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Effects of Testing Variables on the Strength of High-Strength (90 MPa) Concrete Cylinders

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Synopsis: A full factorial experimental design was used to investigate the effects of the following variables on cylinder strength: end preparation (sulfur capping versus grinding), cylinder size (100 versus 150 mm diameter), type of testing machine (1.33-MN capacity versus a 4.45-MN capacity), and nominal stress rate (0.14 versus 0.34 MPa/s). Two levels of strength were used (45 and 90 MPa), and three replicates were tested for each run. Specific gravities were measured to check on the consistency of cylinder fabrication. Statistical analyses indicated that all the factors had significant effects on the measured compressive strength. On average, the 100-mm cylinders resulted in about 1.3% greater strength, the faster stress rate produced about 2.6% greater strength, the ground cylinders were 2.1% stronger, and the 1.33-MN testing machine resulted in about 2.3% greater strength. There were significant interactions among the factors, so that the effects were greater than the average values for particular factor settings. For example, the effect of end preparation depended on the strength level. For the 45-MPa concrete, there was no strength difference due to the method of end preparation, but for the 90-MPa concrete, grinding resulted in as much as 6% greater strength in certain cases. Analysis of dispersion indicated that the 100-mm cylinders had higher within-test variability, but the differences were not statistically significant. Recommendations for modifications to testing standards are provided.

Keywords: Capping (of concrete test specimens); compressive strength; cylinders; high-strength concretes; standards; statistical analysis; stresses; test equipment

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INTRODUCTION

In the United States, the compressive strength of the 150 by 300-mm cylinder is the basis for acceptance of concrete. Although a seemingly simple procedure, results are only reliable when specimens are prepared in a standard manner and tested in standard procedure on machines that satisfy prescribed criteria. Failure to follow the standards can lead to low or erratic measured strength that may be interpreted as a deficiency in the concrete (Richardson 1991). Standards for testing concrete are an outgrowth of experiences gained from testing ordinary strength concrete (< 40 MPa). With the advent of high-strength concrete, problems have been reported in measuring strengths of test specimens (Hester 1980), and the adequacy of the current standards have been questioned (Carrasquillo and Carrasquillo 1988).

This study was undertaken to examine the basis of current testing standards and to provide the technical basis for modifications to improve the reliability of testing high-strength concrete. The study involved a literature review and a designed experiment to establish the significance of selected factors on the measured strength of molded, high-strength concrete specimens. This paper is a summary of the complete report of this study (Carino, et al. 1993).

PAST RESEARCH

A brief review is provided of previous studies that form the basis of the current standards for measuring compressive strength. The topics to be covered are specimen size, end preparation, testing machine characteristics, and rate of loading.

Specimen size

One of the problems in testing high-strength concrete is that a large capacity machine is needed to test 150-mm diameter cylinders. As a result, there is interest in allowing the use of 100-mm cylinders as the basis for quality control and acceptance testing. However, current ASTM standards (e.g. ASTM C 31) recognize the 150-mm cylinder as the standard size, and only permit other sizes if specifically required by the project specifications.

H. F. Gonnerman conducted a comprehensive study on the effects of specimen size and shape on the measured compressive strength (Gonnerman 1925). Concrete strength varied from 10 to 30 MPa. He concluded that 100 by 200-mm cylinders were suitable test specimens provided the ratio of cylinder diameter to maximum aggregate size was not less than about 3. The increased strength of 100-mm cylinders compared with 150-mm cylinders was felt to be *"not important."*

J. Tucker was one of the first to provide a theoretical explanation for the effect of specimen size on the average strength and the dispersion of strength (Tucker 1927, 1941, 1945). Based on the *strength-summation theory* (strength of a specimen equals sum of strength contributed by individual elements), Tucker concluded that the compressive strength is *independent* of diameter for the same height-diameter ratio. The standard deviation, however, was expected to inversely related to diameter. Thus the standard deviation of 100-mm cylinders would be expected to be 1.5 times that of 150-mm cylinders.

In 1951, W. H. Price reported on the factors, including cylinder size, which influence concrete strength (Price 1951). For cylinders with a height-diameter ratio of 2 and maximum size of aggregate less than or equal to one-fourth the diameter, it was found that the strength of a 100-mm diameter cylinder were about 4% greater than the strength of 150-mm diameter cylinder.

A. M. Neville reported on an empirical study to relate the strength measured on one concrete specimen to the strength measured on another specimen of a different shape or size (Neville 1966). Based on empirical relationships, the strength of a 100-mm cylinder was expected to be 3 to 4% greater than a 150-mm cylinder.

V. M. Malhotra concluded that, in general, the strengths of 100-mm diameter cylinders were higher than those of 150-mm cylinders (Malhotra 1976). There were indications, however, that the reverse was true at low strength levels, and that the strength differences increased with strength level. Malhotra noted that the within-test variability of 100-mm cylinders was larger than that of 150-mm diameter cylinders, and that more than twice the number of the smaller cylinders would have to be tested to measure the strength with the same precision.

Recent published and unpublished data, comparing the compressive strength of 100-mm cylinders with the strength of 150-mm cylinders, were analyzed by the authors. These data include normal strength and high strength concrete. Figure 1(a) shows the strength of the 100-mm cylinders plotted as a function of the strength of the 150-mm cylinders. Figure 1(b) shows the strength ratios as a function of the 150-mm cylinder strength. A correlation analysis of strength ratio versus compressive strength of the 150-mm cylinders resulted in a correlation coefficient of 0.003, and there were no obvious non-linear trends in the data. Thus it is concluded that the strength ratio does not appear to be a function of compressive strength. The average value of the strength ratios is 1.038 with a standard error of 0.002. In summary available data suggest that the compressive strength measured using 100-mm cylinders is, on average, expected to be about 4% greater than that measured using 150-mm cylinders.

Some of the data in Fig.1 included information on the variability of the strength for the two cylinder sizes. It was found that the median coefficient of variation for the 100-mm cylinders is 3.2% and the median for the 150-mm cylinders is 2.7% (Carino et al. 1993). The ratio is about 1.2, which is slightly lower than the value of 1.5 based on Tucker's strength summation theory.

<u>End Condition</u>

One of the earliest comprehensive studies of the effects of end preparation on the measured cylinder strength was carried out by H. F. Gonnerman (Gonnerman 1924). At that time, the standard method for capping cylinders was by using neat cement paste. Gonnerman investigated the possibility of an economical alternative to cement paste caps. Other cementitious materials, as well as unbonded sheet materials, were investigated. The concrete strengths ranged from 7 to 38 MPa and tests were performed on 150 by 300-mm cylinders. It was found that caps of gypsum or a mixture of gypsum and portland cement resulted in strengths similar to those with neat portland cement caps. The unbonded sheet materials resulted in lower strengths, and it was observed that the *reductions were greater for the higher concrete strengths*. This was one of the first studies to show that selection of the proper capping material becomes more critical with increasing strength level of the concrete.

In 1926, there was a report on the use of a *sand cushion* to eliminate the need of bonded caps (Purrington and McCormick 1926). Fine sand was placed in a confining container having an inside diameter of 165-mm. In a comparative study using 14 and 21-MPa concrete, it was reported that the strength of the cylinders tested with the sand cushion were similar to those tested with cement paste caps. In a subsequent study, the strength of cylinders capped on both ends were compared with the strength of cylinders capped on top and the bottom resting in a sand cushion (McGuire 1930). The effect of the inside diameter of the restraining ring was investigated by using three sizes: 160, 170 and 215 mm. It was concluded that the 160-mm restraining ring resulted in strengths similar to that when caps were used on both ends, but the larger rings resulted in drastic strength reductions. The sand cushion was not adopted as a routine method, but it has recently been suggested as an alternative to grinding the ends of high-strength concrete cylinders (Boulay and de Larrard 1993). For 75-MPa concrete, cylinders strengths using the sand box were the same as for ground cylinders. However, for 100- and 120-MPa concretes, cylinders tested with the sand box had 5 and 11% lower strengths, respectively, than ground cylinders.

In 1927, O. V. Adams, reported on the successful use of aluminous cement[b] for capping (Adams 1927). The use of aluminous cement was spurred by a need for a suitable capping material for cores which had to be moisture conditioned prior to testing. The caps were formed by placing a collar around the cores, the collars were filled with a mortar of aluminous cement and fine sand, and a glass plate was used to press out the excess mortar.

In 1928, P. J. Freeman reported on the use of sulfur mortar for capping cylinders (Freeman 1928). Unlike the vertical capping method currently used with sulfur mortar (ASTM C 617)[c], Freeman used a horizontal capping device. The mortar was composed of 50% sulfur, 31% silica, 9% alumina, and other unspecified materials, and it attained a compressive strength of 55 MPa when molded into 50 by 100-mm cylinders. Freeman noted that for a thin, 150-mm diameter specimen of mortar, the strength was *"far above this."* According to Freeman, the appearance of the broken specimens *"has convinced those using the material that the results are better than can be obtained by any other system of capping with other materials"* (Freeman 1930). By 1939, sulfur mortar was used to cap cylinders in many laboratories (Timms 1939).

In 1941, Troxell presented the results of a comparative study of the effects of capping materials and end conditions on the measured strength of 75 by 150-mm molded cylinders. The capping materials included plaster of Paris, a high-strength gypsum product (Hydrostone), a sulfur-silica mixture, and 1.6-mm steel shot in a

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[b]Aluminous cement is a hydraulic cement in which the cementitious compounds are predominantly calcium aluminates. One of its characteristics is a very high rate of strength development, and about 80% of its long-term strength can develop within 24 h (Neville 1973).

[c]AASHTO designations of referenced ASTM standards are given in the reference list.

retaining head. Cylinders were produced with plane normal ends and with defective ends. Two nominal strength concretes were used: 20 and 55 MPa. Thus this is one of the first studies employing what can be considered as a high-strength concrete. The bonded caps varied in thickness from about 1.5 to 6 mm. Sulfur caps were formed using a vertical capping apparatus. The conclusions of the study were as follows:

- Cylinders capped with the high-strength gypsum or the sulfur mortar resulted in higher measured strengths and better uniformity compared with those capped with plaster of Paris or the steel shot. In general, the high-strength gypsum was superior to the sulfur mortar.
- Shot caps resulted in low strengths, especially when testing specimens with concave ends.
- Cylinders capped with plaster of Paris resulted in low strengths especially for the cylinders with defective ends.
- Moist storage of cylinders capped with the sulfur mortar prior to testing did not have an adverse effect on strength.

A very interesting discussion of Troxell's paper was presented by A. J. Durelli, who used photoelasticity to study the two-dimensional stress distributions in thin, rectangular, plastic plates loaded in compression along opposite edges. These studies showed that stress concentrations exist at the loaded ends of the specimens even when they are perfectly flat. Different capping materials were found to alter the stress distribution. Soft capping materials, such as lead and rubber, which can flow outward when the specimen is loaded, produced outward radial stresses at the end of the specimen. Durelli demonstrated that by using an appropriate capping material, the stress distribution at the ends of the specimen could be made nearly uniform.

