Rod	2	B
24	2	High	Low	150	Rod	3	B
21		High	High	100	Rod	3	B
22		High	High	100	Rod	2	B
15		High	High	150	Rod	3	B

TABLE 3—DENSITIES OF HARDENED CYLINDERS

Mixture	ID	Run	Diameter (mm)	Density, Mg/m³		
				Replicate 1	Replicate 2	Replicate 3
1	NL-R3-B	17	100	2.428	2.434	2.417
	NL-R2-B	18	100	2.435	2.425	2.429
	NL-R3-A	1	100	2.440	2.444	2.434
	NL-V2-B	2	100	2.436	2.429	2.419
	NL-R3-B	3	150	2.434	2.434	2.424
	NL-V2-A	4	150	2.429	2.431	2.419
2	NH-R2-B	19	100	2.391	2.400	2.407
	NH-R3-B	5	100	2.402	2.398	2.409
	NH-V2-A	6	100	2.410	2.401	2.401
	NH-R3-A	7	150	2.400	2.407	2.400
	NH-V2-B	8	150	2.422	2.423	2.427
	NH-R3-B	23	150	2.391	2.404	2.397
3	HL-R2-B	20	100	2.459	2.455	2.442
	HL-R3-B	9	100	2.459	2.450	2.462
	HL-V2-A	10	100	2.439	2.453	2.445
	HL-R3-A	11	150	2.450	2.454	2.449
	HL-V2-B	12	150	2.451	2.448	2.450
	HL-R3-B	24	150	2.446	2.446	2.451
4	HH-R3-B	21	100	2.406	2.379	2.408
	HH-R2-B	22	100	2.387	2.384	2.375
	HH-R3-A	13	100	2.426	2.402	2.408
	HH-V2-B	14	100	2.400	2.374	2.403
	HH-R3-B	15	150	2.386	2.391	2.385
	HH-V2-A	16	150	2.403	2.383	2.402

Mixture	Average Density, Mg/m³	Stand. Dev. of Density, Mg/m³
1	2.430	0.007
2	2.405	0.010
3	2.451	0.006
4	2.395	0.014

TABLE 4—RESULTS OF DATA ANALYSIS (REGRESSION) OF DENSITY RATIO (CONSOLIDATION EXPERIMENT)

R squared = 57.7 % R squared (adjusted) = 37.9 %
s = 0.0031 with 48 - 16 = 32 degrees of freedom

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-ratio
Regression	0.000424	15	0.00003	2.92
Residual	0.000311	32	0.00001	

Variable	Coefficient	Standard Error of Coefficient	t-ratio	Probability
Constant	1.000010	0.0004	2.224	≤ 0.0001
Cement Content (CC)	0.000000	0.0004	0.000	0.9963
Slump	0.000000	0.0004	0.000	0.9890
CC*Slump	0.000000	0.0004	0.000	0.9963
Size	-0.000385	0.0004	-0.857	0.3978
CC*Size	-0.000815	0.0004	-1.810	0.0795
Slump*Size	0.000265	0.0004	0.588	0.5604
Method	-0.000415	0.0004	-0.922	0.3634
CC*Method	-0.000777	0.0004	-1.730	0.0936
Slump*Method	0.001002	0.0004	2.230	0.0330
Size*Method	0.001710	0.0004	3.800	0.0006
Operator	0.000140	0.0004	0.310	0.7583
CC*Operator	0.000844	0.0004	1.880	0.0697
Slump*Operator	0.000273	0.0004	0.607	0.5482
Size*Operator	-0.000944	0.0004	-2.100	0.0438
Method*Operator	-0.001248	0.0004	-2.780	0.0091

TABLE 5—CYLINDER STRENGTH RESULTS FOR CONSOLIDATION EXPERIMENT

Run	ID	Cylinder Strength, MPa	Adjusted Transformed Strength
1	NL-R3-A-1	29.66	0.025120
	NL-R3-A-2	29.52	0.020600
	NL-R3-A-3	29.31	0.013536
2	NL-V2-B-1	27.56	-0.048139
	NL-V2-B-2	28.31	-0.021396
	NL-V2-B-3	29.02	0.003550
3	NL-R3-B-1	28.42	-0.017477
	NL-R3-B-2	29.72	0.027248
	NL-R3-B-3	29.55	0.021639
4	NL-V2-A-1	28.43	-0.016963
	NL-V2-A-2	29.07	0.005186
	NL-V2-A-3	28.55	-0.012904
5	NH-R3-B-1	24.82	0.009139
	NH-R3-B-2	25.65	0.041940
	NH-R3-B-3	25.98	0.054680
6	NH-V2-A-1	23.83	-0.031683
	NH-V2-A-2	23.46	-0.047373
	NH-V2-A-3	23.55	-0.043659
7	NH-R3-A-1	24.50	-0.003954
	NH-R3-A-2	24.74	0.005852
	NH-R3-A-3	24.72	0.004937
8	NH-V2-B-1	24.78	0.007518
	NH-V2-B-2	24.65	0.002306
	NH-V2-B-3	24.60	0.000296
9	HL-R3-B-1	71.75	0.053795
	HL-R3-B-2	71.89	0.055719
	HL-R3-B-3	71.62	0.052061
10	HL-V2-A-1	64.91	-0.046400
	HL-V2-A-2	68.00	0.000188
	HL-V2-A-3	64.90	-0.046539
11	HL-R3-A-1	67.31	-0.010137
	HL-R3-A-2	67.46	-0.007901
	HL-R3-A-3	59.50*	Outlier
12	HL-V2-B-1	66.36	-0.024212
	HL-V2-B-2	67.76	-0.003426
	HL-V2-B-3	67.04	-0.014128
13	HH-R3-A-1	62.34	0.057721
	HH-R3-A-2	63.23	0.072049
	HH-R3-A-3	63.46	0.075675
14	HH-V2-B-1	59.41	0.009674
	HH-V2-B-2	55.63	-0.056175
	HH-V2-B-3	57.41	-0.024565
15	HH-R3-B-1	57.91	-0.015905
	HH-R3-B-2	58.86	0.000286
	HH-R3-B-3	58.01	0.014135
16	HH-V2-A-0	58.62	-0.003719
	HH-V2-A-2	55.18	-0.064136
	HH-V2-A-3	56.71	-0.036770

