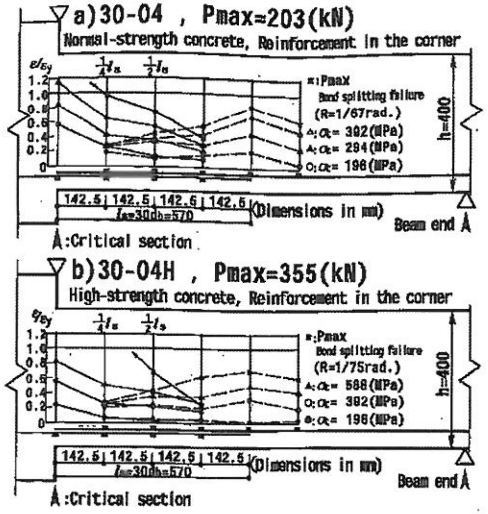


Figure 7—Progress of a yield zone

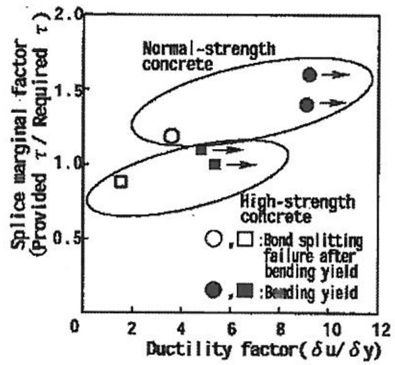


Figure 8—Relationship between splice marginal factor and ductility factor

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# Shortcomings of Current Compression Strength Tests for HSC and a Proposed Solution

by I. Luker and S.W. Tabsh

**Synopsis:** This study discusses the possible ways in which the characteristics of a testing machine can influence the strength of a HSC specimen. Particular attention is given to the platen rotation, which is caused fundamentally by the eccentricity of the reaction force from the specimen, and results in non-uniform straining over the loaded area of the specimen. The strain gradient is measured by a parameter denoted "strain-ratio," while the apparent strength is expressed by a parameter referred to "strength efficiency." An empirical method for establishing the relationship between strength efficiency and strain ratio is described. This is done using batches of similar HSC specimens deliberately subjected to different degrees of non-uniform straining and compared to predictions using simple theory. It is found that the test results confirm the validity of the theoretical assumptions. Strain measurement between the loading platens during a regular compression strength test is suggested as a practical proposition due to its economic benefit.

Keywords: compressive strength; concrete; modeling; precision; strain; stress; testing

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## INTRODUCTION

Compressive strength data for concrete is necessary to ensure quality control of the material. Hardened concrete is typically evaluated for acceptance using either 152 mm by 305 mm cylinders or 150 mm cubes. For high strength concrete (HSC), smaller cylinders and cubes have been utilized because the capacity of some testing machines may be limited. The measured results of the compressive strength are dependent on strict adherence to standardized procedures. Experience has shown that most testing errors produce lower-than-actual strength results (Richardson 1991).

The consequences of obtaining incorrectly low results of concrete strength can lead to delays, costly follow up testing, unnecessary conservatism, and possible rejection of potentially good concrete. The important variables encountered in testing of concrete are sampling, casting, curing, transporting, capping, testing, and reporting. For testing, the parameters that affect the results the most are: (1) humidity and temperature, (2) loading rate, (3) specimen misalignment, (4) loading platens, (5) specimen behavior, (6) seating behavior, (7) machine calibration, (8) frame stiffness, and (9) post-failure inspection.

Loss in strength of a specimen can be produced if the specimen is non-uniformly strained at the maximum load on it, particularly for HSC. This non-uniformity is caused mainly by rotation of the upper platen's ball joint and distortion of the frame of the test machine, which are themselves caused by the reaction from the specimen being eccentric from the centerline of the machine. The eccentricity can result from either the inhomogeneity of the specimen or misalignment of its geometric centerline with that of the machine. The size of the ball joint is important to its resistance to rotation, and also influences the stiffness of the upper loading platen which can affect the stress distribution in the specimen. A flexible frame will stretch during loading, thus storing more elastic energy and following more closely the rapid deformation of the specimen. The mode of failure of a specimen tested in such a machine will be more explosive, but not necessarily resulting in lower compressive strength (Richardson 1991).



