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# SOFTENING BEHAVIOUR OF CONCRETE UNDER UNIAXIAL COMPRESSION

M.R.A. van Vliet and J.G.M. van Mier
Stevin Laboratory, Delft University of Technology
Delft, The Netherlands

## Abstract

The softening behaviour of concrete as found in laboratory tests depends strongly on structural aspects such as specimen dimensions, boundary conditions, feed-back signal and testing machine characteristics as well as on the concrete composition. In order to investigate these effects, the RILEM Committee 148ssc proposed a round robin test. The main goal of the round robin is to obtain a definition of a test-method for compressive strain softening behaviour. To contribute to this round robin, uniaxial compression tests have been performed in the Stevin Laboratory on concrete prisms with a constant cross section of 100x100 mm$^2$. Specimens with heights of 25, 50, 100 and 200 mm made of concrete qualities with compressive cube strengths of 50 MPa and 80 MPa, were loaded under two different restraining conditions. The tests were deformation controlled using the average vertical displacement of four LVDTs at the corners of the specimen as feed-back signal. Additionally the lateral deformations were measured by three horizontal LVDTs placed on each specimen side. One of the most important results of the tests is the reduction of the frictional stresses between concrete specimen and steel loading platen, by using an intermediate layer of teflon sheets and grease. When comparing these test results to those in which specimen and loading platen were in direct contact, the influence of the specimen height on the compressive strength is found to disappear.

## 1 Introduction

In order to design concrete structures Finite Element Methods are a frequently used tool. A FEM program however, needs material parameters as input to describe material behaviour. The stress-strain relationship of concrete is one of those input parameters used in calculations of structures with different dimensions, varying from specimens of laboratory scale to full size structures. In case the compressive softening curve of concrete could be considered a material property this approach would be correct, but that would mean independence of, for example, specimen size and boundary conditions. Thus the way in which the softening curve was obtained should exclude any influences on the result.

Part of the above mentioned structural influences has already been investigated, be it that a full overview in which the effect of each parameter is summarized is not available. Van Mier (1984) extensively investigated the softening behaviour of concrete under uniaxial and multiaxial loading conditions. His tests were performed on specimens with a cross section of 100x100 $mm^2$ and heights of 50, 100 and 200 mm. For all specimens the same concrete quality was used. As the significant influence of boundary restraint was known already, in all tests steel brushes were used to reduce the frictional stresses between specimen and loading platen. A strong dependency of the post-peak strains on the specimen size was found, which attributed to localization of deformations. The way in which localization takes place strongly depends on the specimen height, as small specimens simply restrict the size of the localizations that occur. The effect of the slenderness on the stress-strain curve is shown schematically in Fig. 1a, assuming that the boundary restraint is eliminated.

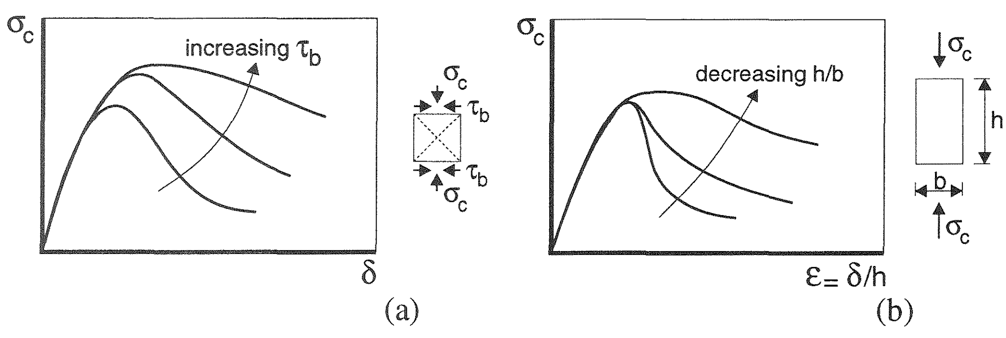



Fig. 1. Effect of specimen slenderness (a) and boundary restraint (b) on the compressive stress-deformation behaviour of concrete (Van Vliet and Van Mier, 1994)

