SIZE EFFECT IN SOFTENING OF CONCRETE LOADED IN COMPRESSION

R.A. Vonk [*], H.S. Rutten [*], J.G.M. Van Mier [**], H.J. Fijneman [*]

A series of tests was carried out to investigate the size effect in softening of concrete loaded in uniaxial compression. Specimens of different size and shape were tested. Internal macrocrack patterns were studied to obtain a better understanding of the observed mechanical behavior. Peak stress and post–peak behavior were found to be dependent on specimen size probably due to localization of cracking and deformations. The observed mechanical behavior and cracking show that localization in uniaxial compression is not as good as in uniaxial tension: cracking is more widely distributed, thus resulting in a more complex softening behavior than in tension. Test results indicate propagation of macrocracks and the start of localization before peak stress is reached.

INTRODUCTION

It is well known that softening of concrete in tensile tests goes hand in hand with localization of deformations in narrow zones. The specimen then no longer acts as a continuum and the mechanical response becomes dependent on the size of the specimen. Bazant (1) showed that localization in the smallest possible volume is the most preferred state of deformation for a softening material. This is a physical law and there are no obvious reasons why it should only apply to tension tests and not to compression tests.

Van Mier (2) was the first to show that there is probably a size effect in compressive softening too. He carried out tests on specimens differing in height and found different stress–strain curves. When comparing the post–peak stress–deformation curves for the specimens of different height, he found a striking resemblance. For localized softening behavior in tension, these curves are also found to be the same. This indicated the applicability of the same localization theory to uniaxial compression. For compressive softening this was not always recognized, because of the distributed nature of cracking found in uniaxial compression tests, where the boundary conditions admit unrestrained lateral deformations. However, standard compression tests on cylinders and some multiaxial compression tests show highly localized cracking and consequently localization of deformations. This shows that localization in compressive loading depends on the state of loading and boundary conditions.

[*] Eindhoven University of Technology, the Netherlands
[**] Delft University of Technology, the Netherlands

Recent tests showed that softening of concrete loaded in uniaxial compression is very sensitive to the boundary conditions in the tests (Vonk et al.(3)). One of the conclusions from the test results was that the steel brushes used by Van Mier (2) in his tests can slow down softening significantly. The reason for this is the continuous increase of the confining shear forces induced in the concrete specimen by the bending of the brush rods following the lateral expansion of the softening concrete.

EXPERIMENTAL GOALS AND SET–UP

To study the subject of size effect in softening of concrete loaded in uniaxial compression more thoroughly and have a comparison for the test results of Van Mier, a series of tests with teflon platens was planned in which the height and width of the specimens were varied. Three different heights (50,100,200 mm) and two different widths (50,100 mm) were used, resulting in 6 types of specimens of square cross–section. Both height and width were varied to be able to study the influence of size combined with the influence of the boundary conditions. Four identical tests were carried out per type of specimen.

EXPERIMENTAL TECHNIQUE

Loading technique

All specimens were loaded in deformation control with teflon platens at a constant strain rate of $1x10^{-5}$/sec irrespective of their height. Teflon platens are platens of tempered and polished steel, slightly greased and covered with a thin sheet of teflon (0.05 mm thick). Friction tests showed that these platens have an initial coefficient of friction of approximately 0.035, which reduces rapidly to 0.01 after some sliding. Previous uniaxial compression tests on 100–mm concrete cubes did not show a significant influence of the teflon platens on the measured strength (Vonk et al. (3)). The same tests showed that teflon platens slow down softening less than steel brushes do.

Preparation of specimens

A normal weight concrete with a 150–mm cube strength of 57 N/mm^2 was used. The mix proportions per m^3 were: 340 kg cement, 170 kg water and 1828 kg river gravel and sand. The maximum aggregate size was 8 mm. The specimens were sawn out of the core of large blocks in order to obtain specimens as homogeneous as possible. Attention was paid to the direction of casting, which was taken parallel to the direction of loading. After demoulding the blocks were kept under water for 28 days. The specimens were then sawn out of the blocks and grounded. Until 2 hours before testing, the specimens were stored at a relative humidity of 100 %.

