STRAIN SOFTENING OF CONCRETE IN COMPRESSION*

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Abstract
Strain softening of concrete in uniaxial compression critically influences the way concrete structures are designed. Yet it is not explicitly included in many design methodologies. This may be partly due to the fact that it is often difficult to obtain post-peak pesponse especially for higher strength concrete and that the response depends also on the geometry of specimens, boundary conditions, and testing machine parameters. To delineate the influence of various parameters, a round robin test program is being persued by RILEM Committee 148 SSC 'Strain Softening of Concrete.' Results obtained from one laboratory participating in this round robin test program are discussed. The discussion includes methods to obtain the strain softening response of concrete in compression. The effects that the platens, lubrication between platens and specimen, specimen size, and measurement gage length have on obtained results are explored.

1 INTRODUCTION

RILEM committee 148 SSC "Strain Softening of Concrete" is pursuing a round robin program to establish a test method for determining the strain softening behavior of concrete in uniaxial compression. This report presents the goals of

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the committee, an introduction to strain softening, the purpose for studying strain softening, and discussion of some results obtained at Northwestern University as part of the joint program.

Concrete is a heterogeneous material composed of aggregate, sand, and cement which has preexisting microcracks even prior to application of any load. Upon loading, these microcracks propagate and new ones form. The load carrying capacity of concrete decreases after the peak load as deformation increases. This phenomenon is called softening. Strain softening of concrete occurs when the microcracks coalesce to form a zone of damage, weakening the concrete so its load carrying capacity is diminished. Additional deformation of the zone of damage weakens it further, and softening continues. The development of macrocracks introduces localized failure of concrete. Due to this localization, concrete does not behave as a homogenous material and its behavior becomes very sensitive to properties such as size and shape. Understanding the process of softening is important since design of reinforced concrete structures is based on the ultimate strength capacity which utilizes a portion of the postpeak or strain softening branch of concrete in uniaxial compression. Furthermore, understanding the mechanisms of failure of concrete in compression can lead to more rational basis for design and to better predictions of properties such as axial deformation at failure and ductility of columns and the rotational capacity, balanced steel ratio, and ultimate moment capacity of beams.

Due to its many advantages (greater strength, stiffness, and durability), high strength concrete has been widely used for high-rise buildings, bridges, and off-shore oil platforms. High strength concrete allows larger usable space in the building by reducing the size of columns. It also makes it possible to use thinner sections, smaller number of girders and longer span for bridges. The 70-story Lake Point Tower, built in Chicago in 1965 , had maximum design strength of 51.7 MPa. The Water Tower Place built in 1975 used 62.1 MPa concrete, and 70 MPa was needed for the 68-story Scotia Plaza Tower in Toronto completed in 1988. 311 South Wacker Drive in Chicago used high strength concrete up to 83 MPa. Some buildings built recently included experimental columns made of 100 MPa concrete [1]. Along with these advantages, high strength concrete is also more brittle in compression, making the understanding of the strain softening behavior even more vital for proper design. As high strength concrete (HSC) becomes popular, it becomes more important to understand its behavior and establish proper experimental testing procedures and data interpretation.

2 ROUND ROBIN TEST PROGRAM

As stated earlier, RILEM Committee 148 SSC "Strain Softening of Concrete" is pursuing a round robin testing program. The ultimate goal of this committee is to establish testing procedures for strain softening of concrete in order to aid in a more rational basis for design of reinforced and prestressed concrete structures. The design criteria should be based on correct understanding of material behavior, and influences of test parameters need clarifying. The goals of this committee should also be helpful in development of new materials and of constitutive modeling. The committee is chaired by Professor S. P. Shah, and Dr. Jan van Mier from Delft University is the secretary of the committee.

The primary mission of the round robin test program is to examine the effects of typical interlaboratory variations and procedures. These effects include the lateral confinement on the specimens provided by loading platens. Lubricated as well as non-lubricated platens have been tested with several different types of lubricants being used. Allowing the platens to rotate versus making them rigid and test machine stiffness are among the test machine characteristics being investigated. Also being investigated are differences in gage lengths of the measuring LVDTs, composition of the feedback signals, and size and shape of the specimens. These variables are all being tested and developed for a wide range of concrete compositions and strengths. Each laboratory is using equipment and procedures which are familiar to them; this includes feedback signals, specimen preparation, and lubricants. Allowing this freedom can lead to investigations by each laboratory, and by comparing experiences, new procedures may develop.