After localization it is not possible anymore to regard the specimen as a continuum, resulting in the use of displacements in stead of strains. When doing so for the post-peak softening curves, Van Mier found the influence of the specimen height to disappear, resulting in curves that were almost on top of each other. Later Vonk (1992) continued the investigation of the concrete behaviour under uniaxial compression, mainly focussing on the influence of different friction reducing interlayers. Moreover, numerous numerical simulations of concrete softening under compression were carried out. Next to a second kind of steel brushes, consisting of longer brush rods, he also used a sheet of teflon as intermediate layer. The tests in which the boundary restraint was actively reduced were compared with tests in which so called "dry platens" were used. These "dry platens" consisted of polished and hardened steel platens that were in direct contact with the ground concrete surface. These test results confirmed the earlier findings of Kotsovos (1983). The influence of increasing frictional stresses between specimen and loading platen is shown schematically in Fig. 1b.

In order to get a complete overview of the influence of the parameters mentioned above on the softening behaviour of concrete, as well as the influence of measuring and control devices, testing machine parameters and concrete quality, RILEM Comittee 148ssc was founded. As part of the round robin proposed by Comittee 148ssc, the compression tests described in this paper have been performed. After describing the test set-up, the results are presented followed by a discussion that focusses on the influence of specimen size, boundary conditions and concrete quality.

## 2 Outline of experiments

### 2.1 Test set-up

For the tests described in this paper, prisms with a constant cross section of 100x100 $mm^2$ and heights of 25, 50 , 100 and 200 mm were used. The tests were carried out on a uniaxial compression machine with a capacity of 3000 kN. The machine is controlled by a closed loop servo hydraulic system. Of the two loading platens the lower one is fixed as the upper loading platen is connected to the machine by a hinge. In this way the upper platen can adjust to geometrical imperfections of the test specimen. After the load has increased to some extent, the upper loading platen is automatically fixed and keeps this same position during the rest of the test.

As one of the requirements of the round robin was a loading platen size matching the size of the specimen, an extra set of loading platens has been made. These hardened and polished steel platens have the same cross section as the concrete specimens and a height of 75 mm each.

All compression tests have been performed under deformation control. On each specimen except those with a height of 25 mm, four vertical and twelve horizontal LVDTs were placed (Fig. 2). The 4 vertical LVDTs with a maximum working range of $\pm$ 5 mm were adjusted to the loading platens at the corners of the specimen, which gives a gauge length of $L_{specimen}$ +