In 1944, T. B. Kennedy reported on a comparative study of capping materials (Kennedy 1944). The study was prompted by an observation that specimens capped with a particular sulfur mortar resulted in higher strengths when the caps were 20 to 24 hours old compared with caps that were only 5 hours old. The main objective was to investigate the effects of cap age on the measured strength. Four capping materials were used, two commercial sulfur-silica compounds and two gypsum products. Nominal concrete strength varied from 20 to 50 MPa, test specimens were 150 by 300-mm cylinders, and sulfur caps were formed with a horizontal capping device. Except for tests to study the effect of cap thickness, sulfur caps were about 6 mm thick and the gypsum caps were about 1.5 mm thick. In the study of the sulfur compounds, cylinders were made with flat ends and with tops having a 6-mm *"step"* over one-half of the end area. The main conclusions were:

- The effect of cap age was very different for the two sulfur compounds.
- The stepped-end condition did not have an appreciable effect on the measured strength when sulfur caps were used (gypsum materials were not tested with stepped-ends).
- For compressive strengths up to 38 MPa, the better sulfur compound and the two gypsum materials resulted in equally adequate caps. While an age of 1

hour was adequate for the sulfur caps, the gypsum caps should be allowed to harden for 3 hours.

- Caps should be made as thin as possible.

In 1958, Werner reported on three series of studies on capping materials, which included concretes up to 48 MPa in strength (Werner 1958). The principal conclusions were:

- Cylinders capped with aluminous cement had the highest strength in all cases except one.
- The use of different capping materials had greater effects on the strengths of cylinders made of high-strength concrete compared with cylinders of low-strength concrete.
- Cylinders of high-strength concrete with rough ends resulted in lower strengths than similarly capped cylinders with smooth ends. For the low-strength cylinder, the surface condition had negligible effects on measured strength.
- The thickness of the sulfur caps affected the measured strength of the high-strength concrete cylinders. Thicker caps produced with the horizontal capping device resulted in about 5% lower strengths.

These studies reinforced Gonnerman's earlier findings that the choice of capping material is of greater importance when testing high-strength concrete.

Werner measured the compressive strength and sonic modulus of elasticity of specimens made of the capping materials. To gain additional insight into the relationship between capping material and measured concrete strength, Werner's data were examined further by the authors. Figures 2(a) and 2(b) show the relationships between average cylinder strength and the strength and stiffness of the capping material. These figures show clearly that there are correlations between the mechanical properties of the capping material and the resulting cylinder strength. It is not obvious, however, whether it is the strength or the stiffness of the capping material that plays the fundamental role in affecting the measured cylinder strength.

Few developments were reported during the 1960s related to capping methods. In the 1970s, interest developed in using an unbonded capping system composed of neoprene rubber pads restrained by metal rings with slightly larger diameters than the cylinder. One of the early published studies comparing the so-called *pad-cap* system with conventional capping methods was reported in 1985 (Ozyildirim 1985). Over 400 pairs of 150-mm cylinders were prepared under field conditions and tested with sulfur-mortar caps and unbonded caps. The concrete strength varied between 20 and 40 MPa. The sulfur-mortar capped cylinders resulted in a statistically higher strength, however, the difference was only 0.4 MPa. No statistically significant differences in variability were noted for the two capping methods.

Carrasquillo and Carrasquillo (1988b) reported on a laboratory study of unbonded caps that involved concrete strength ranging from 17 to 114 MPa. This study demonstrated that the pad-cap system resulted in strengths similar to those with sulfur caps. It was also reported that the pad-cap systems tended to reduce the variability of the measured strengths.

Richardson reported on a statistically designed laboratory experiment to compare unbonded caps with sulfur-mortar caps (Richardson 1990). The differences in cylinder strengths obtained by the two capping methods were compared under 12 testing conditions, some of which were outside of the requirements of current ASTM standards. Ten concrete batches were used, with a strength range from about 25 to 40 MPa. A comparison of the overall means of the strengths for the two capping methods showed no differences.

Chojnaki and Read reported on a study to examine the effects of end preparation, specimen size, testing machine, and testing speed on the measured strength of high-strength concrete cylinders (Chojnaki and Read 1991). Six end preparation conditions were investigated, as follows: capped with sulfur capping compound; ground; ground and capped with sulfur compound; cut with a diamond saw and capped with sulfur compound; ground and tested with unbonded pad-caps; and unbonded pad-caps. Two nominal strength levels were studied: 70 MPa and 90 MPa. For the 70-MPa mixture, the mean strength of the pad-cap cylinders was 96% of the strength of the ground cylinders. For the 90-MPa mixture, the mean strength of the pad-cap cylinders was about 98% of the mean strength of the ground cylinders. For both strength levels, there appeared to be no significant differences between the mean strengths of the sulfur-capped cylinders and the ground cylinders.

Pistelli and Willems analyzed strength results from field-prepared cylinders to examine the effects of cylinder size and end preparation methods (Pistelli and Willems 1993). The compressive strength of the concrete varied from about 20 to 120 MPa. The strength of 100-mm and 150-mm cylinders were compared using sulfur caps, unbonded pad-caps, and grinding. In general, the cylinders tested with pad-caps resulted in higher strengths, especially for strengths above about 60 MPa. The variability of the pad-cap cylinders was reported to be lower than that of the sulfur-capped cylinders. Strengths of cylinders tested with pad-caps were also compared with strengths of cylinders whose ends were ground flat. On average, the pad-capped cylinders had 97% of the strength of the ground cylinders.

Two recent studies focused on the effects of end preparation on measured strength of high-strength concrete specimens. In one study (Lessard, et al. 1993), five high-strength mixtures in the range of 115 to 130 MPa were used to compare the strength of ground cylinders with cylinders capped with a sulfur compound. The 50-mm cube strength of the sulfur compound ranged from 55 to 62 MPa. The caps were from 1 to 2 mm thick. Nine to 12 replicate tests were performed at an age of 91 days using 100 by 200-mm cylinders. On average, the capped cylinders resulted in 1.5%

lower strength, but the difference was not statistically significant. The dispersion, however, was affected by the end conditions: the ground cylinders had a coefficient of variation of 2.1% compared with 3.6% for the capped cylinders.

The other study compared the strength of 100-mm cylinders tested with three end conditions: capped with a high-strength sulfur compound, with ground ends, and with unbonded pad-caps (French and Mokhtarzadeh 1993). Strengths in excess of 100 MPa were tested. It was reported that all three end conditions resulted in similar strengths. The cylinders with ground ends produced only 1% higher strength than those with sulfur caps. For strengths between 50 and 80 MPa, the cylinders with unbonded pad-caps were reported to have slightly higher strength than the ground cylinders. The specimens with unbonded pad-caps, however, were reported to have violent failures due to energy stored in the neoprene pads.

Testing Machine Characteristics

Background — Before reviewing research related to the effects of testing machine characteristics on the measured compressive strength, general information on testing machines is provided. In general, two types of testing machines are used to measure compressive strength of concrete specimens: (1) a screw-type and (2) a hydraulically-operated type. In a screw-type machine, the load is applied by a moving crosshead. The movement of the crosshead is produced by the rotation of motor-driven screws as shown in Fig. 3(a). The lower platen of a screw-type machine remains stationary. The rate of deformation of the specimen is controlled by the rotation speed of the screws and the stiffness of the machine. In a hydraulically-operated machine, the crosshead remains stationary and the specimen is loaded by a moving piston as shown in Fig. 3(b). The rate of movement of the piston is controlled by the flow rate of fluid into the cylinder. In a high-quality, hydraulically-operated machine a flow control system is used to maintain a nearly constant fluid flow rate into the cylinder (Turner and Barnard 1962, Hinde 1964).

Figure 3(c) is a simplified spring model of the testing machine and the test specimen, which is useful for understanding the interactions between specimen and testing machine (L'Hermite 1954, Sigvaldason 1966a). The longitudinal stiffness of the machine is represented by a spring with stiffness k_m, which depends on the size and length of the machine columns, the stiffness of the crosshead, the stiffness of the bearing blocks, and the stiffness of the load measuring system (Sigvaldason 1966a). For a hydraulically-operated machine, the flexibility of the hydraulic piping system and the fluid height in the piston contribute to reducing the overall machine stiffness (Vutukuri, et al. 1974, Turner and Barnard 1962). Thus the testing machine stiffness is affected by more factors than the dimensions of the structural frame. The test specimen is represented by a spring having a stiffness k_s, which depends on the concrete modulus of elasticity, the cross-sectional area, and the length of the cylinder. Microcracking in the concrete causes the modulus of elasticity to decrease with increasing strain, and the value of k_s is not constant during a compression test. In addition to longitudinal stiffness, a testing machine is also characterized by its *lateral stiffness*, which refers to the resistance to horizontal movement (or rotation) of the crosshead with respect to the lower platen.

Figure 3(d) shows the deformations of the specimen and the testing machine for a given amount of crosshead or piston movement, δ_t. The specimen compresses by an amount δ_s and the testing machine elongates by an amount δ_m. Compatibility of deformations requires that $\delta_t = \delta_s + \delta_m$, and equilibrium requires that the compressive force acting on the specimen, P_s, is balanced by the tensile force, P_m, in the testing machine.

C. S. Whitney presented one of the first explanations of the effect of testing machine stiffness on the specimen's load-deformation behavior in a compression test (Whitney 1943). He noted that the descending portion of the load-deformation curve is affected by the relative stiffnesses of the machine and the specimen[d]. Whitney noted the following:

"Shortly after the maximum load, the slope of the concrete curve becomes equal to that of the machine curve. The elastic recovery of the machine at that stage is rapid enough to maintain the load required to continue the straining of the cylinder without operating the machine. At this point the strain starts to increase automatically and rapid failure follows."

The interaction between testing machine and specimen described by Whitney can be understood by considering work and stored energy (Hudson, et al. 1972, Salamon 1970). During the ascending-load portion of the test, work is done by the piston (or crosshead) to compress the specimen and elongate the testing machine. The work done on the machine is stored as elastic strain energy (analogous to stretching a rubber band). When ultimate load is reached, the load stops increasing and begins to decrease. As the load decreases, the testing machine loses some of its *stretch* and releases stored energy. This released energy is added to the energy supplied by the motion of the piston (or crosshead) to compress the specimen. Figures 4(a), 4(b) and 4(c) illustrate the work required to compress the specimen by additional amounts $\Delta\delta_s$ at different points beyond the ultimate load. The energy released by the testing machine is also indicated. In Fig. 4(b), the energy released by the machine is less than the work required to compress the specimen. This difference must be provided by additional movement of the piston (or crosshead), and a *stable* condition exists. In going from Fig. 4(a) to Fig. 4(c), the released energy increases with each incremental shortening of the specimen. In Fig. 4(c), the slope of the specimen load-deformation curve equals $-k_m$, and for an incremental deformation, $\Delta\delta_s$, the released energy equals the work required to deform the specimen. This is the point of *instability*. Beyond this point, more energy is available than can be

[d]During the descending portion of the load-deformation curve, the specimen stiffness is negative, which means that less force is needed for further deformation of the specimen (called *strain softening*).

absorbed by the specimen, and the specimen literally *explodes*. To avoid such an explosive failure, it is necessary to have a *hard* testing machine so that the machine stiffness k_m always exceeds the absolute value of the specimen stiffness k_s during the test.