TEST RESULTS

Stress–strain curves

The average stress–strain curves for all types of specimens are given in figure 1. Significant differences are found around peak stress and in the softening branch. Analysis of the test data shows that peak stress increases with a decrease in specimen height and width. An overview of the separate peak–stress data is given in figure 2. Calculating the fracture energy by integration of the stress–strain curve, we find that the ductility increases with a decrease of the height. No significant differences are found for specimens of the same height but different in width.

Localization of deformations and cracking

Crack patterns were recorded at the end of the tests by means of ultraviolet photography of slices of concrete impregnated with a fluorescent epoxy resin (figure 3). Localization of macrocracks and consequently of deformations is particularly clear in the slender specimens. Basically, all the specimens show the same macrocrack pattern: irregularly shaped cracks parallel to the direction of loading, which are incidentally connected dividing the specimen into pieces which can shear off. The crack spacing is approximately equal in size to the largest aggregate fraction (4–8 mm). The number of active inclined macrocracks one meets on an axial line through the specimen is important for the localization of axial deformations. This number is limited, which indicates localization of deformations. It is not exactly one as in uniaxial tension. This can be explained by the composite structure of the material, which forces the cracks to follow a tortuous path, making shearing and opening a process which involves complicated motion and changes in load. The cracks can lock up, which causes new crack formation broadening the shear band and confusing the localization picture. However, this can still mean that only a single macrocrack at a time is active over the height. The crack patterns show that the mechanical resistance of the specimen in this final state of softening is mainly due to aggregate interlock, friction and damage in the already present shear band. In the vicinity of peak stress a more pronounced influence of crack initiation and propagation will be found.

DISCUSSION OF TEST RESULTS

Size effect in peak stress

Differential shrinkage is not likely to be the cause of the size effects found, because of the careful preparation of the specimens. It is well known that the confining stresses induced in the specimen by the loading platens have a significant influence on peak stress and post–peak behavior (Schickert (4), Kotsovos (5), Vonk et al. (3)). Therefore the influence of the boundaries must be considered when an increase of peak stress is observed for a decreasing specimen height. It seems that some influence of the boundaries can be found in the test results. However, the complete size effect can not be due to this effect only. No significant differences in peak stress were found in previous tests with teflon platens and brushes (3). It is believed that brushes do not influence peak stress significantly (2,4,5). Tests carried out by Schickert (1) indicate that the influence of the boundaries on peak stress for specimens with a height–width ratio of 2 or more is probably negligible. A significant part of the influence of the boundaries can probably be eliminated by comparing test results for specimens of the same shape, because for those specimens the relative influence of the boundaries is the same. Figure 2 shows that for specimens of the same shape still a significant size effect can be found. Even, when comparing specimens of the same height but with a different width, a decrease of peak stress is found for an increase in width. Considering the influence of the boundaries, an increase of peak stress would be expected. According to the weakest link theory or the size effect law of fracture mechanics (1) peak stress should decrease when specimen size increases. A good correlation can be found between peak stress and specimen volume supporting the last two theories. Peak stress decreases when the volume of the specimen increases.

Size effect in softening

In figure 4 the test results for the specimens with a width of 100 mm are compared with the test results of Van Mier (2) for the same specimen types and approximately the same type of concrete. For the ease of comparison the stresses have been made dimensionless. The differences in pre–peak behavior are caused by the different loading directions relative to the direction of casting. The figure shows that curves are approximately the same for the specimens with a height of 200 mm and that the differences grow when the height decreases. This can be explained by the difference in confining stresses induced in the concrete by the loading platens (3). A consequence is that the tests presented here do not show the same post–peak stress–deformation behavior as found in the tests of Van Mier. Still a size effect is present when we compare tests on specimens with the same shape in figure 1.