TABLE 6—RESULTS OF DATA ANALYSIS (REGRESSION) OF ADJUSTED TRANSFORMED CYLINDER STRENGTHS (CONSOLIDATION EXPERIMENT)

R squared = 81.2 %   R squared (adjusted) = 72.0 %
s = 0.0181 with 47 - 16 = 31 degrees of freedom

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-ratio
Regression	0.043960	15	0.002931	8.90
Residual	0.010209	31	0.000329	

Variable	Coefficient	Standard Error of Coefficient	t-ratio	Probability
Constant	0	0.0027	0.000	1.0000
Cement Content (CC)	0	0.0027	0.000	1.0000
Slump	0	0.0027	0.000	1.0000
CC*Slump	0	0.0027	0.000	1.0000
Size	-0.007480	0.0027	-2.810	0.0085
CC*Size	-0.009454	0.0027	-3.550	0.0012
Slump*Size	-0.002305	0.0027	-0.867	0.3928
Method	-0.021395	0.0027	-8.040	≤ 0.0001
CC*Method	-0.004456	0.0027	-1.680	0.1039
Slump*Method	-0.002629	0.0027	-0.988	0.3306
Size*Method	0.015462	0.0027	5.810	≤ 0.0001
Operator	-0.004179	0.0027	-1.570	0.1263
CC*Operator	0.002597	0.0027	0.976	0.3366
Slump*Operator	0.002924	0.0027	1.100	0.2801
Size*Operator	-0.000802	0.0027	-0.301	0.7651
Method*Operator	-0.003158	0.0027	-1.190	0.2442

TABLE 7—CYLINDER STRENGTH RESULTS FOR LAYERS EXPERIMENT

Run	ID	Cylinder Size, mm	Layers	Group	Cylinder Strength, MPa	Adjusted Transformed Strength
17	NL-R3-B-1 NL-R3-B-2 NL-R3-B-3	100	3	R3-100	29.438 29.435 29.286	-0.007256 -0.007359 -0.012459
18	NL-R2-B-1 NL-R2-B-2 NL-R2-B-3	100	2	R2-100	30.234 30.035 30.814	0.019407 0.012819 0.038411
3	NL-R3-B-1 NL-R3-B-2 NL-R3-B-3	150	3	R3-150	28.420 29.720 29.553	-0.042468 0.002257 -0.003352
5	NH-R3-B-1 NH-R3-B-2 NH-R3-B-3	100	3	R3-100	24.823 25.651 25.979	-0.010945 0.021855 0.034595
19	NH-R2-B-1 NH-R2-B-2 NH-R2-B-3	100	2	R2-100	24.997 24.790 24.848	-0.003937 -0.012265 -0.009927
23	NH-R3-B-1 NH-R3-B-2 NH-R3-B-3	150	3	R3-150	25.330 24.611 24.868	0.009284 -0.019529 -0.009131
9	HL-R3-B-1 HL-R3-B-2 HL-R3-B-3	100	3	R3-100	71.749 71.887 71.625	0.025789 0.027713 0.024055
20	HL-R2-B-1 HL-R2-B-2 HL-R2-B-3	100	2	R2-100	69.360 71.209 71.354	-0.008069 0.018234 0.020272
24	HL-R3-B-1 HL-R3-B-2 HL-R3-B-3	150	3	R3-150	67.398 67.364 67.589	-0.036773 -0.037275 -0.033945
21	HH-R3-B-1 HH-R3-B-2 HH-R3-B-3	100	3	R3-100	59.749 59.662 61.102	0.021210 0.019748 0.043602
22	HH-R2-B-1 HH-R2-B-2 HH-R2-B-3	100	2	R2-100	56.858 57.469 56.978	-0.028395 -0.017704 -0.026284
15	HH-R3-B-1 HH-R3-B-2 HH-R3-B-3	150	3	R3-150	57.911 58.856 58.013	-0.010046 0.006144 -0.008276