Research results — Systematic studies of the effects of testing machine characteristics on the measured compressive strength of concrete specimens were conducted in the 1950s and 1960s in the United Kingdom (Wright 1957; Cole 1964, 1967; Newman and Lachance 1964). The overall objective was the development of standards for compression testing machines (Newman and Spooner 1969).

In the United Kingdom, the standard compression test specimen is a cube, and there is a fundamental difference between testing cubes and vertically-cast cylinders. As is known, the quality of concrete is better at the bottom of a cast specimen than at the top (Cole 1967, Newman and Spooner 1969). As a result, the modulus of elasticity and strength varies with elevation (Newman and Sigvaldason 1965). To avoid capping, cubes are tested on their sides. The loading direction is, therefore, perpendicular to the casting direction. When the cube is subjected to a *uniform deformation* through a spherically-seated bearing block, the stress distribution will not be uniform. The side of the cube with the higher elastic modulus will have a higher stress. The non-uniform stress distribution is equivalent to an axial load plus a bending moment. If there is sufficient friction in the spherical seat, the moment can be resisted, there is no rotation of the spherical head, and uniform deformation is maintained. The bending moment is, in turn, imparted to the testing machine, and high lateral stiffness becomes critical to maintain a uniform deformation. For the cylinder, the uniform compressive deformation leads to a uniform stress, because there is no variation in elastic modulus through a cross section. Thus there is no bending moment, there is no tendency for rotation of the spherical seat, and the lateral stiffness of the machine is not as critical.[e]

Research results revealed the following as the most important testing machine characteristics (Newman and Spooner 1969):

- behavior of the spherical seating
- testing machine stiffness
- planeness of bearing blocks
- alignment of machine components and test specimen

Compression tests are typically carried out with the specimen resting on a fixed bearing block and the top of the specimen bearing against a spherically-seated block, which accommodates any non-parallelism between the loaded surfaces of the specimen. One of the earliest studies on bearing blocks suggested that, to ensure a uniform stress distribution, the spherically-seated block should be free to rotate during

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[e]This assumes that the all components of the testing machine are aligned, the cylinder is properly centered, and the cylinder has uniform properties through its cross section.

the test (Schuyler 1913). Studies in the 1960s, however, proved conclusively that the spherically-seated block should behave as a fixed block after the initial alignment has occurred (Newman and Sigvaldason 1965; Sigvaldason 1966b, 1966c; Cole 1967; Newman and Spooner 1969). To achieve fixed behavior, the frictional resistance of the spherical seating has to overcome any tendency towards rotation due to the eccentricity between the reaction force in the specimen and the center of the seating. This resistance can be ensured by using a lubricant that allows the mating surfaces of the spherical seat to make contact after initial alignment (Sigvaldason 1966c, Cole 1967, Newman and Spooner 1969). Light motor oils and petroleum jelly have been found to be appropriate lubricants, while high-pressure greases are inappropriate. It was found that cylinders are less sensitive to the details of spherical-seating behavior than cubes (Sigvaldason 1966b).

The effect of testing machine stiffness on the measured compressive strength is not understood with the same certainty as is the effect of the spherically-seated block. There are two kinds of stiffnesses that need to considered: longitudinal and lateral. As was explained, the longitudinal stiffness plays a key role in the behavior after the ultimate load has been reached (Whitney 1943). In general, a hard testing machine is desirable to avoid explosive failures, which induce rapid deterioration of machine components and loss of accuracy (Sigvaldason 1966a, 1966b). Sigvaldason (1966a) noted that the descending portion of the load deformation curve of concrete cubes was about one-fourth as steep as the ascending portion. On this basis, he suggested that the longitudinal stiffness of a cube testing machine should exceed about 1.8×10^9 N/m. Other studies, however, have shown that the slope of the descending portion of the load-deformation curve is dependent on the strength level of the concrete (Barnard 1964, Wang et al. 1978). For high-strength concrete cylinders, the descending slope can be as steep or even steeper than the ascending slope (Shah et al. 1981). As a result, a stiffer machine than suggested by Sigvaldason would be needed to avoid explosive failure of high-strength concrete specimens. Assuming that the machine stiffness should be at least twice the initial stiffness of a 150 by 300 mm high-strength cylinder having an initial elastic modulus 45 GPa, the required machine stiffness would be have to be about three times the value suggested by Sigvaldason.

There is controversy regarding whether longitudinal stiffness affects the measured compressive strength. L'Hermite (1954) proposed that the large amount of stored energy in a soft machine would play a role in initiating failure at a lower load compared with a hard machine. No experimental evidence, however, was available to confirm this theory. Glucklich and Cohen (1967) used the principles of fracture mechanics to develop a theory to explain why a soft testing machine should result in lower measured strength. Bažant and Panula (1978) predicted that machine stiffness would affect the ultimate strength if the specimen were assumed to have a nonuniform distribution of strength through the cross section and if the strain at peak stress were assumed to decrease with increasing strength level of the concrete. On the other hand, Wright (1957) found that measured cube strength was not affected by the introduction of relatively flexible proving rings in series with the specimens.

Sigvaldason (1966b) performed a comparative study using two machines whose longitudinal stiffnesses differed by a factor of 20. No difference was observed in the measured strength for a 32-MPa concrete. Mindess and Bentur (1984) reviewed research on the effects of longitudinal stiffness and performed tests of cement paste specimens using six different machines. It was concluded that longitudinal stiffness had little or no effect on compressive strength of paste specimens.

Cole (1967) noted that longitudinal stiffness did not appear to affect strength, but he stated the following:
"However, the testing machine's lateral rigidity is usually related to the longitudinal rigidity and it is the lateral rigidity which will have a marked effect upon the mode of failure of a brittle test specimen."

Sufficient lateral stiffness is critical to maintain uniform deformation of cube specimens during testing (Newman and Spooner 1969). The non-uniform stress distribution in a cube, due to variations in elastic modulus through the cross section, leads to an eccentric load in the specimen. If the testing machine has low lateral stiffness, the eccentric load causes excessive lateral deformations of the frame. This, in turn, causes a relative rotation between the bearing blocks, and the specimen is no longer subjected to uniform deformation. Lateral deformations can also be induced by improper alignment of cubes or cylinders with respect to the center of the machine. The eccentric load due to specimen misalignment tends to produce lateral motion of a flexible frame, which causes nonuniform straining of the specimen. If the frame has high lateral stiffness, the specimen can be uniformly compressed even if it is misaligned (L'Hermite 1954). This provides for a relatively simple procedure to judge the adequacy of lateral stiffness (Newman and Spooner 1969). Test specimens are placed in the machine with different amounts of misalignment, and the resulting compressive strengths are compared with those of properly aligned specimens. A machine with low lateral stiffness will show marked strength reductions with increasing misalignment (Cole 1964, Sigvaldason 1966b). Alternatively, a steel tube, which is instrumented with strain gages around its circumference, can be placed between the bearing blocks at difference eccentricities and loaded to different levels. The strain gage readings are noted as a function of the amount of misalignment (Foote 1970). Large differences among the measured strains indicate non-uniform straining of the tube.

Plane bearing blocks are necessary to assure reproducibility of the stress distributions from one test specimen to another. Contrary to intuition, when a perfectly flat concrete specimen is compressed between flat, steel bearing blocks, the compressive stresses at the interfaces are not uniformly distributed (Newman and Lachance 1964, Ottosen 1984). The stresses at the perimeter of the cylinder are higher than the nominal stress.

Loading rate

The strength of concrete, like most materials, is dependent on the rate of loading. Therefore, standards for measuring compressive strength specify allowable loading rates to ensure comparable results among laboratories. These loading rates are specified in terms of either a stress rate or a strain rate. For example, ASTM Test Method C 39 allows a stress rate of 0.14 MPa/s to 0.34 MPa/s. Assuming that the elastic modulus is about 25 GPa, this stress range corresponds to strain rates of 6 to 14 microstrain/s.

One of the first published studies on the effect of loading rate on measured compressive strength of concrete cylinders (150 by 300 mm) was reported by Abrams (1917). Tests were conducted with a screw-type testing machine. Two testing methods were used: (1) about 10% of the expected ultimate load was applied at a fast deformation rate (347 microstrain/s), and the remainder of the loading was performed at rates ranging from 8 to 208 microstrain/s; (2) cylinders were loaded at a fast rate (347 microstrain/s) up to various percentages of the expected ultimate load, and the remainder of the loading was accomplished at a rate of 14 microstrain/s. Three concrete mixtures were used with nominal strengths of 6, 12 and 20 MPa. The results for the first method showed that an increase in the deformation rate increased the measured strength, and that the stronger concretes were more sensitive to loading rate. The results from the second loading method showed that the fast loading rate during the first part of the test had no measurable effect on the ultimate strength, even when the fast rate extended to about 90% of the expected strength. Based on these results, Abrams recommended that, for testing economy, specimens should be loaded at a fast rate to about 50 to 75% of the expected strength and thereafter loaded at deformation rates of 14 to 28 microstrain/s[f].

In 1936, Jones and Richart reported on a study in which 150 by 300-mm cylinders were loaded at nine different rates so that ultimate loads were reached within 1 second to 4 hours (Jones and Richart 1936). Tests were performed on a screw-type machine. Three concrete mixtures were used with nominal strengths of 14, 24, and 35 MPa. It was noted that, although tests were performed with a constant crosshead speed, the load rate increased gradually at the start of the tests as *slack* was taken out of the loading system. The loading rate was computed from the straight-line portion of the load-time history, which extended from about 25 to 90% of the ultimate load. Stress rates from 1.7 kPa/s to 26 MPa/s were obtained. On average, the strength was found to be a linear function of the logarithm of the stress rate. Based on the published relationship, an increase in stress rate from 0.14 MPa/s to 0.34 MPa/s is expected to produce about a 3% increase in the measured strength.

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[f]The actual recommendations were 0.25 to 0.50 mm/min, but these have been changed to microstrain/s by dividing by 300 mm, the approximate height of the cylinders.

Petkov reported on a study of the effect of loading rate on the measured cube strength (Petkov 1964). Nine concrete mixtures were used and the cube strengths varied from about 6 to 25 MPa. A hydraulic testing machine was used, and stress rates were approximately 0.05, 0.2 and 0.5 MPa/s. Based on Petkov's results, an increase in loading rate from 0.14 MPa/s to 0.34 MPa/s would be expected to result in a 1.4% strength increase.