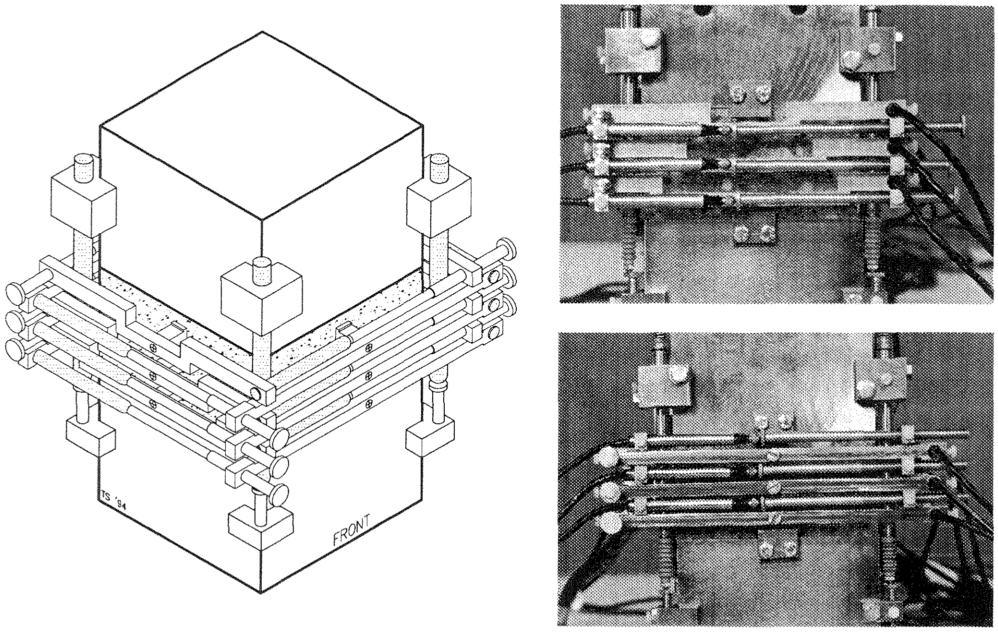



Fig. 2. Experimental set-up for compression tests, $L_{specimen}$=50 mm

62.5 mm. In this way the axial deformations were measured of which the average value in return was used as a feed-back signal to control the tests. The applied average vertical deformation rate was 1 $\mu$m/s.

In order to measure the lateral deformations, three LVDTs were placed on each specimen side. One in the middle of the specimen and the other two 10 mm below the top end and 10 mm above the specimen bottom end respectively. On the specimens with a height of 25 mm, only one LVDT was placed on each side in the middle of the specimen. The horizontal LVDTs had a maximum working range of ± 2 mm.

## 2.2 Specimens

To prepare the test specimens, prisms with dimensions of 150x150x600 $mm^3$ were cast in six batches, in six subsequent weeks. Three batches were of normal strength concrete (NSC), the other three were of high strength concrete (HSC). In Table 1 the mixtures are given that were used to obtain the two different concrete qualities.

In each batch three prisms and nine control cubes with dimensions 150x150x150 $mm^3$ were cast. At an age of 2 days prisms and cubes were demoulded and put in a fresh water basin. 14 days after casting the prisms were sawn into four specimens with heights of 25, 50, 100 and 200 mm which were put back in the water basin. Within the next week all specimen sides were ground flat and parallel, in order to get a good contact between specimen and loading platen, and to facilitate the adjustment of the transducers on to the specimens. At an age of 28 days the specimens were taken out of the water, and put in a plastic bag that was sealed afterwards. At the same time, six control cubes were taken out of the water basin in order to determine the cube compressive strength and the tensile splitting strength.

Table 1. Concrete mix properties

| | Unit content kg/m$^3$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 8-4* | 4-2* | 2-1* | 1-0.5* | 0.5-0.25* | 0.25-0.125* | PCB | MS | SP | w/c |
| NSC | 540 | 363 | 272 | 272 | 234 | 127 | 375 | - | - | 0.5 |
| HSC | 540 | 363 | 272 | 272 | 234 | 127 | 500 | 35 | 10 | 0.35 |

* grain size in mm, PCB: Portland Cement B, MS: Microsilica, SP: Superplasticizer

Test procedure was as follows. A specimen was taken from the plastic bag and surface dried, such that the measuring device could be attached. After a few more hours the specimen was tested.

### 2.3 Boundary conditions

Half of the tests has been performed putting specimen and loading platen in direct contact with each other. When using loading platens of hardened, polished steel and ground concrete, considerable frictional stresses between specimen and loading platen can develop. Therefore, in addition to these loading platens with High Friction (HF), loading platens with a friction reducing material between concrete and steel were used. This intermediate layer was built up out of two teflon sheets with a thickness of 0.1 mm each and a grease layer of 0.05 mm in between. The latter type of loading platens will be referred to as Low Friction (LF) platens.

## 3 Experimental results

In section 2 the experimental set-up and the specimen preparation was discussed; in this section the main experimental results will be shown. After a short explanation of the corrections that were made to the original test data, an overview of the different experiments is given by means of stress-strain curves. Comparing these stress-strain curves the effects of specimen height, boundary friction and concrete quality on the experimental results will be discussed. More detailed discussions will be given using the peak stresses, peak strains and normalized stress-strain curves.