TABLE 8—ANALYSIS OF VARIANCE OF ADJUSTED TRANSFORMED STRENGTH FOR LAYERS EXPERIMENT

Source	Degrees of Freedom	Sums of Squares	Mean Square	F-ratio	Probability
Constant	1	0.000000	0.000000	0.00000	1.0000
Cement Content	1	0.000000	0.000000	0.00000	1.0000
Slump	1	0.000000	0.000000	0.00000	1.0000
CC*Slump	1	0.000000	0.000000	0.00000	1.0000
Group	2	0.005511	0.002756	15.682	≤ 0.0001
CC*Group	2	0.002616	0.001308	7.4448	0.0031
Slump*Group	2	0.005047	0.002524	14.362	≤0.0001
CC*Slump*Group	2	0.000789	0.000394	2.2450	0.1277
Error	24	0.004217	0.000176		
Total	35	0.018181			

TABLE 9—MEAN VALUES OF AVERAGE ADJUSTED STRENGTHS FOR COMBINATIONS OF *CEMENT CONTENT*, *SLUMP*, AND *GROUP* IN LAYERS EXPERIMENT

Cement Content	Group	Slump	
		Low	High
Normal	R3-100	-0.0090	0.0152
	R2-100	0.0235	-0.0087
	R3-150	-0.0145	-0.0065
High	R3-100	0.0259	0.0282
	R2-100	0.0101	-0.0241
	R3-150	-0.0360	-0.0041

TABLE 10—SIGNIFICANT DIFFERENCES BETWEEN MEANS OF *GROUPS* WITHIN EACH MIXTURE FROM LAYERS EXPERIMENT

Reference letter in Fig. 11	Mixture	Difference		Probability
		I.D.	Value	
a	1 (NL)	(R3-100) – (R2-100)	-0.0326	0.0108*
b		(R2-100) – (R3-150)	0.0381	0.0068*
		(R3-100) – (R3-150)	0.0055	0.8796
	2 (NH)	(R3-100) – (R2-100)	0.0239	0.1091
		(R2-100) – (R3-150)	-0.0022	0.9786
		(R3-100) – (R3-150)	0.0216	0.1578
	3(HL)	(R3-100) – (R2-100)	0.0157	0.3644
d		(R2-100) – (R3-150)	0.0461	0.0011*
c		(R3-100) – (R3-150)	0.0619	< 0.0001*
e	4(HL)	(R3-100) – (R2-100)	0.0523	0.0003*
		(R2-100) – (R3-150)	-0.0201	0.2006
f		(R3-100) – (R3-150)	0.0322	0.0229*

*Statistically significant at 0.05 level

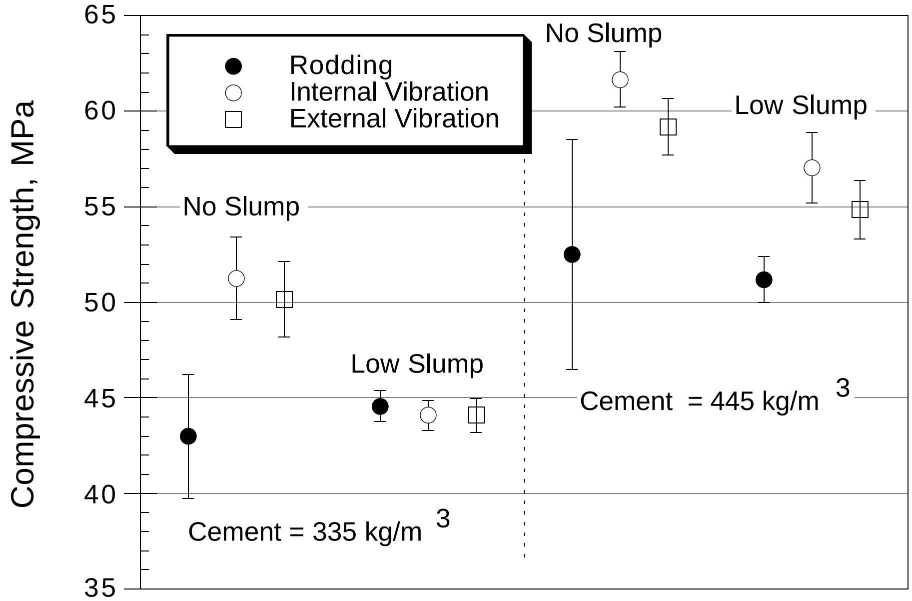

Fig. 1—Compressive strength of 150 x 300-mm cylinders as a function of consolidation method and slump (data from Whitehurst and Goodwin 1963)