In a recent study, Chojnacki and Read investigated the effect of loading rate on the measured strength of high-strength concrete cylinders (Chojnacki and Read 1991). Two nominal strength levels were used: 70 and 90 MPa. Cylinders were 100 and 150 mm in diameter. Three loading methods were used:

- at a rate of 0.15 MPa/s for the entire test (slow),
- at a rate of 0.35 MPa/s for the entire test (fast), and
- at a rate of 0.70 MPa/s for the first 50% of the test and at a rate of 0.25 MPa/s for the remainder of the test (medium).

In general, the third loading scheme resulted in large scatter. The slow stress rate resulted in 2.2 to 3.5% lower strength than the fast rate, depending on cylinder size and strength level of the concrete.

OBJECTIVE

The above review has examined some of the key factors that affect the results of compression tests of concrete specimens. A vast amount of data provide the bases for current testing standards. The review has shown that the measured strengths of high-strength concrete specimens are more sensitive to changes in testing conditions than are ordinary strength specimens. Questions have been raised about the ability of current standards to provide for reliable test results when applied to high-strength concrete. The purpose of the experimental program was to examine the effects of variations of key factors on the measured compressive strength of high-strength concrete cylinders. The overall objective is to recommend modifications to existing standards to ensure their applicability to testing high-strength concrete.

EXPERIMENTAL STUDY

Design of Experiment

The scope of this study was limited to examining the effects of a limited number of factors, which were judged to be important based on the review of research and existing ASTM standards (Carino et al. 1993). The following factors were investigated:

- specimen size (100 mm versus 150 mm diameter)
- end preparation (sulfur mortar caps versus grinding)
- testing machine (1.33 MN versus 4.45 MN capacity)

- loading rate (0.14 MPa/s versus 0.34 MPa/s)
- strength level (45 versus 90 MPa)

Two strength levels were used to determine whether there were interactions between the other factors and strength level.

A full, factorial experimental design was used with three replicates for each combination of factors. Because it would not have been possible to test 150-mm cylinders of the 90-MPa concrete on the 1.33-MN capacity testing machine, a third mixture with a nominal strength of 65 MPa was substituted. As a result, the *strength* factor was *nested* in the factors *testing machine* and *size*, and this made subsequent data analysis more complicated. The three replicates were tested on different days (with the exception of the 65-MPa cylinders). Any differences due to day-to-day effects were taken into account by treating day as a *blocking factor*. Table 1 shows the 32 combinations of factors that were used. Each combination is identified by the *run number*. The runs from each replicate were tested in random order each day to avoid contaminating the factor effects with uncontrollable systematic changes in the test set-up within each day (see Carino, et al. 1993 for details).

<u>Concrete mixtures</u>

The batch weights per cubic meter are given in Table 2. The coarse aggregate was a crushed traprock with a bulk specific gravity (dry) of 2.90, and the fine aggregate was a natural sand with a bulk specific gravity of 2.59. Due to the required number of specimens and the limited capacity of the laboratory mixer, more than one batch was used for each mixture. The batch sizes and the number of batches for each mixture are listed at the bottom of Table 2. For each mixture, the batches were mixed consecutively and placed in a large pan, where they were mixed together manually with shovels. The properties of the fresh concrete are given in Table 3. Note that the 90-MPa mixture had a significantly higher air content than the other mixtures.

<u>Specimen Preparation</u>

Specimens were prepared at the laboratory of the National Ready Mixed Concrete/National Aggregates Association. Single-use, plastic molds were arranged in regular patterns within two empty curing tanks. The molds were filled in a random order to minimize the contamination of the factors effects with systematic specimen-to-specimen differences. The molds were filled in three layers, and each layer was rodded 25 times. After each layer had been rodded, the sides of the molds were struck 10 to 15 times with the tamping rod to close up any holes left by the rod and to eliminate large air bubbles. The top surfaces of the cylinders were finished with wood floats, and the curing tanks were filled with water to submerge the cylinders. The water served to provide moisture for curing and to moderate any temperature differences between the 100-mm and 150-mm cylinders during the early stages of hydration. Thermocouples were used to measure early-age temperature histories. Only minor differences were noted in the early-age temperatures of the two cylinder sizes (Carino, et al. 1993). The acceleratory period of hydration was indicated as the time when the cylinder temperatures rose above the water temperature. For the 90-MPa mixture, the temperature rise did not begin until the next day. Apparently, the large dosage of high-range water reducer had a significant retarding effect on the 90-MPa mixture.

The cylinders were kept under water in their molds for two days, at which time they were stripped and returned to the curing tanks. On the fifth day, they were removed from the tanks, and they were weighed first in air and then submerged in water to obtain their specific gravities. After weighing, average diameters were determined and the cylinders were placed in a moist room for subsequent curing. On the 19th day, the cylinders were moved to NIST for end preparation and subsequent strength testing. Prior to capping or after grinding, the lengths and longitudinal resonant frequencies (ASTM C 215) were measured. Cylinder lengths were measured before and after each cap was applied to obtain the *nominal* cap thickness. If the nominal thickness *exceeded 4 mm*, the cap was removed and a new one was applied.

Testing Procedure

The 4.45-MN, servo-controlled testing machine was operated at a constant rate of piston travel. Preliminary tests were required to determine the rates of piston travel to produce the *low* and *fast* loading rates of 0.14 MPa/s and 0.34 MPa/s for the two cylinders sizes. Based on these preliminary tests, the following rates were used to control the testing speed:

Cylinder size, mm	Rate of piston travel, mm/s: 45 MPa		90 MPa	
	Slow	Fast	Slow	Fast
100	0.11	0.25	0.08	0.18
150	0.14	0.33	0.11	0.27

The rate of piston travel was maintained constant throughout an entire test, and digital time histories of the piston position and the compressive load were recorded.

The 1.33-MN testing machine has a pacer dial for manual control of the loading rate. Once the correct loading rate was obtained at the start of a test, the flow valve was not adjusted during the remainder of the test (in accordance with ASTM C 39). A displacement transducer was used to measure the change in distance between the top of the piston and the machine crosshead. The time history of the transducer output was recorded by a computer. The load history was also recorded by using a pressure transducer connected to the hydraulic weighing system.

Figure 5(a) shows an example of the recorded histories of stress versus time and piston position versus time for the 4.45-MN machine. Note that the piston position is a linear function of time because that is the method used to control the loading rate. The stress-history is nonlinear at the beginning of the test and when the ultimate load is being reached. In between these two extremes, the stress increases approximately linearly with time. A best-fit line was fitted to the straight-line portion of the stress history, and the value of the slope was used as the *nominal stress rate* for the test. Figure 5(b) shows an example of the recorded data for a test on the 1.33-MN machine. Again, a straight-line was fitted to the middle portion of the stress-history to obtain the nominal stress rate for the test. Note that as the ultimate load is being reached on the 1.33-MN machine, there is an increase in the rate of relative movement between the piston and the crosshead. Therefore, the deformation rate of the specimen increases as the ultimate load is being reached.

The original plan was to test replicate specimens of each run at ages of 27, 28, and 29 days. Preliminary tests at 14 days, however, indicated that cylinders of the 65-MPa mixture were close to the anticipated 28-day strength. There was concern that at 28-days, the 65-MPa cylinders would be too strong to test on the 1.33-MN machine. Therefore, all the 65-MPa cylinders were tested on the same day at an age of 20 days. To simplify subsequent data analysis, the measured strengths were treated as though they were obtained on three separate days.

RESULTS

Specific Gravity

Specific gravities were measured to identify specimens with abnormally low densities, to examine whether there were systematic differences in density due to cylinder size, and to provide data for computing the dynamic modulus of elasticity from resonant frequencies. Table 4 shows the averages and standard deviations for the different groups. Data analyses indicated that for both the 45-MPa and 90-MPa mixtures, the 100-mm cylinders were denser than the 150-mm cylinders (Carino, et al. 1993). The difference, however, was greater for the 90-MPa mixture.

Cap Thickness

Table 5 summarizes the averages and standard deviations of the *nominal* cap thicknesses obtained by measuring the lengths of the cylinders before and after each cap was applied. On average, the nominal thicknesses of the top caps were about 0.5 mm greater than those of the bottom caps. This is expected because of the more irregular surface at the tops of the cylinders. After the cylinders were tested for compressive strength, portions of caps were removed from randomly selected cylinders and their thicknesses were measured with a caliper. Four portions were measured for each cap, and the average was compared with the nominal thickness. It was shown that the nominal cap thickness based on the length measurements were indeed good indicators of average cap thickness (Carino, et al. 1993).

Loading Rate

Table 6 summarizes the averages and standard deviations of the nominal stress rates based on the straight-line portions of the measured stress histories. Data analyses indicated that at the *slow* rate, the mean rate for the 100-mm cylinders on the 1.33-MN machine was significantly higher than the means for the other three groups. At the *fast* loading rate, the mean rates for tests on the 4.45-MN machine were significantly lower that the mean rates on the 1.33-MN machine. The measured stress histories provide data on the variability in the nominal stress rate that can be expected for tests performed in accordance with ASTM C 39. For the 4.45-MN machine, the pooled standard deviation was 0.022 MPa/s, and for the 1.33-MN machine the value was 0.018 MPa/s.

Wave Speed

Although it was not a primary objective of this study, measurements of longitudinal resonant frequency were made prior to testing the cylinders, using the impact procedure in ASTM C 215. The resonant frequency and cylinder length were used to calculate the longitudinal wave speed. The results were as follows:

Nominal Strength, MPa	Nominal Diameter, mm	n	Average Speed, m/s	Standard Deviation, m/s
45	100	24	4197	16
	150	24	4185	14
65	150	12	4418	9
90	100	24	4390	16
	150	12	4348	13

It was found that, for the 45- and 90-MPa mixtures, there were statistically significant differences between the average wave speeds for the two cylinder sizes.

The longitudinal resonant frequencies were also used to calculate the dynamic modulus of elasticity by using the relationship in ASTM C 215 (Carino, et al. 1993).

Strength

Table 7 summarizes the compressive strength results. For each run number, the individual test results, the average, standard deviation and coefficient of variation are given. Figure 6(a) shows the individual results as a function of the run number. Visual examination of the spread of the replicate results shows that the strengths for the 90-MPa mixture were more variable than for the 45-MPa mixture. Hence the coefficient of variation is a better indicator of test dispersion. Figure 6(b) shows the coefficient of variation versus run number. Note that the tests of the 65-MPa mixture (Run #s 25, 26, 29 and 30) had very low variability.

ANALYSIS OF STRENGTH DATA

Analysis Technique

As mentioned, a full factorial experimental design was used in this study. This type of design is often used in *screening* studies to determine which of many *factors* have significant effects on the *response variable*. The factors are typically set at pre-determined *levels* or *settings*. This study used two settings for each factor, which are termed the *low setting* and the *high setting*. A *run* represents a particular combination of settings of the factors. In this study, there were 32 runs as listed in Table 1.