### 3.1 Correction of data

The data measured in the compression tests have been corrected in two different ways, both concerning the measurements of the four axial LVDTs. The first correction was made because of the strong increase of the axial deformations in the beginning of the test. This is due to the adjustment of the loading platens to the specimen surface and the compressibility of the teflon interlayer in case of the LF tests. As this behaviour makes the load-displacement curves of the tests shift horizontally, an objective comparison of the deformation values has become impossible. For this reason the first part of the load-deformation curves is replaced by a straight line, which was done by searching the maximum pre-peak slope of the force-displacement curve using the least squares method. From this point a straight line is drawn to the intersection point with the x-axis. Finally the whole curve is shifted horizontally until the intersection point is situated in the origin.

A second correction was necessary because of the way in which the measuring equipment was adjusted. As mentioned before the gauge length is $L_{specimen}$ + 62.5 mm. This implies that the measured axial deformations also contain the deformation of 62.5 mm of the steel loading platens. Therefore all axial deformations have been corrected by the elastic deformation of the loading platens. It is mentioned that the curves shown in this paper have been smoothened, in order to eliminate noises from the experimental data.

### 3.2 Stress-strain curves

In Fig. 3, an overview of the stress-axial strain curves is given for the experiments in which the specimen height, the boundary conditions and the concrete quality are varied. As each kind of experiment has been performed three times, the one that can be regarded as representative for that kind of experiment is plotted. For a full overview of the test results, see Van Vliet and Van Mier (1995).

First the influences of specimen height and boundary restraint on the test results will be discussed for NSC. Comparing the curves of the NSC specimens with different heights and loaded under HF boundary conditions, it can be seen that the specimen height strongly influences the peak load, see Fig. 3a. When comparing the 25 mm to the 200 mm specimens, the peak loads can increase up to 250%. This increase of peak load, is due to the effect of the boundary restraint which is present in almost the whole specimens of 25 mm and 50 mm height. The boundary restraint is caused by the frictional stresses between specimen and loading platens (Fig. 4). As a result, the internal tensile stresses between aggregates and voids causing failure of the concrete (Van Mier, 1984), are only reached at substantially higher loads. For the 100 mm and the 200 mm specimens, larger parts of the specimen are not affected by the frictional stresses. Failure will consequently occur in these parts and thus at lower loads. In contrast to the considerable difference in peak stresses for the tests with HF boundaries, the peak stresses were almost equal for the LF boundary tests which shows the effectivity of the teflon interlayer, at least as peak stress is concerned.

When ductility is defined as the slope of the post-peak stress vs. axial strain curve, the ductility of the LF NSC tests (Fig. 3b) is lower compared