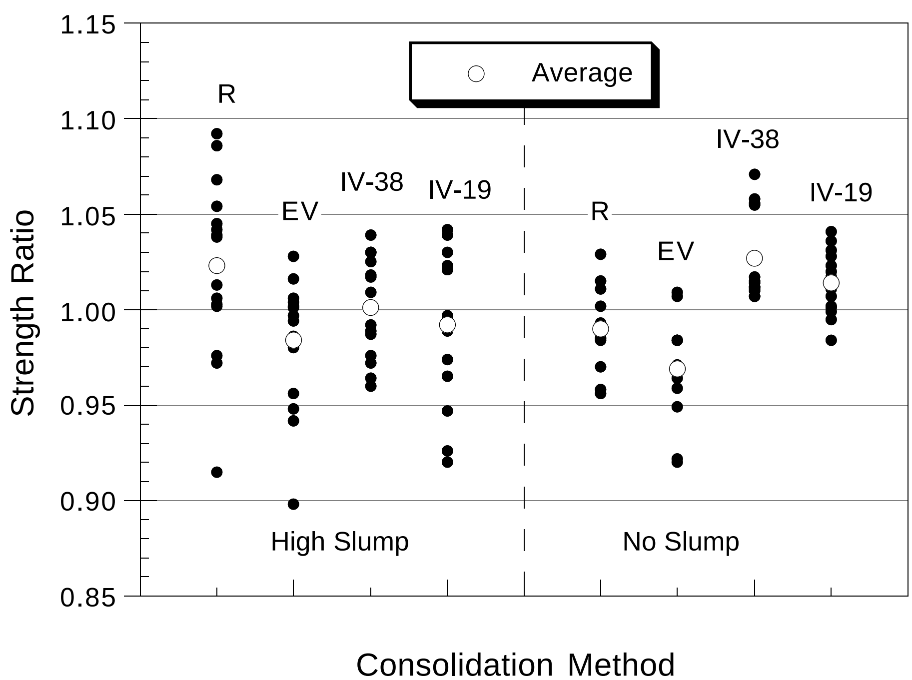

Fig. 2—Effect of consolidation method on cylinder strength (data from Tynes 1962)

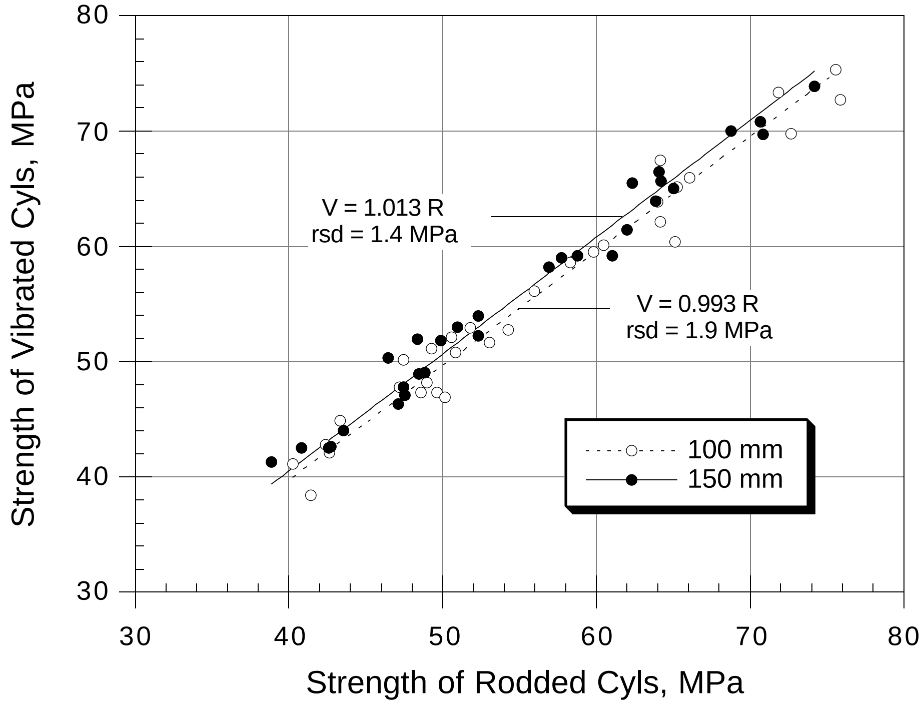

Fig. 3—Compressive strength of vibrated and rodded cylinders (data from Perkins 1986)

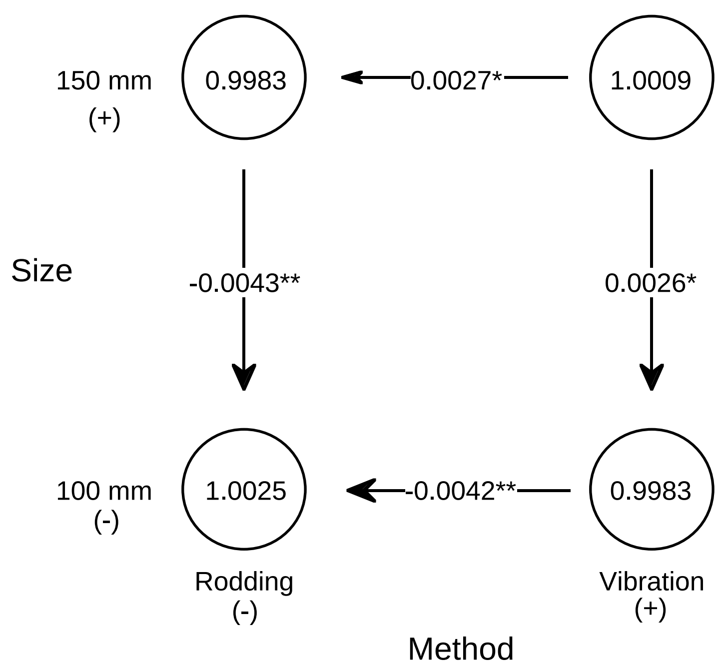

Fig. 4—Two-way table of mean values of density ratios for factors *cylinder size* and *consolidation method*