## RESEARCH SIGNIFICANCE

Despite the potentially serious effect of non-uniform straining on concrete strength, the quantification of the effect, which is the subject of the paper, has not previously been investigated in detail. Theoretical considerations of non-uniform straining for various concrete strengths are verified using laboratory tests. Measurements of strain in a routine compression test to check non-uniform straining are proposed, and a possible way of correcting the erroneous strength result caused by non-uniform straining is included.

## PREVIOUS RESEARCH

Clark et al. (1967) investigated the relative significance of the strain rate and strain gradient for normal strength concrete rectangular prisms. An experimental program was developed which provided for the individual control of bending and axial loads, thus allowing for a constant strain gradient under uniform strain rate. The results showed that non-uniform straining increases the maximum strain that can be reached on the stress-strain curve before crushing occurs.

Dewar et al. (1971) tested six cubes from batches of twelve on one specific machine that was chosen as a reference and the remaining six cubes were tested on another machine under investigation. The results are shown in Fig. 1, where the number of batches is plotted versus the percent difference from the reference machine. The 145 batches in Fig. 1 represent at least twenty machines, most having been assessed at least twice during the period with 2 or 3 sets of cubes of different mould size and/or strength level. Dewar et al. conclude that the machines that gave lower strengths than the reference machine (by at least 4%) most certainly did so because they were not straining their specimens uniformly. The ones that gave higher strengths probably did so because of their non-standard platens.

In 1990, Tanigawa et al. studied the effects of eight end surface treatments and three different stiffnesses of testing machine (20 and 28 tf/mm) with a tilting platen (free versus fixed). Three different concrete strengths were considered: 59 MPa, 83 MPa, and 108 MPa. The test results indicated that the different treatments of the loading surface did not affect the compressive strength except for the case with a friction reducing pad, where a strength reduction of 9% was observed. The compressive strength also tended to decrease as the flatness of the end surface decreased. No significant effect on the measured compressive strength was observed with the difference in the stiffness of the testing machine. The compressive strength is greatly reduced if the loading platen was fixed at the initial loading.

Carino et al. (1994) conducted an extensive study to investigate the effects of testing variables on the measured strength of HSC cylinders. Among the considered variables were the end preparation method and testing machine capacity. Normal and high strength concrete with nominal strengths of 45 and 90 MPa were tested. In general, the results showed that ground cylinders at the ends were 2.1% stronger than those which were capped with sulfer and a 1.33 MN testing machine produced about 2.3% greater strength than a 4.45 MN machine.

Comparisons between machines' testing ability have been conducted by Kennedy et al. (1995). They cast batches of specimens very similar within the batch and then divided them between two or more machines for crushing. Based on their comparative tests between sixteen machines, Kennedy et al. determined that the variability of the test results increases with the mean strength of the concrete. They developed a precision statement based on the 95% confidence limits of between-machine variation in strength given for the same batch of specimens, and recommended it to be included in ASTM C39 (2001).

Burg et al. (1999) investigated the latest technology concerning testing of HSC. They conducted inter-laboratory tests to determine the effect of some test variables on the measured compressive strength of HSC. They found that some test platen designs that meet current requirements result in non-uniform load transfer from the test machine to the concrete specimen. The strain gradient can result in a reduction of measured compressive strength of more than 10 percent for a concrete with compressive strength of 125 MPa. Therefore, Burg et al conclude that the current requirement for test platens is inadequate and needs to be revised, particularly for concrete strength in excess of 70 MPa.

## DEFINITIONS

To observe the effect of strain non-uniformity on concrete specimen strength, the strain-ratio, denoted by ρ, is utilized:

$$\rho = \frac{(\varepsilon_{max} - \varepsilon_{min})/2}{\varepsilon_{mean}} \qquad (1)$$

where $\varepsilon_{max}$ and $\varepsilon_{min}$ are the maximum and minimum strains on opposite sides of the specimen, respectively, and $\varepsilon_{mean}$ is the mean strain on the specimen, i.e. $(\varepsilon_{max} + \varepsilon_{min})/2$. A value of $\rho = 0$ indicates uniform straining, and a value of greater than 1 means that some tensile strain is present in the specimen. Although the strain ratio can be measured at any stage of the test, it is of most significance at peak load on the specimen.

The definition of strain ratio can easily be applied to a cylindrical specimen but the meaning of the strain ratio for a strain gradient across a cube specimen needs to be clarified. The strain ratio for a cube test specimen is defined as that which would result if the slope of the strain gradient on the specimen is perpendicular across the specimen, as shown in Fig. 2.