In a factorial experiment, the *effect* of a factor is the difference between the average response for the runs at the high setting of the factor and the average response for the runs at the low setting. For data analyses, the following were taken as the *high (+1) settings of the factors*:

- cylinder size (size): **150 mm**
- end preparation (end): **grinding**
- testing machine (machine): **4.45 MN capacity**
- stress rate (speed): **0.34 MPa/s**

In addition to the effects of the factors, or the *main effects*, a full factorial experiment also allows determination of the effects due to *interactions* between factors. An interaction exists when the effect of one factor depends on the setting of another factor.

The technique called *analysis of variance* (ANOVA) was used to establish whether the computed effects (differences between means) were statistically significant. In simple terms, ANOVA determines the likelihood that the observed differences in means could be the result of random variation. To perform an ANOVA, there must be an estimate of the within-test variability, which was provided by the three replicates tests for each run. ANOVA compares the differences between the means of different groups with the within-test variability. If the measure of between-group variability is significantly greater than the measure of within-group variability, the differences between means are likely to be real rather than the result of random error. The relative variabilities are expressed by a ratio called the *F-value*. In applying this method, the F-value computed from the data is compared with a tabulated value. If the computed F-value exceeds the tabulated value, one can conclude with a certain degree of confidence that the group means are not equal. The *significance level* indicates the probability of declaring that the means estimated from the data are not equal, when in fact the true means are equal. Usually, a significance level of 0.05 or 0.01 is used to decide whether differences between means are *statistically significant*.

Data Transformation

Prior to carrying out the analyses to determine the effects of the various factors, the strength data were transformed and adjusted. One of the assumptions in ANOVA is that the variance (square of the standard deviation) of the random error is constant across the different factor combinations. As was shown by Fig. 6(a), variability was greater for the 90-MPa mixture than for the 45-MPa mixture, so the coefficient of variation is used as the measure of variability. If the coefficient of variation is constant, the assumption of constant variance can be satisfied by using the natural logarithms of the data. The natural logarithm transformation has a unique mathematical property: the standard deviation of the replicate transformed values approximately equals the coefficient of variation of the replicate real values for coefficients of variation less than 0.3 (or 30%). Hence the individual strength values shown in Table 7 were transformed by taking their natural logarithms. These transformed values are listed in the second, third, and fourth columns of Table 8.

To account for the use of three strength levels and to avoid the possibility that the differences due to strength level would overshadow the effects of other factors, the transformed strengths were adjusted by subtracting the mean (of the transformed values) for each strength level. The last three columns of Table 8 list the adjusted transformed values. These adjusted transformed values are approximately fractional differences between each strength value and the overall average strength for that mixture. For example, an adjusted transformed value of 0.020 indicates that the strength is about 2% greater than the overall mean. The adjusted values in Table 8 and the accompanying settings of the factors, were provided as input to an interactive computer program that analyzes the results of factorial experiments. The factor *day* was used as a *blocking factor* to account for any day-to-day variability that may have been present. To have degrees of freedom to estimate the value of the random error, all interactions between *day* and other factors were assumed to be zero.

Effects on Means

The effects that were found to be statistically significant from the ANOVA are listed in Table 9, and the values of the effects are shown in the second column. As mentioned, these effects represent the differences between the averages at the *high* and the *low* settings of the factor or interaction of factors. Since the differences are between logarithms of strength values and are relatively small, the values of the effects in Table 9 are approximately the differences in average strengths at the high and low settings divided by the average strength at the low setting (Carino, et al. 1993).

The approximate 95% confidence limits of the effects are shown in the last two columns of Table 9. These are based on the estimate of the standard deviation of the effects as explained in the complete report (Carino, et al. 1993). The confidence limits of the main factor effects do not include the value 0, which confirms that these effects are statistically significant. The results in Table 9 are interpreted as follows:

- Overall, the 150-mm cylinders had about 1.3% lower strength than the 100-mm cylinders.
- Overall, the ground cylinders had about 2.1% greater strength than the cylinders with sulfur caps.
- Overall, the 4.45-MN testing machine resulted in about 2.3% lower strength than the 1.33-MN testing machine.
- Overall, the faster loading rate resulted in 2.2% higher strength than the slower rate.
- There are significant interaction effects, so that the effect of a factor depends on the settings of the other factors.

As will be seen, in Table 9 there are four values entered for the *strength*end* interaction effect. Recall that in the experiment design, the 65-MPa mixture was substituted for the 90-MPa mixture when the settings of size and machine were 150 mm and 1.33 MN, respectively. Thus the level of the factor *strength* depended on the settings of the factors *machine* and *size*. In statistical terms, the *factor strength is nested within the factors machine and size*. As a result, effects involving *strength* cannot be averaged over the factors *machine* and *size*. Hence, in Table 9 there are four entries for the *strength*end* effect, each corresponding to a unique combination of *machine* and *size*. The uncertainty is larger for these separately computed effects because fewer (12 compared with 48) individual results are used to compute the averages used to determine each *strength*end* interaction effect. By examining whether the confidence limits include the value 0, it is seen that the *strength*end* interaction effect is statistically significant only in the tests of 100-mm cylinders on the 4.45-MN machine.

Table 9 also indicates that there is a significant effect due to the interaction of *size*end*machine*speed*. As a result, the effect of *end condition* depends on the settings of all the other factors. To obtain an understanding of how the difference between the strength of ground cylinders and capped cylinders is affected by the other factors, it is necessary to analyze the 16 groups involving different combinations of the factors *strength*, *machine*, *size*, and *speed*. Each combination includes three replicate tests with sulfur caps and three with ground ends, and the *end* effect is the difference between the averages. The 95% confidence intervals for the effect of *end condition* for each of the 16 groups are plotted in Fig. 8. The groups are identified by a code that gives the nominal strength, cylinder size, testing machine, and stress rate. The effects have been arranged in decreasing value for the tests at the fast rate, and the effects for the slow rate are shown adjacent to those of the fast rates. While the overall effect of grinding was a 2.1% increase in strength compared with using sulfur caps, Fig. 8 shows that the increase was more pronounced in the tests of the 90-MPa concrete. The highest strength increase due to grinding was more than 6%, and it occurred in the 100-mm, 90-MPa cylinders tested at the fast rate on the 1.33-MN machine.

Because of the significant interaction effect of *size*end*machine*speed*, the effects of *size, machine*, and *speed* are also dependent on the particular settings of the other factors. By using a similar approach to that used for the effect of *end condition*, the effects of *size, machine* and *speed* were determined for the various combinations of the other factors. In this case, there are eight combinations of settings to consider. The effects and their 95% confidence intervals are shown in Fig. 9, where the effects have been arranged in order of decreasing value. The following summarizes the effects of these other factors:

- The overall effect of *size* is 1.3% lower strength for the 150-mm cylinders, but a difference as high as 3.7% occurred for ground cylinders tested at the fast rate on the 1.33-MN machine.
- The overall effect of *stress rate (speed)* is a 2.2% increase in strength at the faster rate, but the difference was as high as 4% in the case of 100-mm ground cylinders tested on the 1.33-MN machine. In general, the effect of stress rate was more pronounced for tests using 100-mm cylinders and for tests on the 4.45-MN machine.
- Overall, tests on the 4.45-MN testing machine resulted in 2.3% lower strength, but the reduction was as much as 4% for the capped, 150-mm cylinders tested at the fast rate. It appears that the capped cylinders were affected more than the ground cylinders.

In summary, the analysis of the data showed that the factors chosen for this experiment had statistically significant effects on the measured cylinder strength. There were, however, significant interaction effects. As a result, the effect of any factor depended on the settings of the other factors. Overall, effects of the factors resulted in strength differences less than 3%. Due to significant interactions, however, effects of a single factor as high as 6% were observed for particular settings of the other factors.

Effects on Dispersion

An analysis was also performed to determine whether the factors affected the dispersion of the test results. To better satisfy the assumptions of normality and constant variance that are fundamental to the application of ANOVA, the measure of dispersion was taken as the natural logarithm of the standard deviation of the transformed data. This is approximately the same as using the natural logarithms of the coefficient of variation *(cv)* of the strength values. To establish whether the factors had statistically significant effects on the dispersion, it was assumed that all interactions involving three or more factors were not significant[g]. If all interaction terms were included in the ANOVA, there would be no degrees of freedom to

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[g]The suitability of this assumption was verified by another analytical technique which considered all interactions and evaluated the significance of the effects by means of a normal probability plot. The normal probability plot was able to identify those effects which were large enough to be considered statistically significant.

evaluate the error, and it would not be possible to discern statistically significant effects.

The ANOVA showed that *cylinder diameter* was the only factor having a statistically significant effect on the dispersion of the test results. As explained in the complete report, the estimate of the ratio of the geometric mean *cv* (150-mm cylinders to 100-mm cylinders) was 0.45 with a confidence interval from 0.26 to 0.77 (Carino, et al. 1993). The geometric mean *cv* for the 150-mm cylinders is 0.008 and is 0.018 for the 100-mm cylinders.

In examining the effect of cylinder size further, it was noted that the geometric mean *cv* for the cases involving 65-MPa concrete was considerably smaller than other values for 150-mm diameter cylinders (see Table 7 and Fig. 6(b)). This could explain why there appears to be a difference in the dispersion for the two cylinder sizes. To examine this further, an analysis was performed using only the tests on the 4.45-MN testing machine, which do not involve the 65-MPa concrete. In this case, the ratio of the geometric mean *cv* (150-mm cylinders to 100-mm cylinders) was 0.71, but the results of the ANOVA indicated that this ratio was not statistically different from 1.0 (Carino, et al. 1993).

CONCLUSIONS

Cylinder size — It was expected that the strength of 100-mm cylinders would be greater than the strength of 150-mm cylinders. The average difference in strength, however, was only 1.3% compared with the expected value of 4% discussed in the review. There was, however, a significant interaction between size and other factors. As a result, differences as high as 4% were observed for particular settings of the other factors studied. It was shown that the 100-mm cylinders were denser than the 150-mm cylinders, and this could explain the greater strength of the smaller cylinders.

End condition — It was expected that the differences between the strengths of the capped and ground cylinders would depend on the concrete strength level. Test results confirmed this expectation. On average, the strength of the ground cylinders was 2.1% greater than the strength of the capped cylinders. However, there was a significant effect due to the interaction of *strength* and *end condition*. As a result, the effect of grinding was generally not statistically significant for the 45-MPa cylinders. On the other hand, grinding resulted in about 6% higher strengths in some of the tests with 90-MPa concrete.

Testing machine — On average, tests on the stiff, 4.45-MN, servo-controlled machine resulted in 2.3% lower strength than tests on the less stiff, 1.33-MN, manually-operated machine. There was also a significant interaction effect among *machine* and other factors, so that the difference was as much as 4% under certain conditions. The lower strength with the 4.45-MN machine was unexpected, and it is believed that the difference is due to the actual strain rate of the specimens as the ultimate loads were reached. For the 1.33-MN machine, the rate of change in the distance between the crosshead and the piston increased as the ultimate load was approached. Thus specimens in the 1.33-MN were subjected to higher strain rates prior to ultimate. These results refute the notion that a less stiff testing machine results in a lower measured strength.