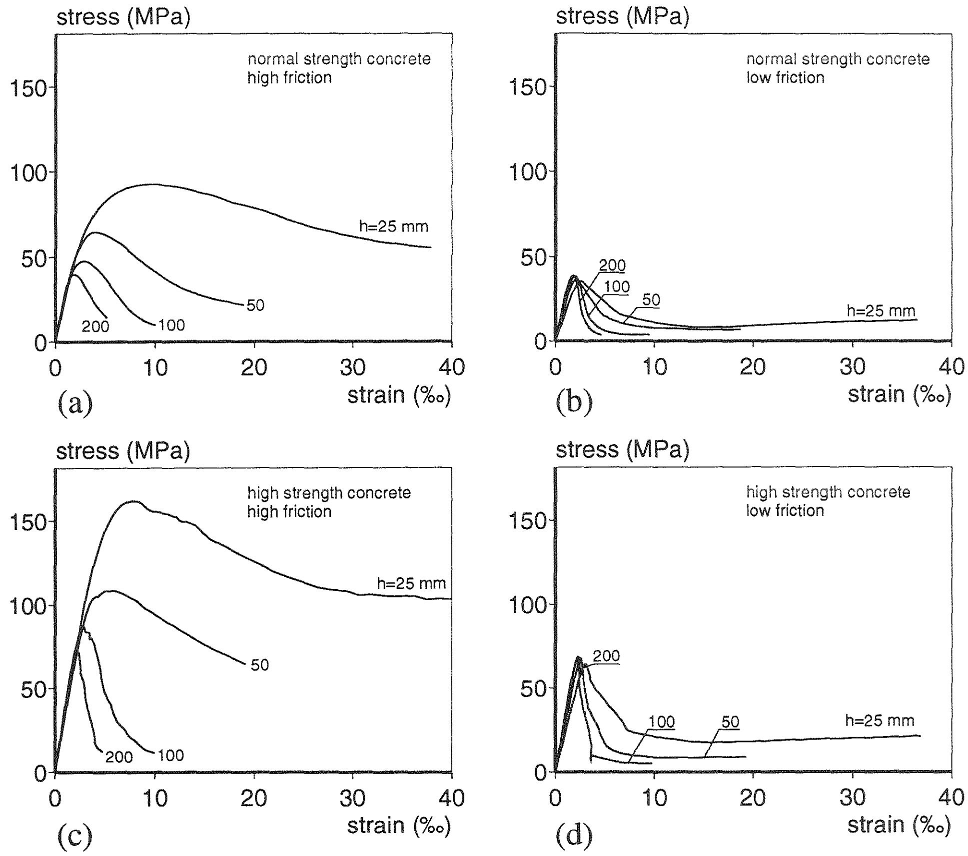



Fig. 3. Stress vs. axial strain for the NSC (a,b) and HSC (c,d) tested under HF (a,c) and LF boundary conditions (b,d)

to the ductility of the HF NSC tests (Fig. 3a). This lower ductility that is found for the LF NSC tests, can be explained by the differences in crack growth for the LF and HF boundary conditions. In case of the LF tests the cracks are free to choose the weakest path throughout the whole specimen (see Fig. 5b), which will yield a minimal release of elastic energy. When parts of the specimen are confined by frictional boundary stresses as in the HF tests, less cracks will develop here (Fig. 5a). The dimension of the part of the specimen that is not influenced by boundary restraint, depends on the specimen height as shown in (Fig. 4). The cracks are forced to grow in parts of the specimen that are not confined. Therefore, for HF boundary conditions this will result in a higher release of elastic energy, compared to a situation without restrictions to crack growth. This restricted crack growth can also be seen when inspecting the crack surface of a HF specimen: it is smoother and shows more splitted aggregate particles than the crack surface of a LF specimen.

The differences in crack growth between the HF and LF boundary conditions are also found in the load-displacement response. As an example,

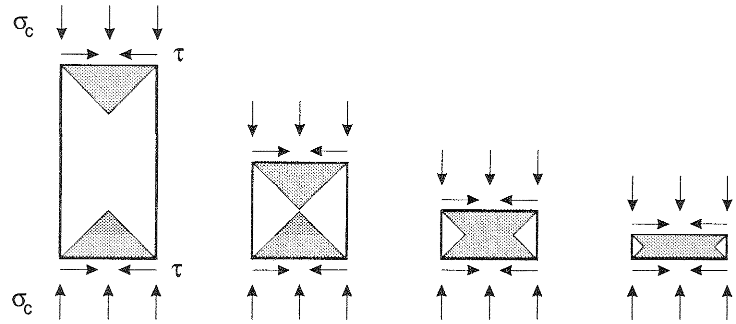



Fig. 4. Confined zones for different specimen heights due to boundary friction

the axial and lateral deformations of the 100 mm NSC specimens of Fig. 5 are plotted in Fig. 6. The axial deformations are measured by the separate LVDTs, whereas the lateral deformations are the average of the deformations measured by the four LVDTs in a horizontal plane.