Strain softening is not a uniform material behavior; instead the cracking occurs in discrete zones and even localizes somewhat similar to plain concrete in tension. Fig. 1 shows a typical stress-strain response as measured by two separate transducers, platen to platen measurement and a surface mounted gage. The responses are similar during the prepeak; however, soon after the peak stress, the measured responses change drastically. These differences mean that strain softening is not a uniform response, but is instead localized. This implies that the strain softening behavior of concrete is dependent not only on material response but also on size, geometry, and other influences.

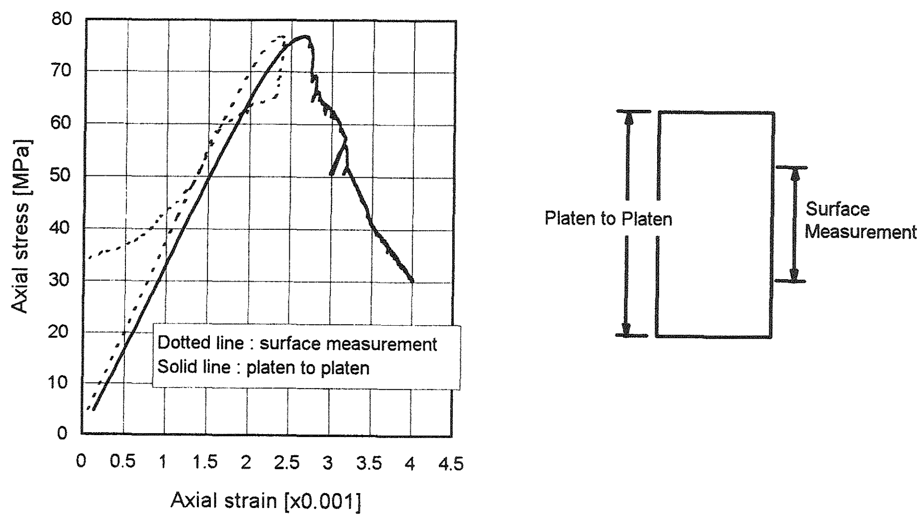

Fig. 1 - Gage length and localization

3 SELECTION OF FEEDBACK SIGNAL

The proper selection of a test control parameter is vital to obtaining the true strain softening branch of concrete. The requirement for a stable and correct test is that no sudden, large releases of energy due to fracturing of the concrete may be allowed. This is usually accompanied by a drop in load during the strain softening branch of the test. Concrete compressive strength, size, geometry, and end constraint can all affect the downward slope of the strain softening branch. Depending on the brittleness of the specimen, different levels of sophistication must be employed in controlling tests from simple, manually controlled machines to closed-loop servohydraulic test machines with complicated feedback signals.

3.1 Axial displacement control

Simply increasing the displacement of the actuator can lead to a stable test as long as the test machine is stiffer than the negative slope of the descending branch of the specimen load-deformation curve [2]. If the test machine is not stiff enough, then the elastic displacement of the test machine will cause displacement of the failure zone. With the use of closed-loop feedback control, the axial deformation can be used to control tests in a manner similar to using the stroke to control a test where the test machine had infinite stiffness. Axial specimen deformation (measured platen to platen) can be used as the feedback control as long as the postpeak of the load-deformation curve does not go vertical or experience snapback.

3.2 Circumferential expansion control

For most tests on strain softening of concrete, the methods described above are adequate; however, in tests involving high strength concrete, lubricants, or long specimens, snapback in the load-deformation curve may occur. For these tests, more sophisticated methods are necessary. In 1981, Shah et al. [3] demonstrated circumferential feedback control; with this method, the circumferential expansion is used to control the test. A cylinder with a circumferential transducer is shown in Fig. 2. As strain softening takes place, vertical cracking occurs in the cylinder and lateral expansion increases rapidly even if snapback in the load vs. axial deformation curve occurs (Fig. 3). Controlling the rate of lateral expansion controls the damage responsible for the strain softening. Very little lateral expansion occurs in the prepeak and a proportionally large amount occurs during the postpeak as shown in Fig. 3. Since the lateral expansion is increased proportionally with time (constant rate), the load up to the peak is applied very quickly, and the descending branch occurs slowly. In some cases, it may only take 1 to 2 minutes to reach the peak stress, while the rest of the test may take 40 minutes or more [4]. Since the displacement at peak is quite small in comparison with the total displacement, considerable transducer sensitivity is lost. Others [5, 6] have used a combination of axial and circumferential displacements to gain stability and sensitivity. Another limitation of the circumferential feedback control method is that it does not lend itself well to testing specimens with aspect ratios L:D much greater than 3 or to other geometry's such as prisms. In the case of testing cylinders with high aspect ratios, the transducer measuring the circumferential expansion must be placed such that it captures the location of the failure. Without being able to predict where the failure will occur, the circumferential feedback control method becomes unreliable.