The proportion achieved of the potential maximum capacity of a specimen is defined as the efficiency of a test, denoted by η. It is defined as the ratio of the apparent strength given by a machine for a test to the strength that the specimen would have had if it had



been uniformly strained during the test. That is:

$$\eta = \frac{\int_A \sigma\, dA}{\sigma_p A} \qquad (2)$$

where σ is a function representing the distribution of stress over the cross-sectional area of the specimen, A, and $\sigma_p$ is the peak stress of the stress-strain relationship for the concrete, assuming a single relationship exists for all regions of the specimen during the test.

## THEORETICAL APPROACH

Non-uniform straining of a concrete specimen causes the ultimate load that a concrete specimen can sustain to be lower than its potential, actual strength. This is because at the instant of maximum load, a part of the specimen in the high strain region will have passed the peak of the stress-strain curve, while the remaining part of the specimen in the low strain region lags behind the peak stress.

A mathematical stress-strain relationship for the concrete in a specimen is needed to develop computationally the relationship between strain ratio ρ and efficiency η. There has been a variety of proposed models during the past two decades for predicting the stress-strain relationship of HSC. The model proposed by Thornfeldt et al. (1987) has been chosen in this study because it represents well the experimental stress-strain relationships published in the literature and it is relatively easy to implement. The model is dependent only on the peak strength of the concrete $\sigma_p$, which makes it particularly useful because when interpreting a value of ρ from a test in practice into a value of η, the only other information available about the concrete is the measured strength. This can be taken as first approximation to the uniform-strain strength, $\sigma_{us}$, which is the same as the peak of the concrete's stress-strain relationship, $\sigma_p$.

In the model developed by Thornfeldt et al., the concrete stress, σ, is related to the strain, ε, by the following equation:

$$\frac{\sigma}{\sigma_p} = \left(\frac{\varepsilon}{\varepsilon_o}\right)\frac{n}{(n-1) + \left(\frac{\varepsilon}{\varepsilon_o}\right)^{nk}} \qquad (3)$$

where $\varepsilon_o$ is the strain at peak stress $\sigma_p$, obtained from:

$$\varepsilon_o = \left(\frac{\sigma_p}{E}\right)\frac{n}{n-1} \qquad (4)$$

and k and n are curve fitting parameters that depend on $\sigma_p$ and the ratio ($\varepsilon/\varepsilon_o$):

$$k = \begin{cases} 1.0 & for\ \varepsilon \le \varepsilon_o \\ 0.67 + \dfrac{\sigma_p}{61} & for\ \varepsilon > \varepsilon_o \end{cases} \quad (5)$$

$$n = \frac{\sigma_p}{17} + 0.8 \quad (6)$$

E is the modulus of elasticity of concrete, obtained for HSC from (Carrasquillo et al. 1981):

$$E = 3300\sqrt{\sigma_p} + 6900 \quad (7)$$

where both $\sigma_p$ and E are in MPa. Typical theoretical stress-strain curves for normal strength concrete (NSC) and HSC using Eq. 3 are shown in Fig. 3.

The method for determining the theoretical relationship between strain ratio ρ and efficiency η for a particular concrete strength consists of starting with Thornfeldt's function of σ-ε relationship. Next, a small strain ratio ρ is selected and a trial-and-error approach is used to produce the combination of $\varepsilon_{max}$ and $\varepsilon_{min}$ that gives the maximum value of the load $\int \sigma\, dA$. The efficiency η for this value of ρ is then obtained from Eq. 2. The strain ratio is incremented up and the procedure is repeated for the new value of ρ. The procedure is concluded when the value of ρ is equal to unity.

## EXPERIMENTAL PROGRAM

To investigate experimentally the effect on apparent strength of non-uniform strain patterns at maximum load, sets of about fifteen 100mm cube specimens were made so that all cubes in each set were as identical as possible. This was achieved by casting the whole set from the same batch of concrete, in identical moulds, all clamped down together on a single vibrating table for simultaneous filling and compaction. The curing environment (submersion in moving water) also affected all cubes equally. For the test results reported in this paper, the sand and stone were from crushed igneous rock and ordinary Portland cement with no additives. Different batch strengths were obtained by varying the water/cement ratio.