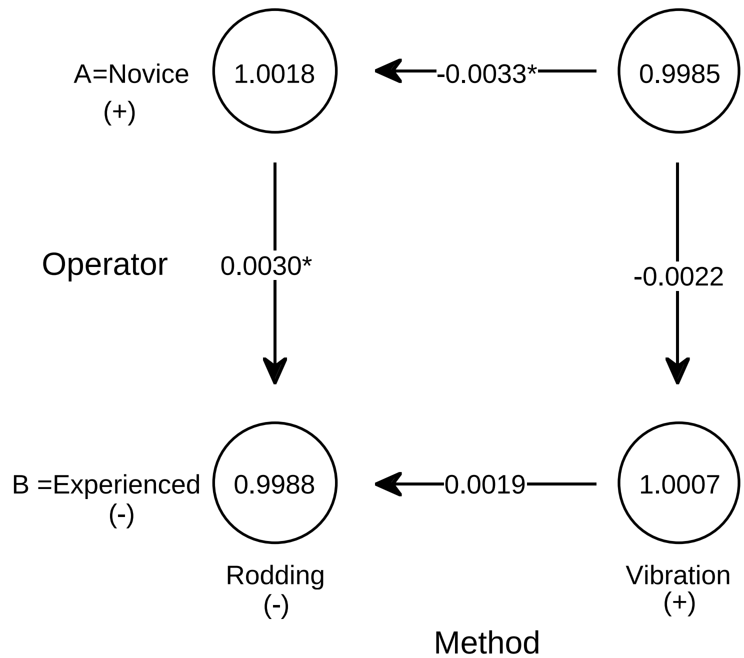

Fig. 5—Two-way table of mean values of density ratios for factors *operator* and *consolidation method*

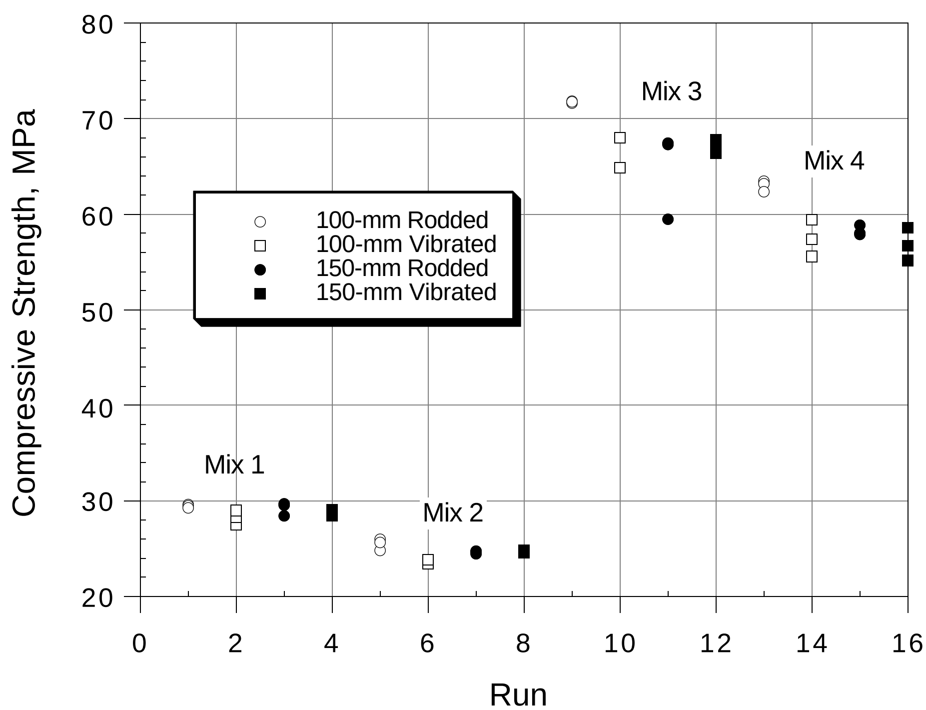

Fig. 6— Cylinder strength versus run number for *consolidation experiment*

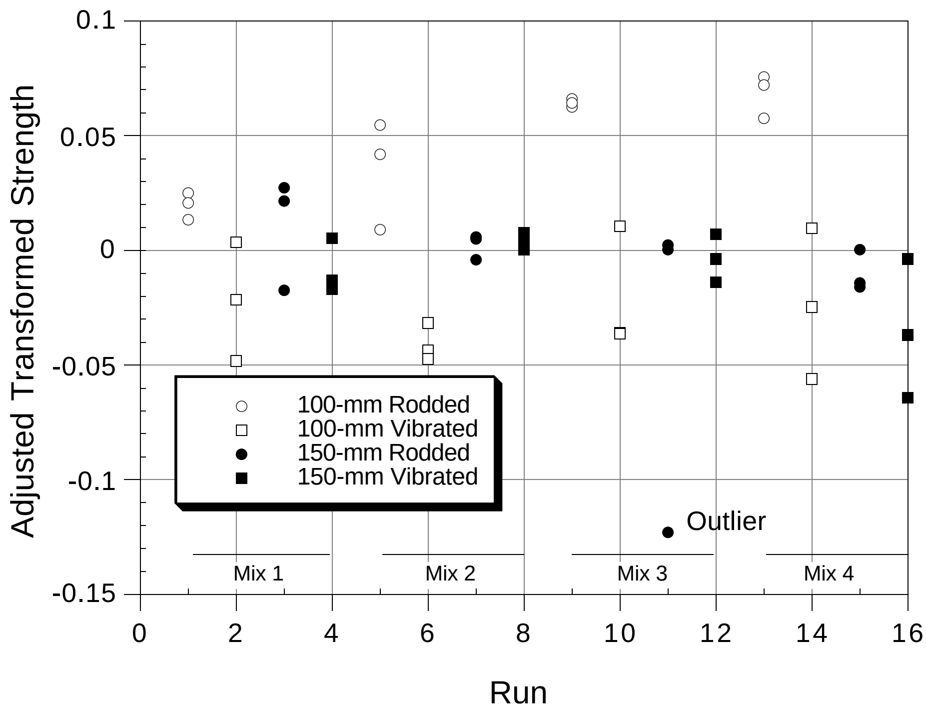

Fig. 7—Adjusted transformed strength versus run number for *consolidation experiment*