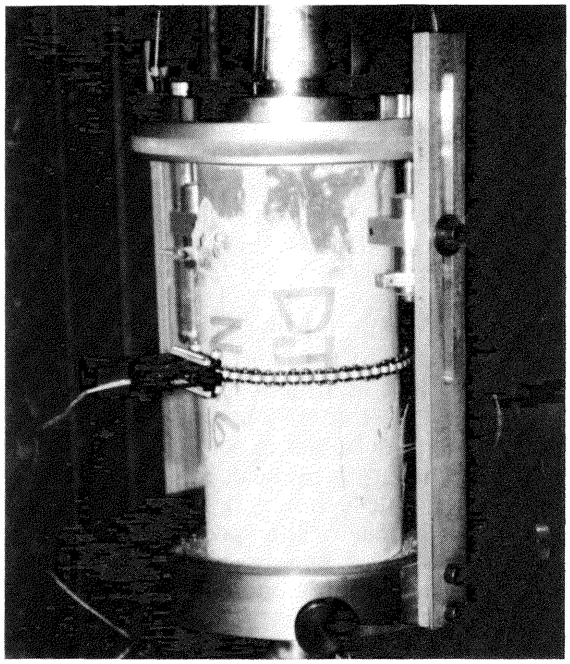

Fig. 2 - Specimen with circumferential gage

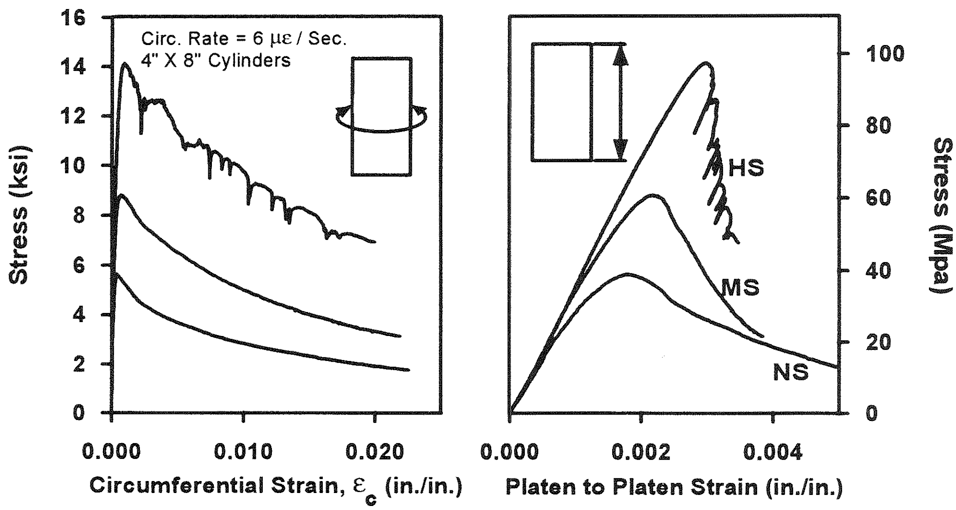

Fig. 3 - Typical stress vs. circumferential strain and stress vs. axial strain plots for HS, MS, and NS specimens

3.3 Combined signal control

An alternative method of feedback control which is a linear combination of force and displacement was originally presented by Okubo and Nishimatsu [7] and has been used by others [8, 9]. This method measures the total specimen deformation and subtracts part of the elastic deformation leaving the inelastic deformation as a stable feedback signal. The feedback signal is calculated as

$$\text{Feedback} = \delta - \alpha \frac{F}{K_0}$$

where δ is the axial specimen displacement, F is the measured force on the specimen, K_0 is the elastic stiffness, and α is a coefficient which must be a positive value less than 1.

Fig. 4 shows the combining of deformation and force where severe snapback occurred to give a feedback signal which always increases. In this test, the concrete specimen was nominally 100 mm in diameter and 550 mm in length and had a compressive strength of about 90 MPa. To understand this combination, one can think of subtracting a value proportional to the change in force from the displacement during prepeak loading and then adding it back as the force decreases along the descending branch, or alternatively, removing a fraction, α, of the elastic response of the specimen in order to obtain the stable inelastic response. This method can be used for any geometry or size of specimen, and location of the failure zone does not need to be known. Proper selection of α must be made and the stiffness should be measured for each specimen.