When LF boundaries are used, localization of deformations and thus non-uniform crack growth takes place after peak load. Owing to this non-uniform crack growth and despite the (supposed) non-rotatability of the loading platens, there can be substantial differences in stiffness over the specimen width. This causes differences in axial deformations (Fig. 6a). For HF tests, fracturing seems to occur more distributed through the specimen's volume. The spalling of the specimen's outer layers is more restrained in the HF case, thereby forcing constant stress-redistributions (Fig. 6b).

The main influences of the specimen height and the boundary restraint have been discussed using the results of the NSC specimens. When comparing the upper and the lower graphs of Fig. 3 it can be concluded that the HSC shows the same softening behaviour as the NSC, both under HF and under LF boundary conditions. The main difference between the two concrete qualities is the ductility, that is consistently higher in case of the NSC specimens. This higher ductility of the NSC can be explained by a

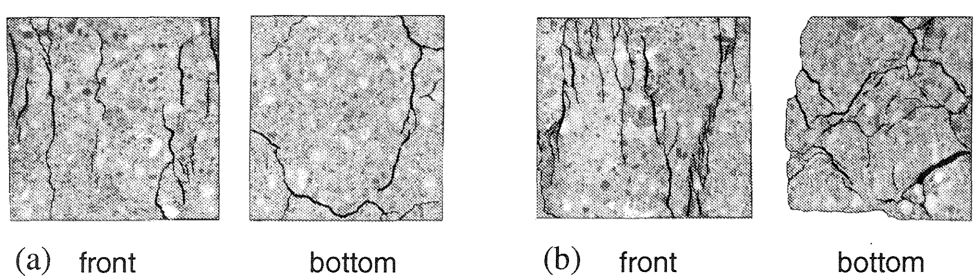



Fig. 5. Crack patterns for 100 mm NSC specimen loaded under HF (a) and LF boundary conditions (b)

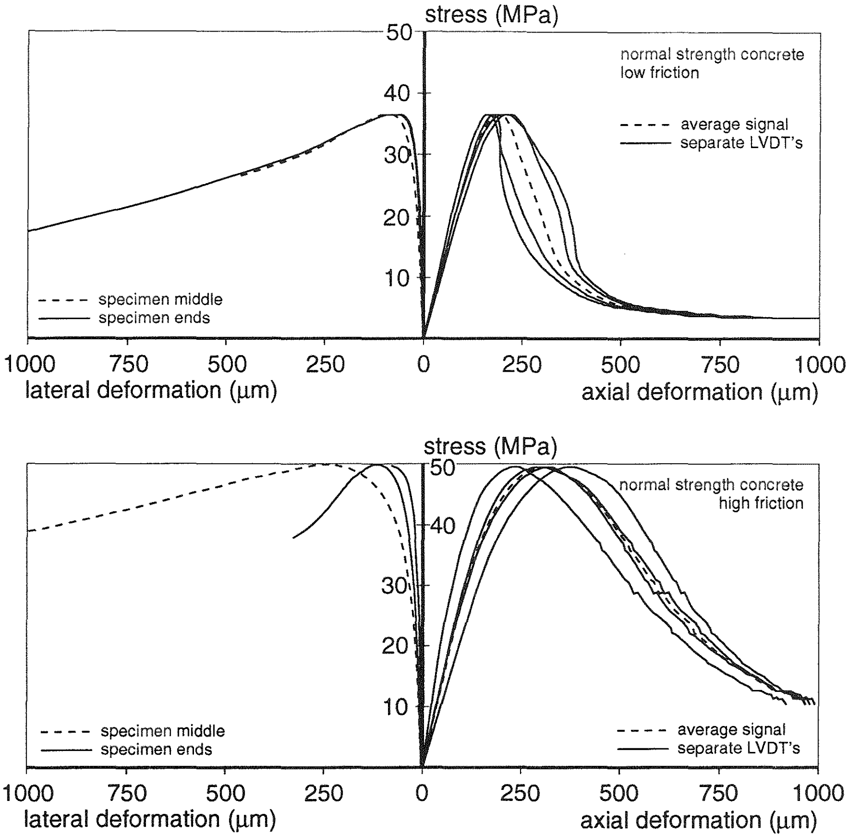



Fig. 6. Axial and lateral deformations of 100 mm NSC specimen under LF (a) and HF boundary conditions (b)