Each cube in a set was tested in the same machine at the same rate of change of mean strain (to eliminate variation in other influences on apparent strength), but at different eccentricities from the machine's centerline. The eccentricity of reaction from the specimen causes distortion of the machine's frame and rotation of the upper platen's ball joint, resulting in non-uniform straining. Compression testing machines vary in their response to an eccentric load, so that there is no single relationship between specimen eccentricity and consequent degree of strain non-uniformity (ρ) ... and error is used on the variation of the eccentricity to get a range of ρ between zero and one from the fifteen specimens available.

The distance between the machine's loading platens at a minimum of three points must be measured throughout the test, simultaneously with a measure of the load on the specimen. A variety of instruments is available to make the distance measurements, including lasers and LVDTs. The results in the present study were obtained using custom-made devices incorporating linear potentiometers, shown in Fig. 4. The device is suspended from the upper platen and movement of the potentiometer is caused by the lower platen pushing up on it. Load can be measured with a pressure transducer in the testing machine's hydraulic system.

## RESULTS

Using the procedure outlined above, theoretical ρ–η curves were generated for moderate and high strength concrete cubes, as shown in Figs. 5 and 6, respectively. Also shown in the figures are experimental results obtained by deliberately placing concrete specimens off-center in the test machine to induce non-uniform straining (i.e. strain measured on the distance between the loading platens). Figures 5 and 6 show that for the same strain ratio the efficiency decreases with an increase in concrete strength. This is mainly due to the increase in the slope of the descending curve of the stress-strain relationship for HSC. The figures also indicate that the theoretical findings are in good agreement with the experimental results. However, the accuracy of fit is better for the moderate strength concrete than for the high strength concrete. The theory slightly overestimates η for the higher strengths, possibly because the theoretical shape of Thornfeldt's σ-ε model might not be as steep as the actual relationship for the higher strength concretes used in this study, and also because the measured strain ratio values for the higher strength concretes might be slightly too low. This would occur if the speed of reading of the displacement measuring instruments was not fast enough to keep up with the fast rotation of the ball joint which sometimes happened when one side of a high strength concrete specimen began to crush.

## PRACTICAL CONSIDERATIONS

The practical use of the results of the study is to interpret knowledge of the degree of non-uniformity of straining that occurs in a test of a concrete specimen and quantify its effect on the measured strength shown by the test machine. This assumes that simultaneous measurements of load and displacement of the platens can be made on test machines used in practice.

It is clear that strain measurement of a concrete specimen at failure during a test is feasible. However, the ease and economics of such measurements are difficult to assess in terms of the savings to be made if higher strength of a concrete specimen is revealed. There are a wide variety of displacement-measuring devices that are now available, and neither their cost nor that of the computing device needed to record the results to calculate the strain ration ρ is prohibitively expensive. Further, the adoption of the "strain cylinder" standard in Europe (EN12390-4:2000), which sets a high standard for the ability of a machine to uniformly strain a specimen, indicates that there are many who believe that there is some economic benefit to be derived from reliably knowing the uniform strain strength of a concrete specimen.

## CONCLUSIONS

Measurements of the distance between the loading platens of a compression test machine can be used to determine the strain gradient in a specimen at its maximum load. Results presented in this paper show the extent to which the strain gradient affects the strength of the specimen. The effect of non-uniform straining on the apparent strength of a concrete specimen has been shown both theoretically and by laboratory tests. The accuracy of the theoretical results is slightly better for moderate strength concrete than for high strength concrete. Some economic benefit may be derived from reliably knowing the strength of a concrete specimen under uniform strain.

## NOTATION

A = area of the end of a specimen onto which compressive stress is applied.
n, k = curve fitting parameters.
E = modulus of elasticity.
$\varepsilon$ = strain in a concrete compression test specimen, along the direction of the stress.
$\varepsilon_o$ = strain at peak stess $\sigma_p$.
$\varepsilon_{min}$ = minimum longitudinal strain in a specimen subjected to a strain gradient.
$\varepsilon_{max}$ = maximum longitudinal strain in a specimen subjected to a strain gradient.
$\varepsilon_{mean}$ = mean longitudinal strain in a specimen subjected to a strain gradient.
$\rho$ = strain ratio, defined in Eq. (1).
$\eta$ = efficiency of a compression test, defined in Eq. (2).
$\sigma$ = compressive stress acting perpendicularly to the ends of a concrete specimen.
$\sigma_p$ = peak of the theoretical stress-strain relationship for the concrete.
$\sigma_{us}$ = compressive strength of a specimen if it had been uniformly strained throughout the test.