Loading rate — It has been accepted that the stress range of 0.14 to 0.34 MPa/s specified in ASTM C 39 is sufficiently narrow to have no measurable effect on strength. Based on the literature review, it was expected that tests at the extremes of the permissible range could result in measurable differences. This expectation was confirmed in this study. On average, the faster rate produced about 2.2% greater strength, which is general agreement with previous work. However, due to interaction among *testing machine* and other factors, the difference was as high as 4% for certain factor settings. Analysis of the nominal stress rates attained during the tests indicated a standard deviation of about 0.02 MPa/s.

Superposition of effects — The above conclusions indicate that the *average (main)* effects of the factors are small and may not be of practical significance. However, the main factors effects are additive, and there are significant interaction effects. As a result, the range of the measured strengths for the different factor settings is of practical significance. In this study strength differences as high as 10% were obtained for extreme settings of the factors (see Fig. 7). To reduce within-laboratory variability, efforts should be taken to provide closer control of those factors which have statistically significant effects on measured cylinder strength.

Effects on dispersion — An analysis of the within-test dispersion indicated a significant effect due to *cylinder size*. The geometric mean coefficient of variation of the 150-mm cylinders was about 45% of that of the 100-mm cylinders. It was concluded, however, that this result was primarily due to the abnormally low variability for the 65-MPa, 150-mm cylinders. When only the tests on the 4.45-MN machine were considered, the geometric mean coefficient of variation of the 150-mm cylinders was about 70% of that of the 100-mm cylinders. This difference, however, was not statistically significant.

Modifications to ASTM standards — Based on the results of the literature review and the experiment, modifications to existing ASTM standards were recommended (Carino, et al. 1993). The following is a summary of the recommendations:

- Change the specified stress rate in ASTM C 39 to 0.25 ±0.05 MPa/s.
- Revise the wording on crosshead movement for screw-type machines.
- Add a performance requirement to ASTM C 617 for capping materials to be used for testing cylinders made of concrete stronger than 50 MPa.
- Permit the use of 100 by 200 cylinders, provided the maximum size of aggregate is less than a specified value.

- Revise the time requirements for mold removal in ASTM C 31 and C 192 to accommodate mixtures that may experience retardation in strength gain due to chemical admixtures.

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TABLE 1 — EXPERIMENTAL DESIGN

Run Number	Nominal Strength, MPa	Cylinder Diameter, mm	End Preparation	Testing Machine, MN	Load Rate*
1	45	100	Sulfur	1.33	Slow
2	45	100	Sulfur	1.33	Fast
3	45	100	Sulfur	4.45	Slow
4	45	100	Sulfur	4.45	Fast
5	45	100	Grind	1.33	Slow
6	45	100	Grind	1.33	Fast
7	45	100	Grind	4.45	Slow
8	45	100	Grind	4.45	Fast
9	45	150	Sulfur	1.33	Slow
10	45	150	Sulfur	1.33	Fast
11	45	150	Sulfur	4.45	Slow
12	45	150	Sulfur	4.45	Fast
13	45	150	Grind	1.33	Slow
14	45	150	Grind	1.33	Fast
15	45	150	Grind	4.45	Slow
16	45	150	Grind	4.45	Fast
17	90	100	Sulfur	1.33	Slow
18	90	100	Sulfur	1.33	Fast
19	90	100	Sulfur	4.45	Slow
20	90	100	Sulfur	4.45	Fast
21	90	100	Grind	1.33	Slow
22	90	100	Grind	1.33	Fast
23	90	100	Grind	4.45	Slow
24	90	100	Grind	4.45	Fast
25	65	150	Sulfur	1.33	Slow
26	65	150	Sulfur	1.33	Fast
27	90	150	Sulfur	4.45	Slow
28	90	150	Sulfur	4.45	Fast
29	65	150	Grind	1.33	Slow
30	65	150	Grind	1.33	Fast
31	90	150	Grind	4.45	Slow
32	90	150	Grind	4.45	Fast

* Slow = 0.14 MPa/s
Fast = 0.34 MPa/s

TABLE 2 — BATCH WEIGHTS, kg/m³

	45 MPa Mixture	65 MPa Mixture	90 MPa Mixture
Cement	323	451	504
Fly Ash	0	0	89
Silica Fume	0	0	59
Coarse Aggregate	1093	1093	885
Fine Aggregate	895	764	704
Water	172	170	183
Water Reducer	0	1.47 L	2.12 L
HRWR	0	2.65 L	17.01 L
W/(C+FA+SF)	0.53	0.38	0.28
Approximate batch size	0.09 m^3	0.06 m^3	0.09 m^3
Number of batches	3	2	2

TABLE 3 — FRESH CONCRETE PROPERTIES

Mixture	Slump, mm	Unit Weight, kg/m^3	Air Content, %	Temperature, C
45 MPa	40	2,456	2.2	19.5
65 MPa	70	2,496	1.4	19.5
90 MPa	250	2,356	4.9	20

TABLE 4 — SUMMARY OF SPECIFIC GRAVITIES OF CYLINDERS

Nominal Strength, MPa	Cylinder Diameter, mm	n	Average Specific Gravity	Standard Deviation
45	100 150	24 24	2.496 2.491	0.006 0.005
65	150	12	2.522	0.001
90	100 150	24 12	2.437 2.423	0.004 0.004

TABLE 5 — SUMMARY OF NOMINAL SULFUR CAP THICKNESSES

	100-mm Cylinders			150-mm Cylinders		
	Bottom	Top	Sum	Bottom	Top	Sum
Average, mm	2.3	2.8	5.1	2.2	2.8	5.0
Standard deviation, mm	0.4	0.5	0.5	0.4	0.4	0.6

TABLE 6 — SUMMARY OF NOMINAL STRESS RATE

Testing Machine, MN	Cylinder Diameter, mm	Rate*	Average Rate, MPa/s	Standard* Deviation, MPa/s
1.33	100	Slow Fast	0.155 0.335	0.023 0.022
	150	Slow Fast	0.135 0.334	0.008 0.014
4.45	100	Slow Fast	0.127 0.305	0.011 0.034
	150	Slow Fast	0.134 0.309	0.013 0.020

**Slow = nominal rate of 0.14 MPa/s*
Fast = nominal rate of 0.34 MPa/s
n = 12

TABLE 7 — COMPRESSIVE STRENGTH RESULTS

Run Number	Compressive Strength, MPa			Average Strength, MPa	Standard Deviation, MPa	Coefficient of Variation, %
	# 1	# 2	# 3			
1	45.13	45.93	46.50	45.85	0.69	1.5
2	46.48	46.77	47.72	46.99	0.65	1.4
3	44.75	45.25	46.87	45.62	1.11	2.4
4	45.56	44.47	46.96	45.66	1.25	2.7
5	45.97	46.06	46.36	46.13	0.20	0.4
6	46.75	48.97	47.99	47.90	1.11	2.3
7	43.90	45.75	44.55	44.73	0.94	2.1
8	45.17	46.70	47.61	46.49	1.23	2.7
9	46.17	46.01	45.04	45.74	0.61	1.3
10	46.36	47.25	46.92	46.84	0.45	1.0
11	42.46	44.55	43.92	43.64	1.07	2.5
12	44.69	45.02	44.55	44.75	0.24	0.5
13	46.03	46.46	46.01	46.17	0.25	0.6
14	46.07	46.76	46.56	46.46	0.36	0.8
15	44.28	45.35	44.67	44.77	0.54	1.2
16	46.30	45.87	45.35	45.84	0.48	1.0
17	88.42	92.13	90.94	90.50	1.89	2.1
18	85.67	89.98	88.55	88.07	2.20	2.5
19	85.42	86.08	81.53	84.34	2.46	2.9
20	88.44	88.22	89.38	88.68	0.62	0.7
21	86.96	88.28	94.64	89.96	4.11	4.6
22	92.31	92.86	96.53	93.90	2.29	2.4
23	87.67	89.71	89.54	88.97	1.13	1.3
24	92.56	90.86	93.09	92.17	1.17	1.3
25	67.55	67.26	67.32	67.38	0.15	0.2
26	69.01	68.66	68.76	68.81	0.18	0.3
27	86.34	86.20	85.89	86.14	0.23	0.3
28	84.87	83.40	90.59	86.29	3.80	4.4
29	68.39	69.01	68.72	68.71	0.31	0.5
30	69.13	68.96	69.39	69.16	0.22	0.3
31	85.40	89.18	89.78	88.12	2.37	2.7
32	91.40	89.88	92.55	91.28	1.34	1.5

TABLE 8 — TRANSFORMED AND ADJUSTED STRENGTH VALUES FOR DATA ANALYSIS

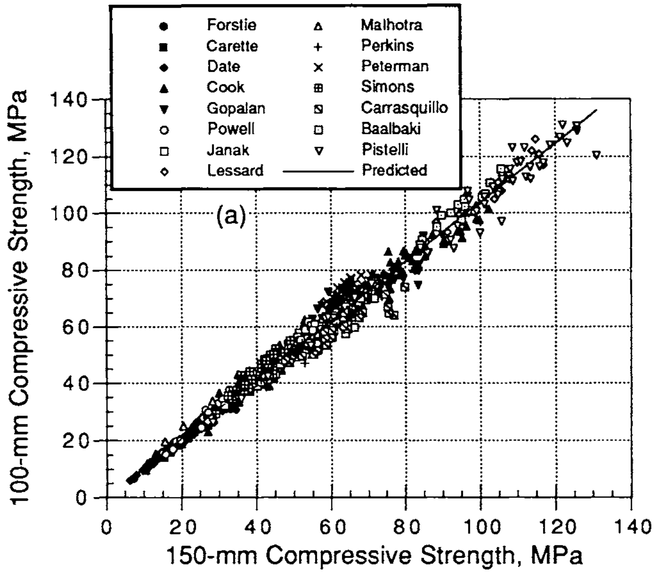
Run Number	Transformed Strength			Adjusted Transformed Strength		
	Ln(#1)	Ln(#2)	Ln(#3)	#1	#2	#3
1	3.8095	3.8271	3.8395	-0.0155	0.0021	0.0144
2	3.8390	3.8452	3.8654	0.0140	0.0202	0.0403
3	3.8011	3.8122	3.8474	-0.0240	-0.0128	0.0223
4	3.8190	3.7948	3.8493	-0.0060	-0.0302	0.0242
5	3.8280	3.8299	3.8364	0.0029	0.0049	0.0114
6	3.8448	3.8912	3.8710	0.0198	0.0662	0.0459
7	3.7819	3.8232	3.7966	-0.0431	-0.0019	-0.0284
8	3.8104	3.8437	3.8630	-0.0146	0.0187	0.0380
9	3.8323	3.8289	3.8076	0.0073	0.0038	-0.0175
10	3.8364	3.8555	3.8484	0.0114	0.0304	0.0234
11	3.7486	3.7966	3.7824	-0.0765	-0.0284	-0.0427
12	3.7997	3.8071	3.7966	-0.0253	-0.0179	-0.0284
13	3.8293	3.8386	3.8289	0.0042	0.0135	0.0038
14	3.8302	3.8450	3.8407	0.0051	0.0200	0.0157
15	3.7905	3.8144	3.7993	-0.0345	-0.0106	-0.0257
16	3.8351	3.8258	3.8144	0.0101	0.0008	-0.0106
17	4.4821	4.5232	4.5102	-0.0063	0.0348	0.0218
18	4.4505	4.4996	4.4836	-0.0379	0.0112	-0.0048
19	4.4476	4.4553	4.4010	-0.0408	-0.0331	-0.0874
20	4.4823	4.4798	4.4929	-0.0061	-0.0085	0.0045
21	4.4654	4.4805	4.5501	-0.0229	-0.0079	0.0617
22	4.5252	4.5311	4.5699	0.0368	0.0427	0.0815
23	4.4736	4.4966	4.4947	-0.0148	0.0082	0.0063
24	4.5279	4.5093	4.5336	0.0395	0.0209	0.0452
25	4.2129	4.2086	4.2095	-0.0141	-0.0184	-0.0175
26	4.2343	4.2292	4.2306	0.0073	0.0022	0.0036
27	4.4583	4.4567	4.4531	-0.0301	-0.0317	-0.0353
28	4.4411	4.4236	4.5063	-0.0473	-0.0647	0.0180
29	4.2252	4.2343	4.2300	-0.0017	0.0073	0.0031
30	4.2360	4.2335	4.2397	0.0090	0.0066	0.0128
31	4.4473	4.4907	4.4974	-0.0410	0.0023	0.0090
32	4.5152	4.4985	4.5277	0.0269	0.0101	0.0394