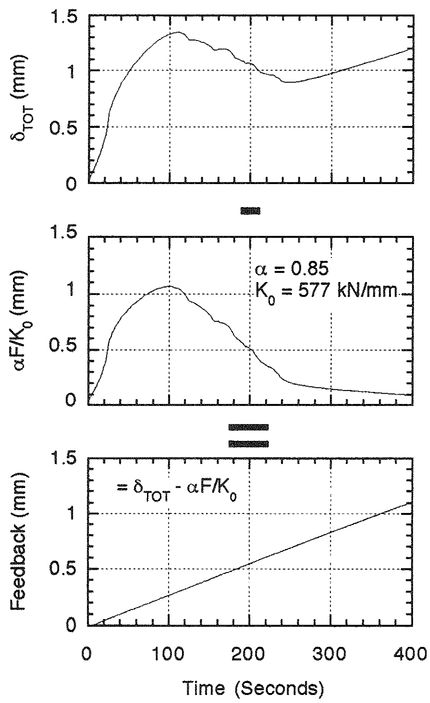

Fig. 4 - Composition and combination of feedback signal

4 END CONDITIONS

The end conditions of the specimen can significantly affect the behavior of the test and experimental results. Normally, when concrete is tested in compression, the bearing blocks consist of a fixed lower platen and a spherically seated upper platen to allow proper seating of the platen in the event the specimen surfaces are not exactly parallel. Rotation of the spherically seated platen during the test can affect results. The stress transfer from the platen to the specimen can be influenced by platen size and stiffness; inadequate stiffness of the spherically seated platen is an important consideration particularly when testing high strength concrete. Different confinement restraints due to lateral friction can be applied whether a brush type or solid platen is used, and whether solid steel bears directly on the concrete or if a lubricant is used. Effects of these conditions on the uniaxial compression testing of concrete are described below.

4.1 Lateral frictional confinement

Loading platens as well as concrete deform when compressive force is applied. The amount of lateral expansion of loading platens is smaller than that of the concrete generating resisting shear forces across the platen-specimen interface. This load transfer mechanism creates a triaxial stress state in the region near the contact zone. The well known conical failure of concrete cylinders tested with dry platen is the result of this loading condition. If the end restraint is reduced by the aid of anti-frictional materials, the behavior of concrete will certainly be changed.

Three different end conditions are discussed in this paper to study the effect of the confining forces from the loading platens: (1) bare steel loading platens without any anti-frictional material, referred to as dry platen (DP), (2) a Teflon (Polytetrafluorethylene, PTFE) sheet of 0.05 mm thickness used with grease, referred to as 'Teflon platen' (TP), and (3) a thin film of lubricant between the concrete and steel platen (a mixture of stearic acid and petroleum jelly introduced by Labuz [10]) referred to as 'lubricated platen' (LP). When the load is applied excess lubricant is squeezed out leaving a thin film between the specimen and loading platens.

A set of HSC specimens (L:D=2) tested under the three different end conditions gives different stress-strain curves as are shown in Fig. 5. The peak stresses and strains at peak for the specimens tested with DP do not show a noticeable difference when compared to those tested with LP or TP. However, the slope of the postpeak curve is considerably steeper with LP (or TP) compared to DP. This means that the end confinement has more of an effect on the softening behavior than on the stress-strain behavior up to the peak.

The softening behavior in Fig. 5 with TP shows a slight sharp drop after the peak load compared to the one with LP. This may be caused by the weak layer of Teflon sheet generating some splitting force on the loading area, or perhaps overcoming the static frictional resistance. This effect is hard to quantify.

With DP the frictional confinement from the loading platens is clearly visible after the peak load by the small lateral expansions at the end of the specimen and large expansion at the middle portion. When anti-frictional materials (LP, TP) were used, the lateral expansion at the middle does not dominate over the

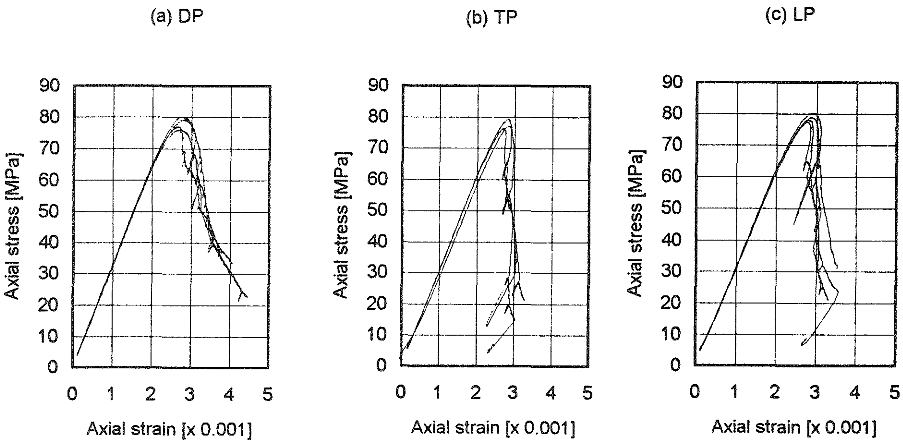

Fig. 5 - Behavior of HSC under different end conditions

expansions at the ends. Nevertheless, the lateral expansion profile was not parallel to the loading axis. Instead, the major expansion of concrete specimen was localized at one end portion of the specimen while the other part exhibits almost no expansion. Fig. 6 shows that anti-frictional materials (LP,TP) reduce the lateral expansions at the middle of the specimens.