Modeling of the size effect

The test results show that softening of concrete loaded in uniaxial compression can not be modeled by linking localized softening and continuum behavior in series as is done for tension. A more complex mixture of volumetric and surface dominated behavior is indicated, which can be modeled by partially linking localized softening and continuum behavior in parallel. A criterion for propagation of the localized behavior will then be needed. Starting with localization of softening before peak stress can explain the influence of the size of the specimen on peak stress. Such a model can be justified by the observation in compression tests that the formation of macrocracks, the cause of localized behavior, starts before peak stress is reached.

REFERENCES

(1) Bazant, Z.P., Journ. of the Eng. Mech. Div., ASCE, Vol. 102 (EM2), 1976, pp. 331–344

(2) Van Mier, J.G.M., "Strain–softening of concrete under multiaxial loading conditions", PhD thesis, Eindhoven University of Technology, 1984

(3) Vonk, R.A., Rutten, H.S., Van Mier, J.G.M., Fijneman, H.J., "Influence of boundary conditions on softening of concrete loaded in compression", in "Fracture of concrete and rock", ed. by S.P. Shah, S.E. Swartz and B.Barr, Elsevier Applied Science, London, 1989

(4) Schickert, G., " Schwellenwerte beim Betondruckversuch", Deutscher Ausschuss für Stahlbeton, Vol. 312, 1980