Average transformed strengths: for 45-MPa mixture = 3.8250; for 65-MPa = 4.2270; for 90-MPa = 4.884

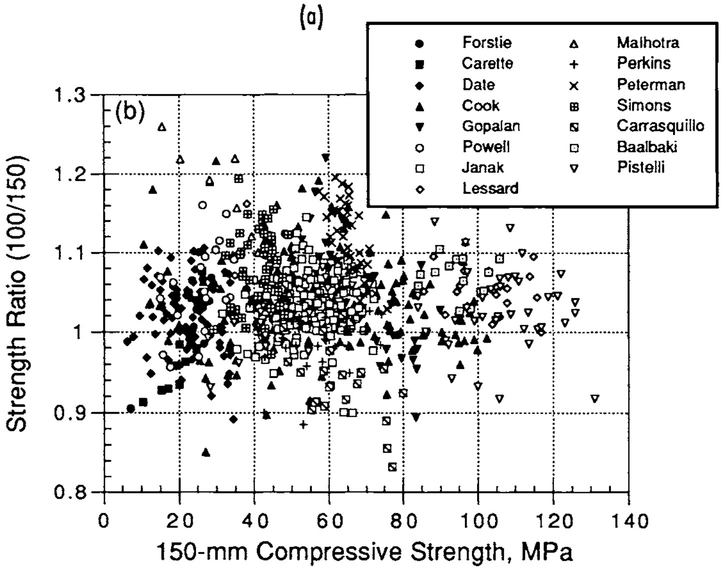
TABLE 9 — SUMMARY OF SIGNIFICANT EFFECTS ON MEANS

Factor	Effect	Uncertainty †	Lower Limit	Upper Limit
Size	-0.013	±0.007	-0.020	-0.006
End	0.021	±0.007	0.013	0.028
Machine	-0.023	±0.007	-0.030	-0.016
Speed	0.022	±0.007	0.014	0.029
End*Strength††				
100 mm - 1.33 MN	0.008	±0.015	-0.007	0.023
100 mm - 4.45 MN	0.023	±0.015	0.008	0.038
150 mm - 1.33 MN	0.006	±0.015	-0.009	0.021
150 mm - 4.45 MN	0.007	±0.015	-0.008	0.022
Size*End*Machine*Speed	0.008	±0.007	0.001	0.015

† See full report for explanation (Carino, et al. 1993)
†† Cannot be summarized as a single effect due to nesting of *strength* within *size* and *machine*. Therefore, four values are given for combinations of *size* and *machine* (the first number listed is the cylinder diameter and the second number is the testing machine capacity).

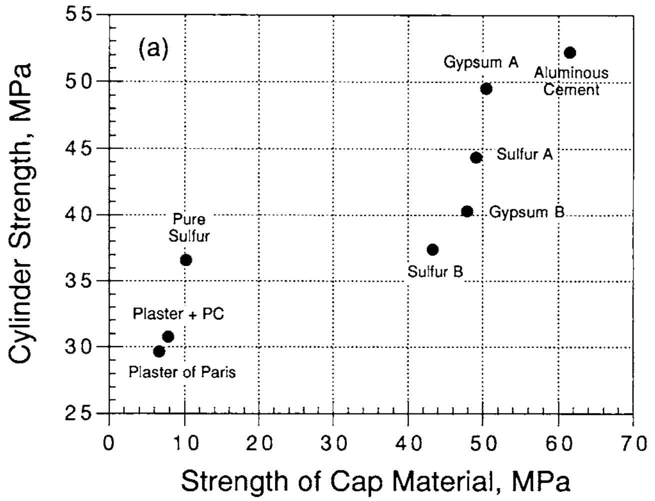


(a)

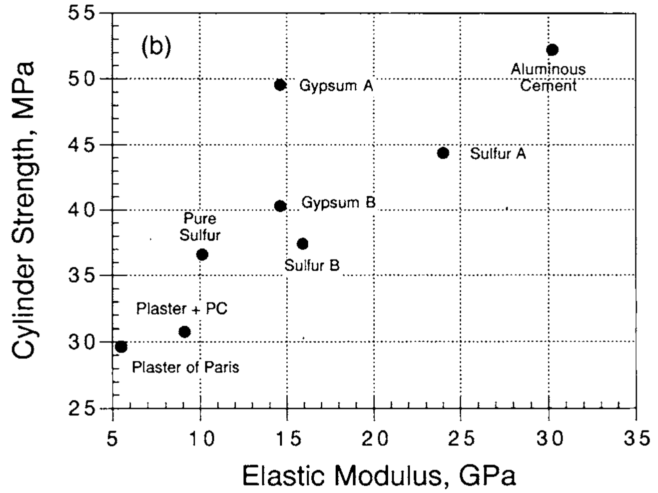


(b)

Fig. 1—(a) Comparison of compressive strength of 100- and 150-mm-diameter cylinders; (b) strength ratio as function of compressive strength of 150-mm cylinders



(a)



(b)

Fig. 2—Cylinder strength as function of: (a) strength of capping material; (b) elastic modulus of capping materials (data from Werner, 1958)

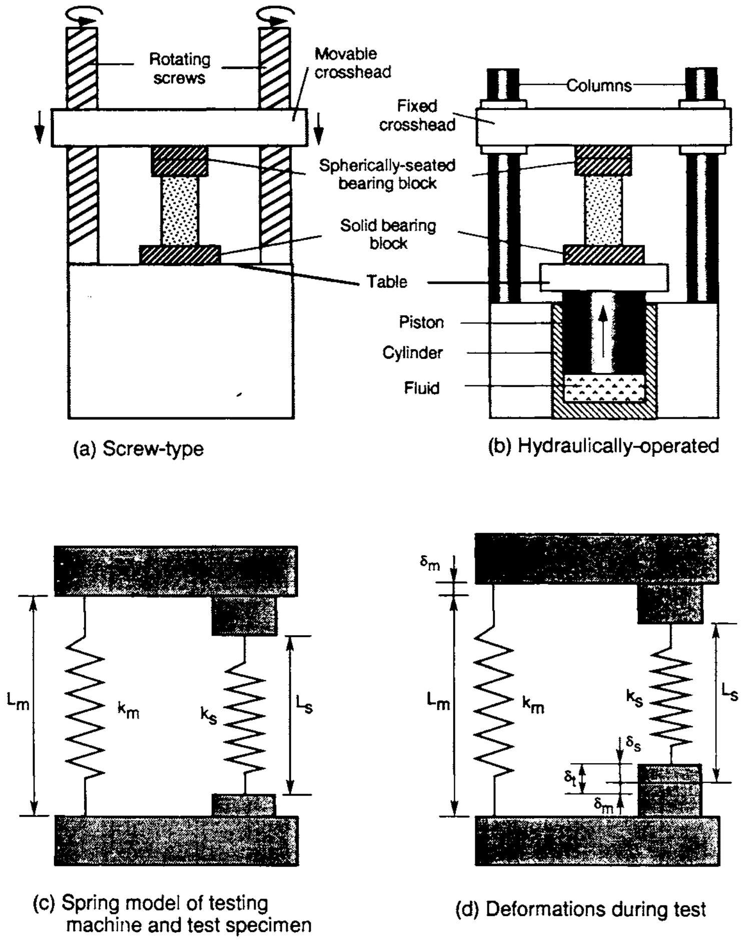


Fig. 3—(a) Schematic of screw-type testing machine; (b) schematic of hydraulically operated machine; (c) simplified spring model of specimen and testing machine; and (d) deformation of specimen and testing maching during testing