4.2 Platen rotation

Even if the stresses were being applied in pure uniaxial compression, another issue is whether the spherically seated platen should be fixed from rotating after seating is completed. The uniform stress loading condition does not cause so much difference in the early stage of the test compared to the uniform deformation loading condition. The rotation of the head is unavoidable after the peak because of the non uniform failure of concrete. Up to the peak load, no or relatively small rotation occurs. After the peak load, the spherically seated platen rotates significantly (Fig. 7). During the postpeak, the specimens tested with DP show different rotation characteristics when compared to those tested with LP or TP. For the specimens tested with DP, the rotation increases to some extent after the peak load. When the load drops to about three quarters of the peak load, the achieved degree of rotation remains constant, or even begins to decrease (Fig. 7a). The internal stresses are redistributed in the specimen at that point. But for the specimens tested with anti-frictional materials (TP or LP), the rotation often increases further on. Therefore, the anti-frictional materials accelerate the localization of failure and prevent the redistribution of internal stresses after the peak.

4.3 Platen stiffness

The loading platens should transfer stress evenly to the specimens. Typically a fixed bottom platen and a spherically seated top platen are used. The spherically seated platen is necessary to obtain proper seating if the specimen ends are not exactly parallel. To examine the stresses at the platen-specimen

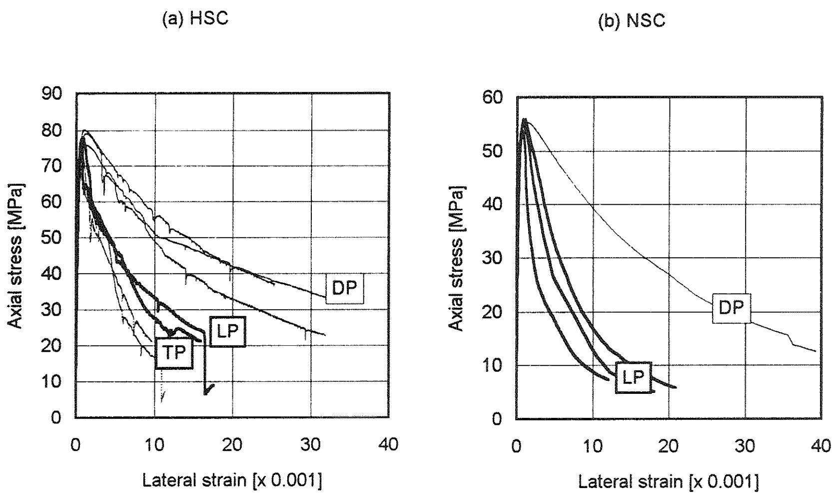

Fig. 6. - Lateral expansion under different end conditions

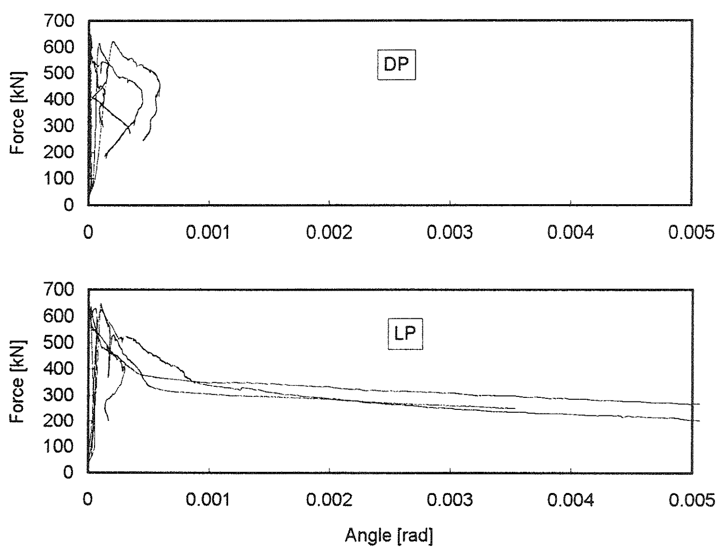

Fig. 7 - Rotation of loading platen measured for HSC

interface, a special device which measures stress distribution was used. The normal stress distribution for a rigid steel platen larger in diameter than the specimen can be seen in Fig. 8, where the stress is greater around the outside of the cylinder. This is normal and not completely unexpected; since the steel platen is larger in diameter than the cylinder, it is effectively stiffer. More interesting is the stress profile of Fig. 9; the stress is higher in the center of the specimen. This is taken between a high strength concrete cylinder and a spherically seated platen which has inadequate stiffness; the stress profile should be the same as in Fig. 8. This indicates that some, not all, spherically seated platens may have inadequate stiffness and may lead to a decrease in compressive strength, shown in Fig. 10 for different compressive strengths of concrete. The decrease in compressive strength is due to the stress concentration in the middle of the specimen and results in splitting failure of specimens instead of cone type when non-lubricated (dry) interfaces are used.

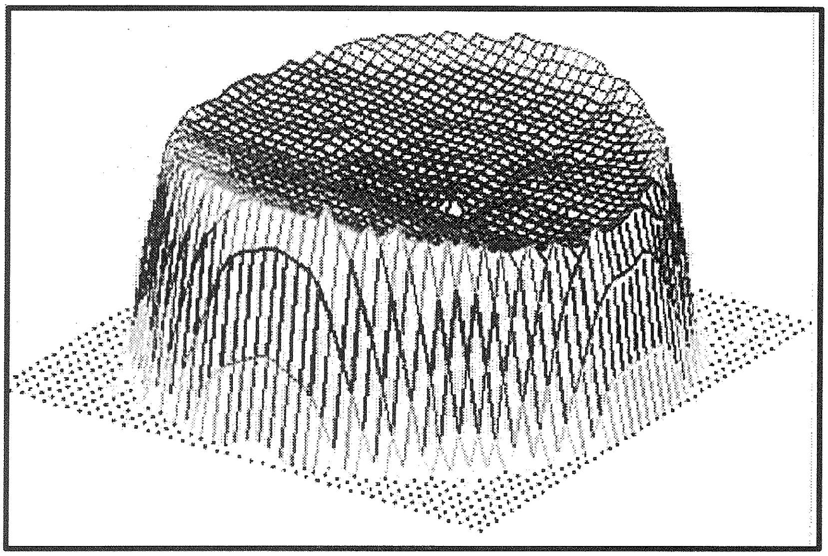

Fig. 8 - Stress distribution applied from solid platen to high strength concrete

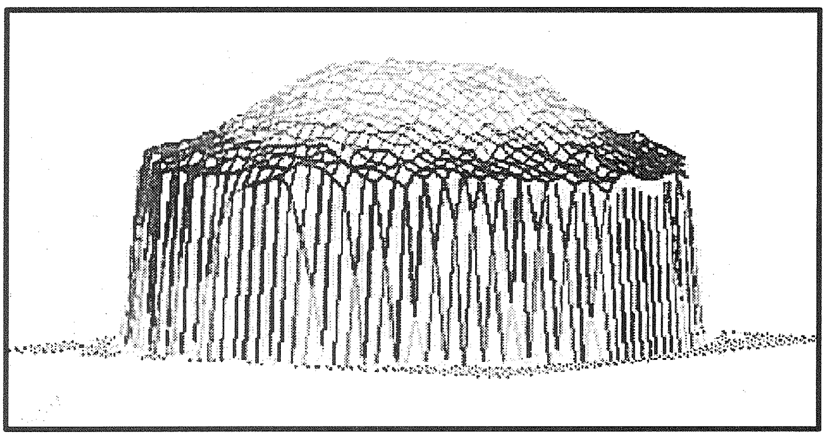

Fig. 9 - Stress distribution applied from inadequately stiff seated platen to high strength concrete