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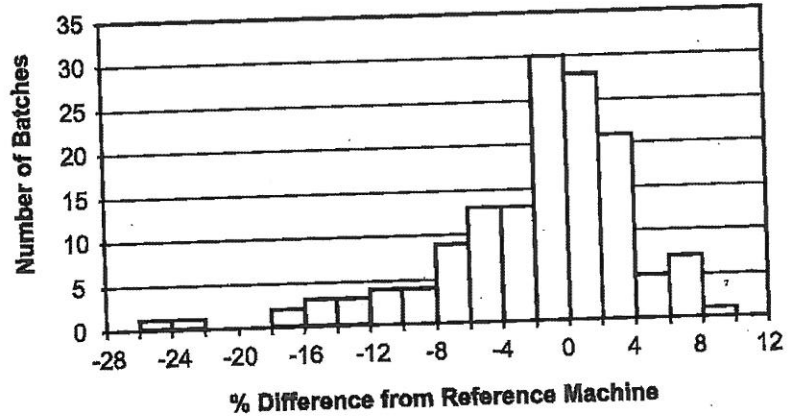


Figure 1—Comparative concrete cube tests on different machines (Dewar et al. 1971).

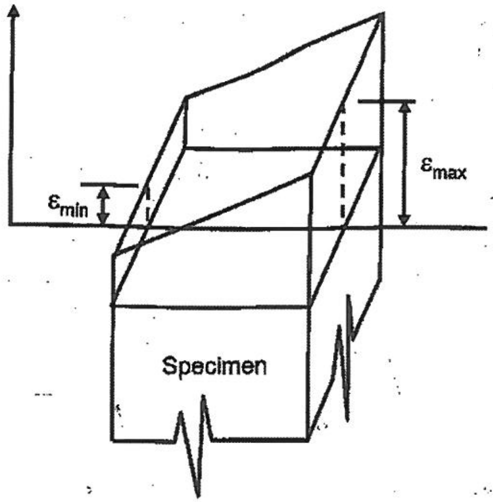


Figure 2—Strain pattern across a concrete cube specimen.

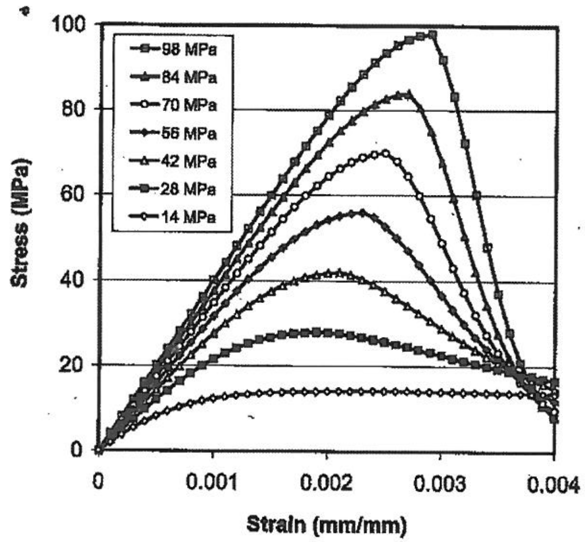


Figure 3—Stress-strain relationships for concrete using Thornfeldt et al. model (1987).



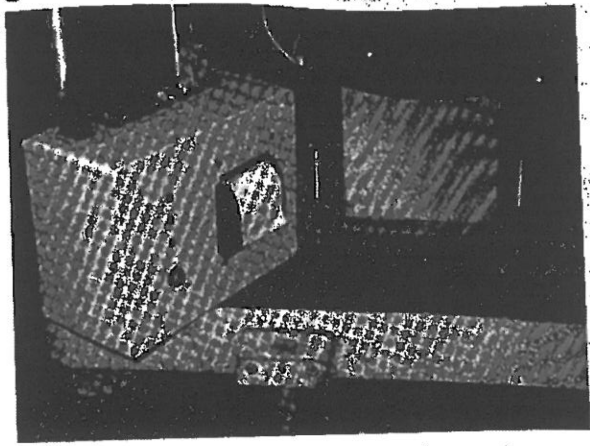

Figure 4—Displacements measurement on a cube specimen during a test.