(5) Kotsovos, M.D., Materials and Structures, Vol. 16 (91), 1983, pp. 3–12

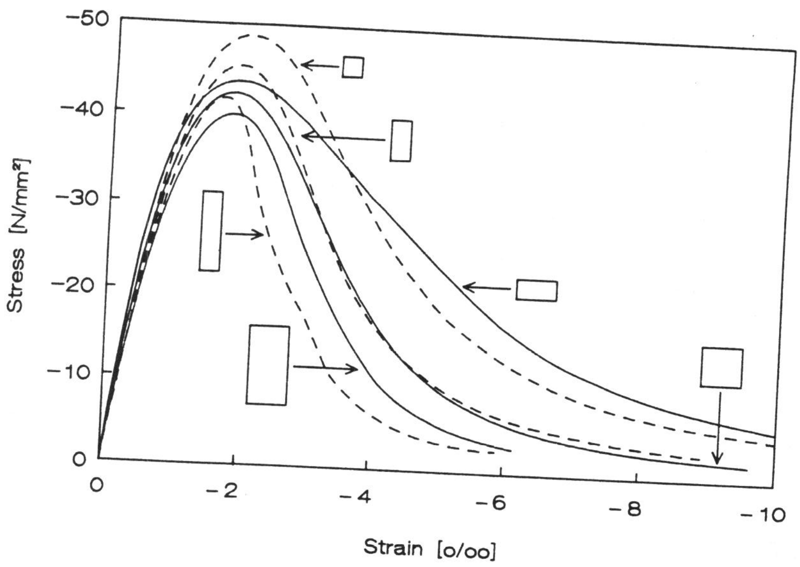


Figure 1 Average stress–strain diagrams for the different specimen types

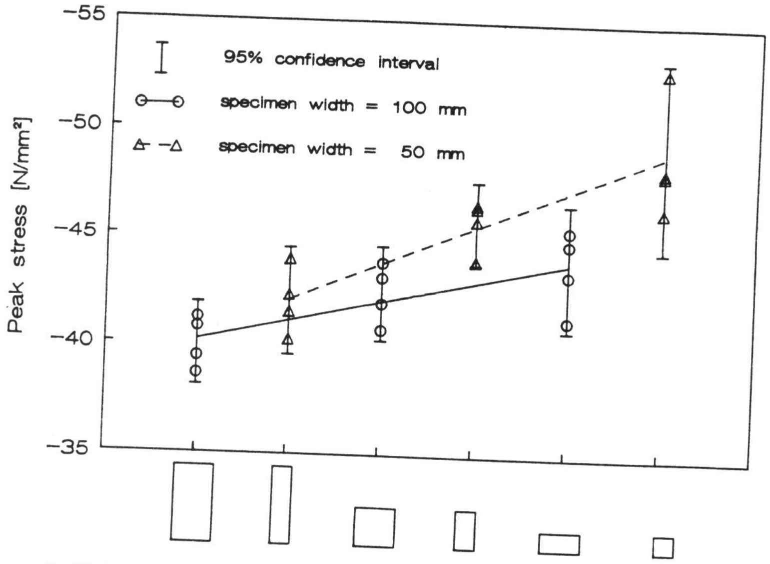


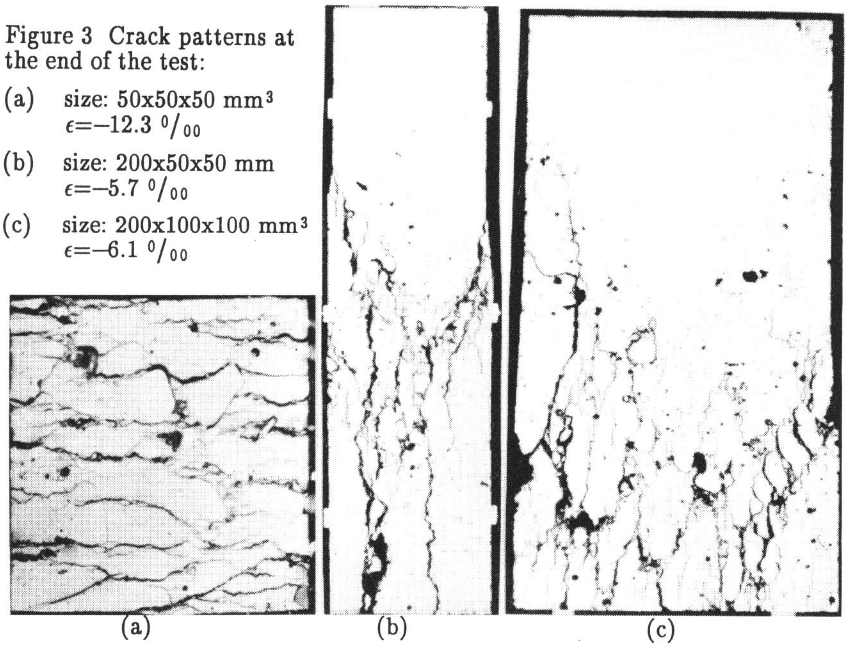
Figure 2 Values for peak stress for all tests

Figure 3 Crack patterns at the end of the test:

(a) size: 50x50x50 mm^3 $\epsilon=-12.3$ $^0/_{00}$

(b) size: 200x50x50 mm $\epsilon=-5.7$ $^0/_{00}$

(c) size: 200x100x100 mm^3 $\epsilon=-6.1$ $^0/_{00}$



(a) (b) (c)

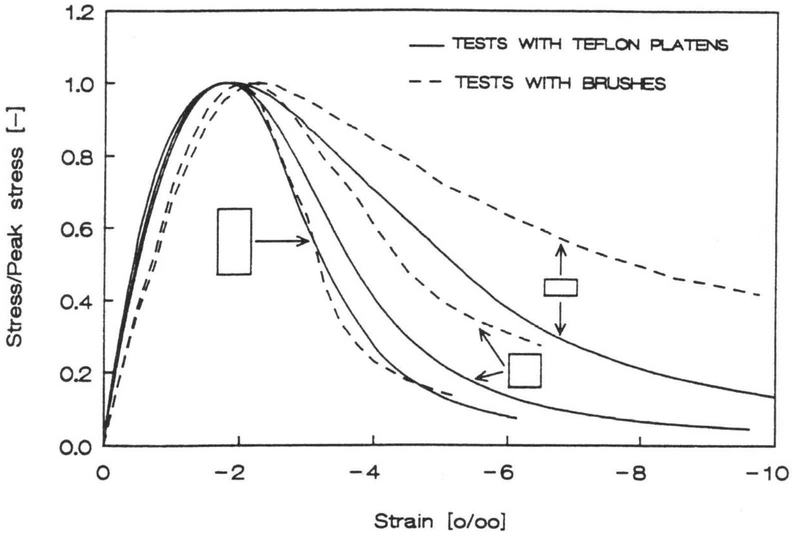


Figure 4 Comparison with tests carried out by Van Mier