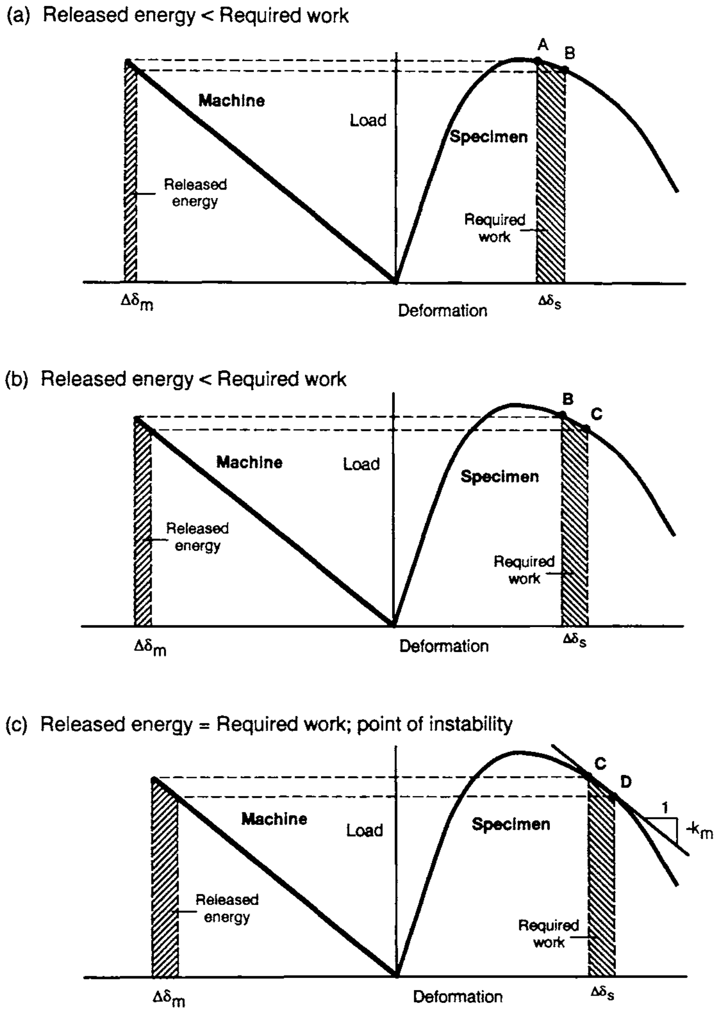
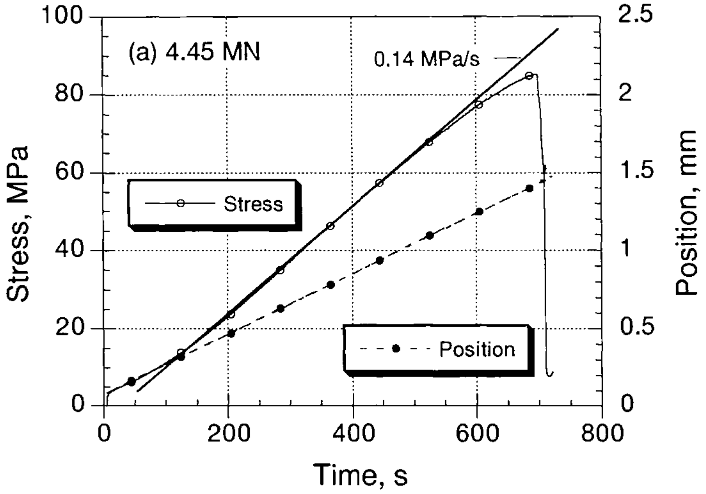
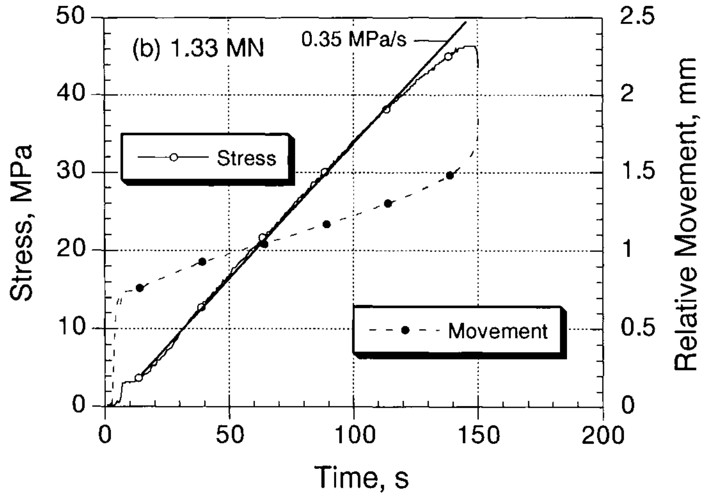


Fig. 4—Energy released by testing machine and work required to deform concrete specimen at different points along descending portion of load-deformation curve of specimen



(a)



(b)

Fig. 5—Examples of recorded stress and deformation histories: (a) Run #31, Day 1 on 4.45-MN machine; (b) Run #14, Day 1 on 1.33-MN machine

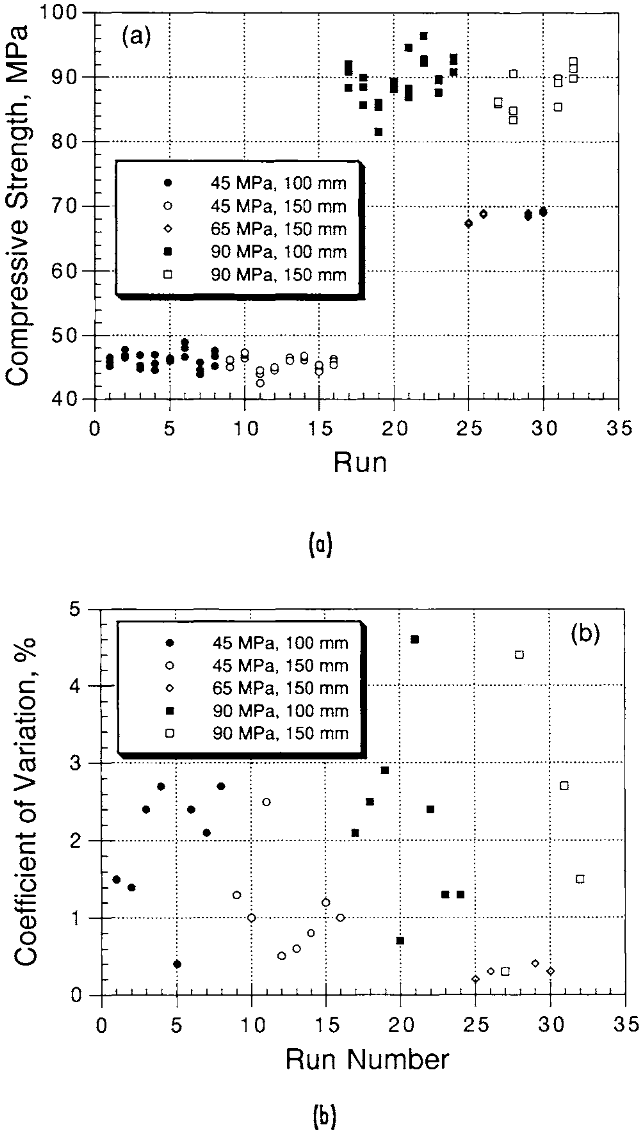


Fig. 6—(a) Compressive strength versus run number; (b) coefficient of variation versus run number

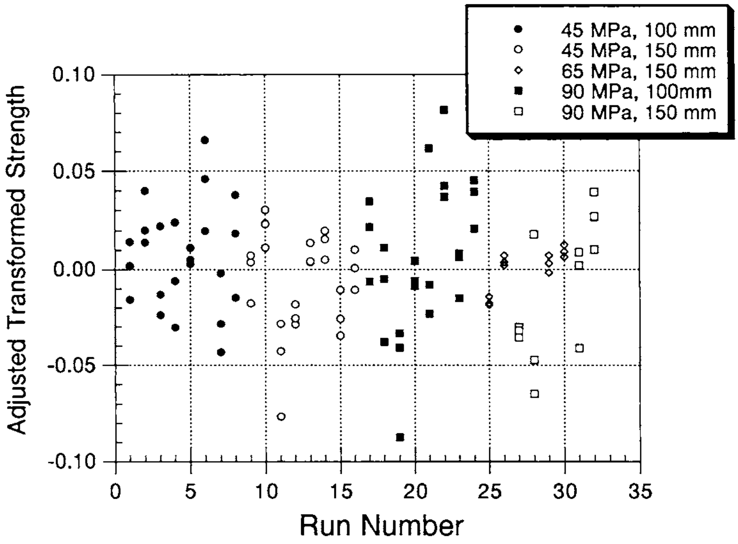


Fig. 7—Adjusted transformed strength versus run number

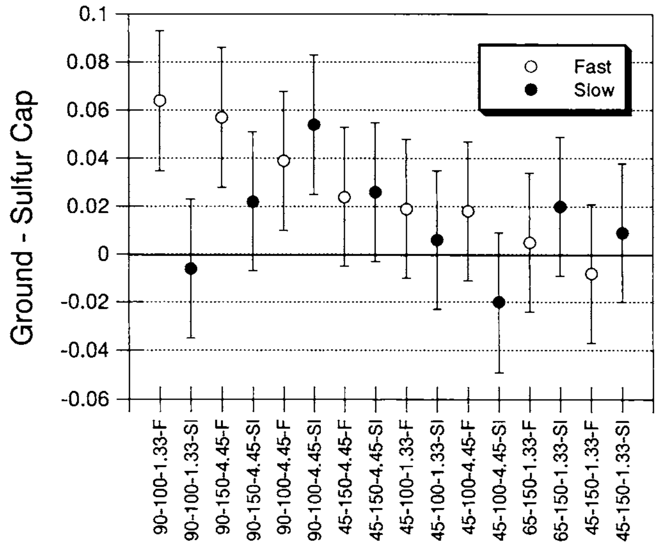


Fig. 8—Approximate 95 percent confidence intervals for effect of end condition (grinding-sulfur caps) for different strength, size, machine, speed combinations

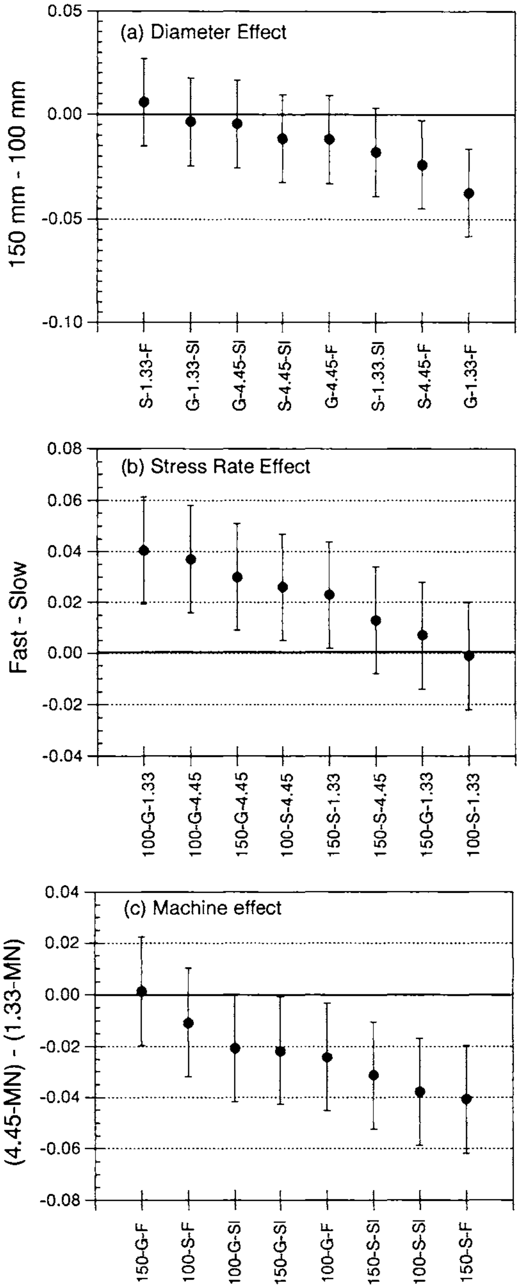


Fig. 9—Approximate 95 percent confidence intervals for effects of diameter, stress rate (speed), and machine for different settings of other factors