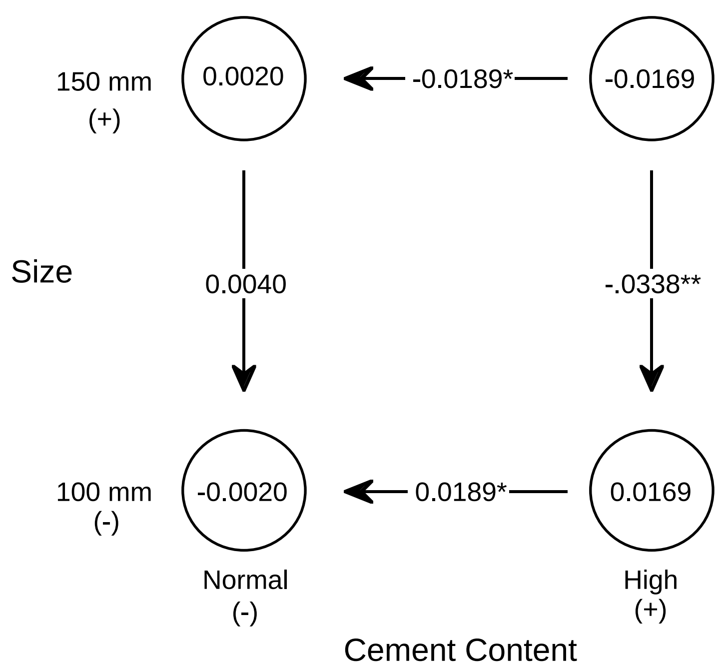

Fig. 8—Two-way table of mean values of adjusted transformed strength for factors *cylinder size* and *cement content*

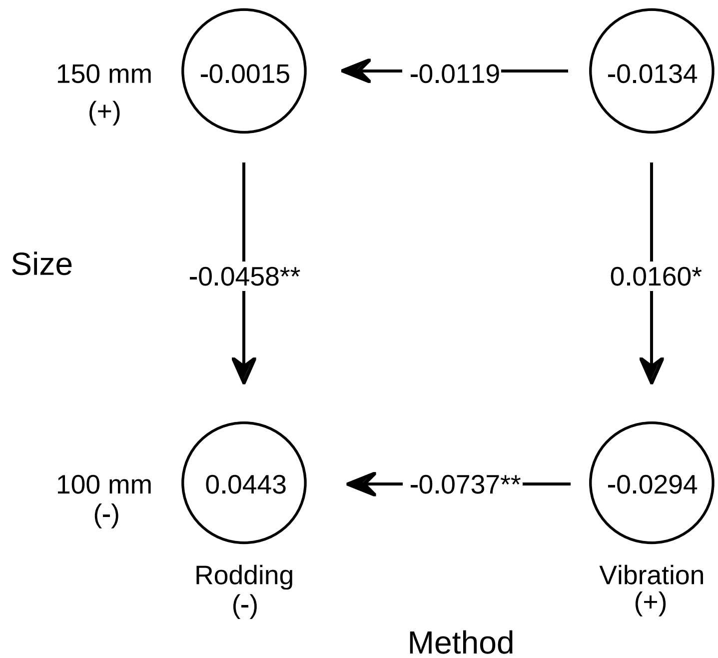

Fig. 9—Two-way table of mean values of adjusted transformed strength for factors *cylinder size* and *consolidation method*