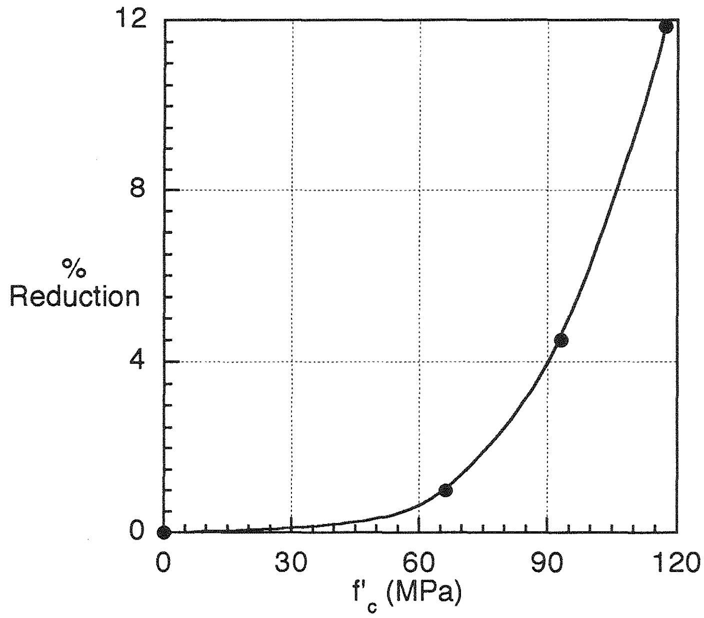

Fig. 10 - Strength loss due to inadequately stiff platen

5 MEASUREMENT GAGE LENGTH

The platen to platen axial measurement includes extra deformation at the interface between concrete specimen and the loading platens. As mentioned earlier, the deformations from the mid-section of the specimen and between the loading platens show different characteristics (Fig. 1). In the prepeak, the strain from the mid-section is smaller than the strain from the platen to platen measurement. This means that the imperfect contact area between the specimen and the loading platens leads to extra deformations. In the postpeak, the extensometer gage reading is disturbed by cracks formed on the specimen surface, and the output becomes unreliable. So the extensometer gage reading is not useful in studying the postpeak branch of the stress-strain curves of concrete.

6 SPECIMEN LENGTH

If the behaviors of concrete specimens show only the material characteristics of concrete, it would not be affected by the lengths of specimens. But, under the shear resistance between the platen and specimen, concrete specimens have complicated triaxial stress state inside and the behavior could not be independent on the distance to the end of the specimen. It was observed that the effect of length is minimized under reduced end confinement using anti-frictional materials even though it is not completely eliminated.

Peak stresses and peak strains of HSC and NSC are strongly affected by the specimen length for specimens with dry platens as shown in Fig. 11a. The shorter specimens show higher peak stresses and peak strains. The difference in peak stress is about 20% between L:D=1 and L:D=2, while only a small difference exists between L:D=2 and L:D=3. When the specimen has a L:D ratio greater than 3, the effects of the confinement become negligible. The effect is due to the triaxial stress state at the end zone which confines the specimen and helps carry more load. It is less noticeable when a lubricated platen is used as shown (Fig. 11b).

The lateral expansion is closely related to the length of a specimen. Fig. 12 shows the relation between the axial stresses and lateral strains at the middle of specimens. The shorter specimens show higher lateral strains than the longer specimens at the same stress level. More macrocracks found in L:D=1 specimens give those higher lateral strains than L:D=2 or L:D=3 specimens. The softening of longer specimens is more dramatic than that of shorter specimens. Due to the localized failure, cracked areas carry more deformations while uncracked portions recover their deformations. Longer specimens have more undamaged portion for the possible deformation recovery during the localized failure. The combination of elastic recovery and localized damage results in steeper drop after the peak in their stress-strain curves as shown.

In a separate study, specimens with L:D ranging from 2.0 to 5.5 were tested. The significant effect of the localization can clearly be seen in Fig. 13. The prepeak stress-strain curves are unaffected by specimen length since their deformations are proportional to their lengths. However, the postpeak portion of the curves become steeper as the length becomes greater. The increase in brittleness with length is directly due to localization; the length of the failure zone does not change and the amount of elastic response increases. In the photograph in Fig. 13, the approximate size and shape of the failure zone remains the same regardless of the specimen length.