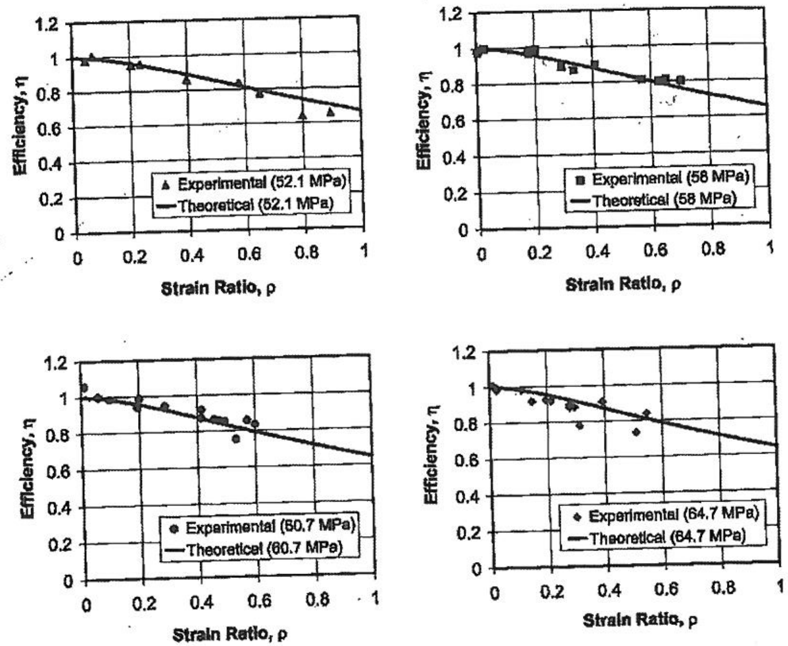


Figure 5—ρ-η relationships for moderate strength concrete

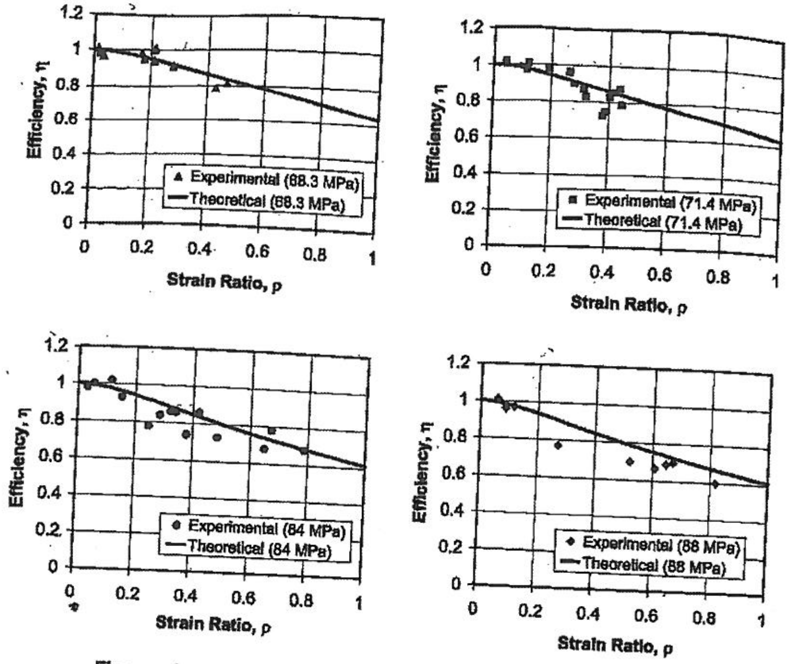


Figure 6—ρ-η relationships for high strength concrete

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# Uniaxially Loaded High-Strength Concrete Spiral Columns

by E. Canbay, B. Koru, G. Ozcebe, and U. Ersoy

**Synopsis:** Three series of tests were carried out to investigate the behavior and strength of high and normal strength concrete spiral columns under uniaxial compressive loading. Five columns with normal strength and fourteen high strength spiral columns were tested. Normal strength and high strength steel were used as spiral reinforcement. The main variables investigated were; (a) volumetric ratio (varied from 0.008 to 0.038) and spacing of spiral reinforcement, (b) ratio of gross to core area (varied between 1.05 and 1.45), and (c) strength of spiral reinforcement. Strength increase and ductility due to the presence of spiral reinforcement were investigated. When high strength concrete is used, the minimum spiral reinforcement required by ACI 318-02 results in extremely small spacing as the ratio of the gross to core area increases. Spacing of the spiral reinforcement can be increased to reasonable values if higher strength steel is used. During the tests it was observed that the columns having high strength spiral reinforcement behaved well, and had adequate ductility.

Keywords: column; confined concrete; ductility; high-strength concrete; spiral