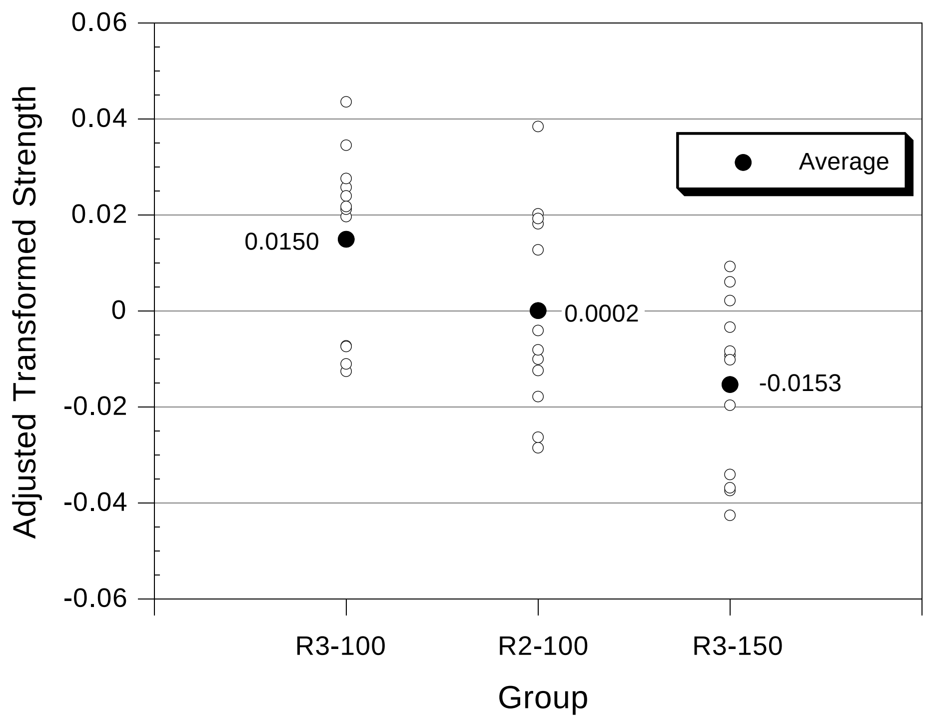

Fig. 10—Individual values of adjusted transformed strengths for the three groups in *layers experiment,* value of means for each group shown with solid circles

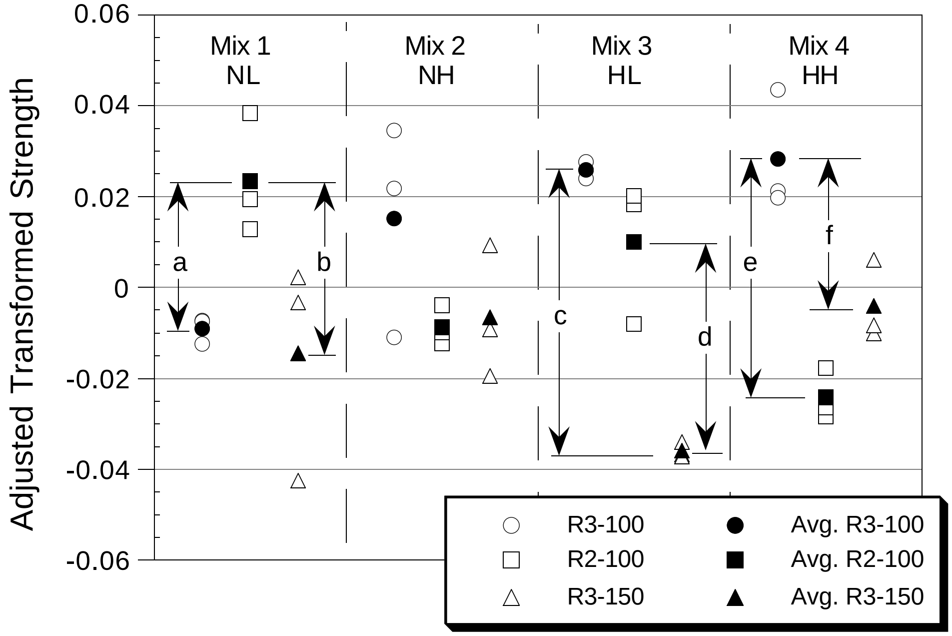

Fig. 11—Individual values of adjusted transformed strengths in *layers experiment*; significant differences between means are indicated (refer to Table 10 for values)