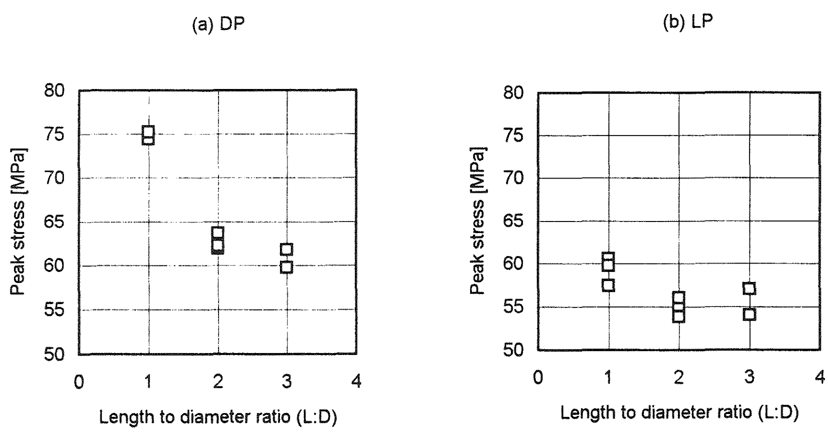

Fig. 11 - Peak stress under different end conditions

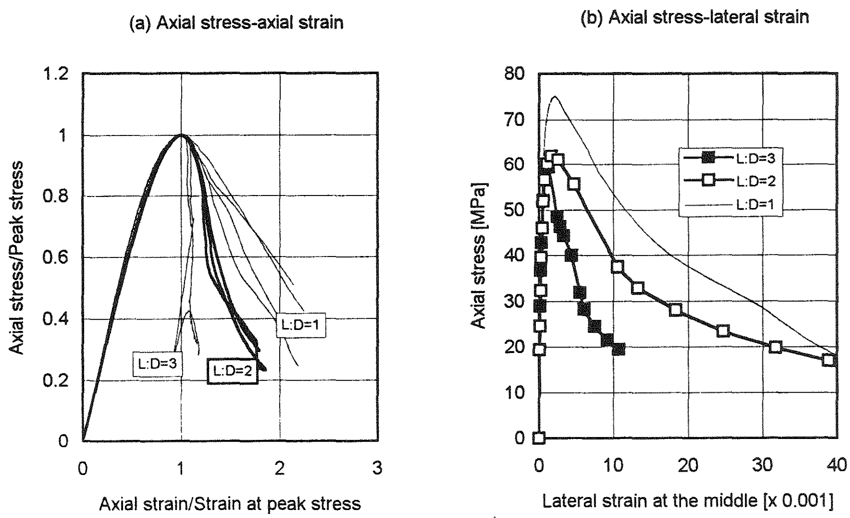

Fig. 12 - Behavior of NSC with DP

7 CONCLUSIONS

Obtaining the strain softening response for concrete is not difficult; however, obtaining meaningful results and interpreting them correctly can be tricky. Many factors besides the material influence the strain softening behavior of concrete. These influences include test control method, boundary conditions such as constraint and rotation, size, and geometry. Proper interpretation of the results is also required in order to give useful meaning to the results and be able to apply them. The information used from testing concrete in compression can lead to better understanding of the material and its behavior. In applying this information, a more rational approach to design of reinforced and prestressed concrete structures may be obtained.

The results discussed in this paper are only from one laboratory involved in the RILEM committee 148 SSC round robin testing program. Once the testing at each individual laboratory is complete, the experiences and results will be gathered and compiled. From the comparisons, recommendations for obtaining meaningful strain softening results will be produced.

8 ACKNOWLEDGEMENTS

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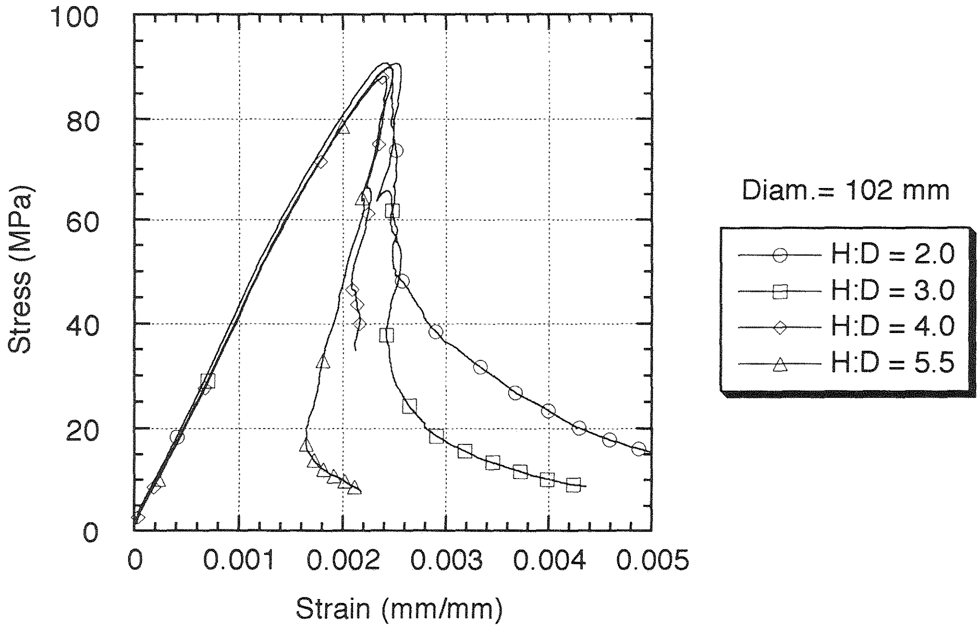

Fig. 13 - Effect of height to length ratio on the strain softening behavior for L:D from 2.0 to 5.5

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