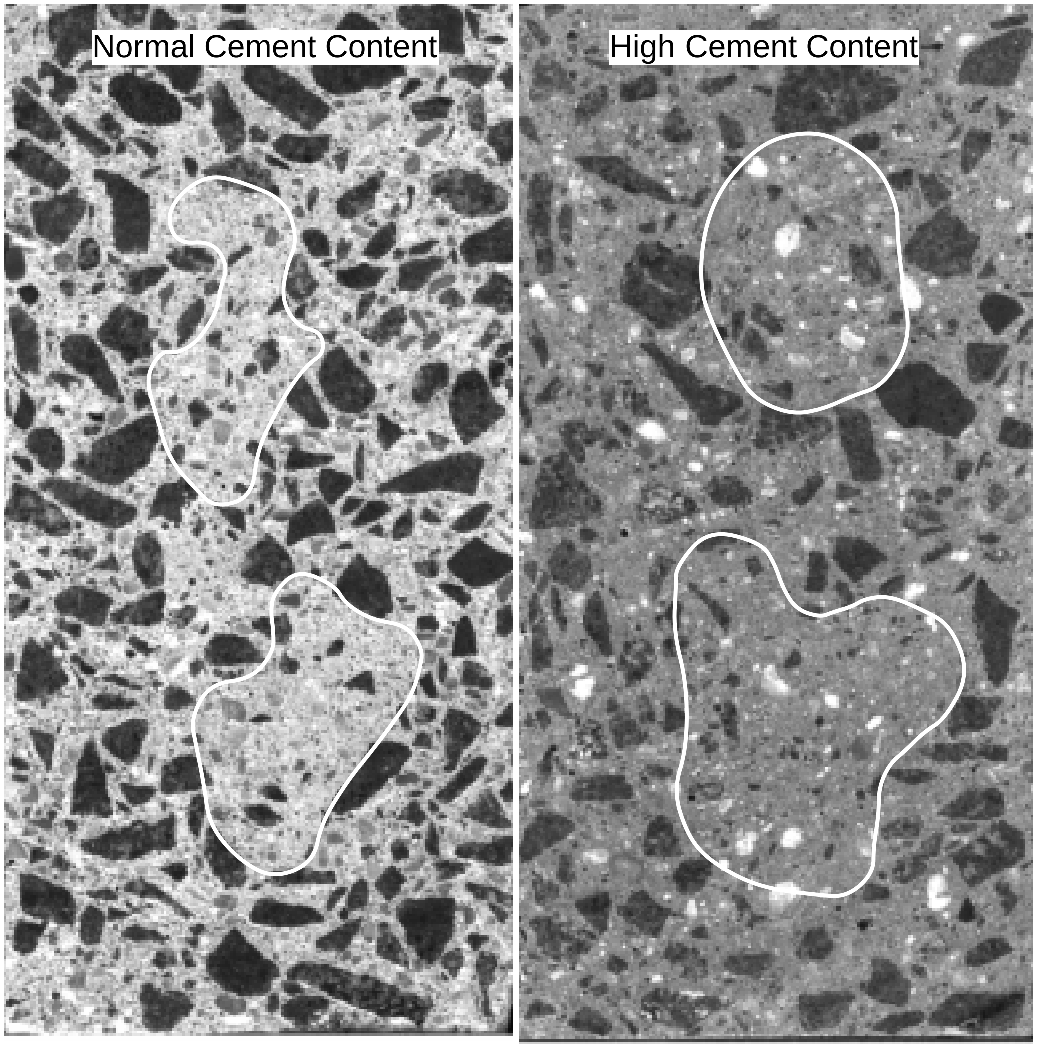

Fig. 12—Cross sections of 100-mm diameter vibrated cylinders made from the high-slump mixtures (NH and HH)

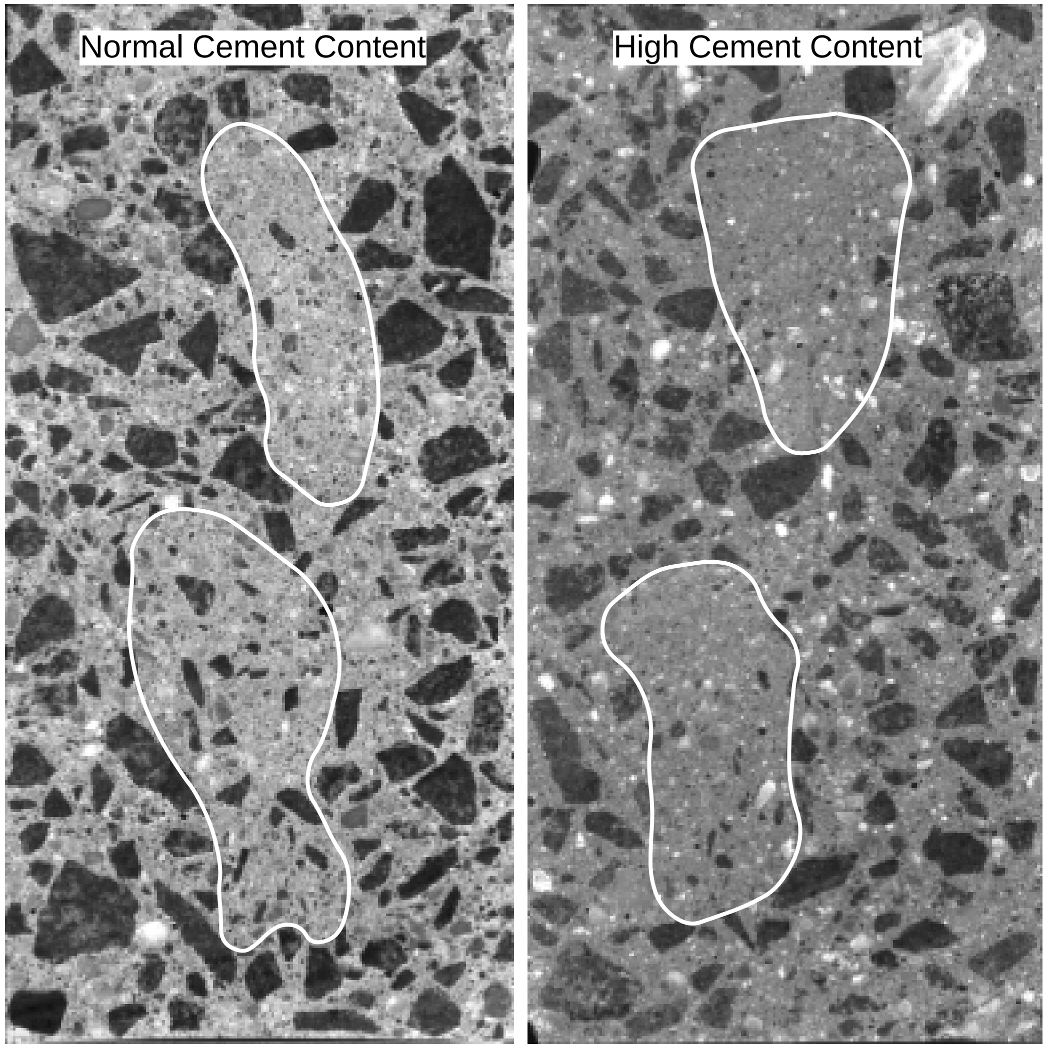

Fig. 13—Cross sections of 100-mm diameter vibrated cylinders made from the low-slump mixtures (NL and HL)