contemplation of the crack processes in concrete. When NSC is loaded, at first microcracks will develop in the bond zones between matrix and aggregates between about 30% and 70% of peak load. The first reason for the cracks to start growing there, is the strength difference between the bond and both matrix and grains. Secondly, stress-concentrations will develop around the interface between the stiff aggregates and the matrix, owing to their difference in Young's modulus. In HSC, the differences in strength and stiffness ratios are equalized, leading to a more homogeneous material structure. As a consequence, crack arrest by stiffer aggregate particles is not possible anymore making the first cracks more critical. Another important factor might be the porosity of the matrix and bond zones in NSC, which again leads to stress concentrations. In HSC this effect will also be substantially less. The aforementioned mechanisms make HSC specimens behave more brittle. This brittle failure made it impossible to control the 200 mm LF experiments by means of the average vertical deformation. Using the (average) lateral deformation as a control signal, will solve this problem.

A final remark concerns the tail of the stress-strain curve of the 25 mm specimens loaded under LF (Fig. 3b,d) . After reaching a lowest point, the tail rises again. Of course, a height of 25 mm is rather extreme compared to the maximum aggregate size of 8 mm, but also the 50 mm specimens show a slight increase of the load at the end of the tail. For higher specimens this phenomenon disappears. It is however most likely that eventually all specimens would show this kind of behaviour, be it at later stages of the loading process. The increase of the applied load could be explained by a kind of natural confinement that is created between the loading platens, owing to their small mutual distance when specimens with a height over width ratio smaller than 1 are tested. At the moment the specimen has totally fallen apart, the load is solely carried by the aggregate particles and can increase again until a second, even higher, peak will be reached. Armer and Grimer (1989) already pointed out this kind of behaviour, be it that in their case the phenomenon of increasing deformational resistance was merely considered a 'thought experiment'.

### 3.3 Scatter in test results

The results at the peak of the stress-strain curves are given in Fig. 7, for all the experiments that have been performed. The peak stresses and strains for both NSC and HSC tested under HF and LF boundary conditions are plotted as a function of the slenderness. The stress values are given in Table 2.

Using teflon sheets and grease as an anti-friction layer between specimen and loading platen is very effective, as can be seen in Fig. 7. The peak stresses have become independent of the specimen height, and the scatter in peak strains has decreased considerably. The values of the ultimate strengths of the smaller specimens are equal to those of the 200 mm specimens. It can be concluded that in the specimens tested under LF boundary conditions no confined zones are present anymore.

Table 2. Peak stresses of the NSC and the HSC experiments

| Height | $\sigma_{peak}$ (MPa) for NSC | | | $\sigma_{peak}$ (MPa) for HSC | | |
|---|---|---|---|---|---|---|
| (mm) | LF | HF | $f'^{*}_{cc}$ | LF | HF | $f'^{*}_{cc}$ |
| 25 | 36.0±0.7 | 95.9±4.9 | 53.8±1.3 | 64.3±1.6 | 153.0±5.6 | 84.9±4.2 |
| 50 | 37.6±1.4 | 65.6±2.7 | | 66.9±2.0 | 110.0±1.1 | |
| 100 | 38.0±1.2 | 48.4±1.0 | | 69.7±3.5 | 87.5±0.7 | |
| 200 | 37.8±0.8 | 39.2±1.2 | | 70.4±1.6 | 73.2±1.6 | |

* Compressive strength of 150 mm control cubes

Apart from the levelling effect of the LF platens according to the peak stresses, also the scatter becomes smaller of both the peak stresses and peak strains (see Table 2), and the test results (Fig. 8). The decreasing scatter of the test results is also found for increasing specimen height. Especially in

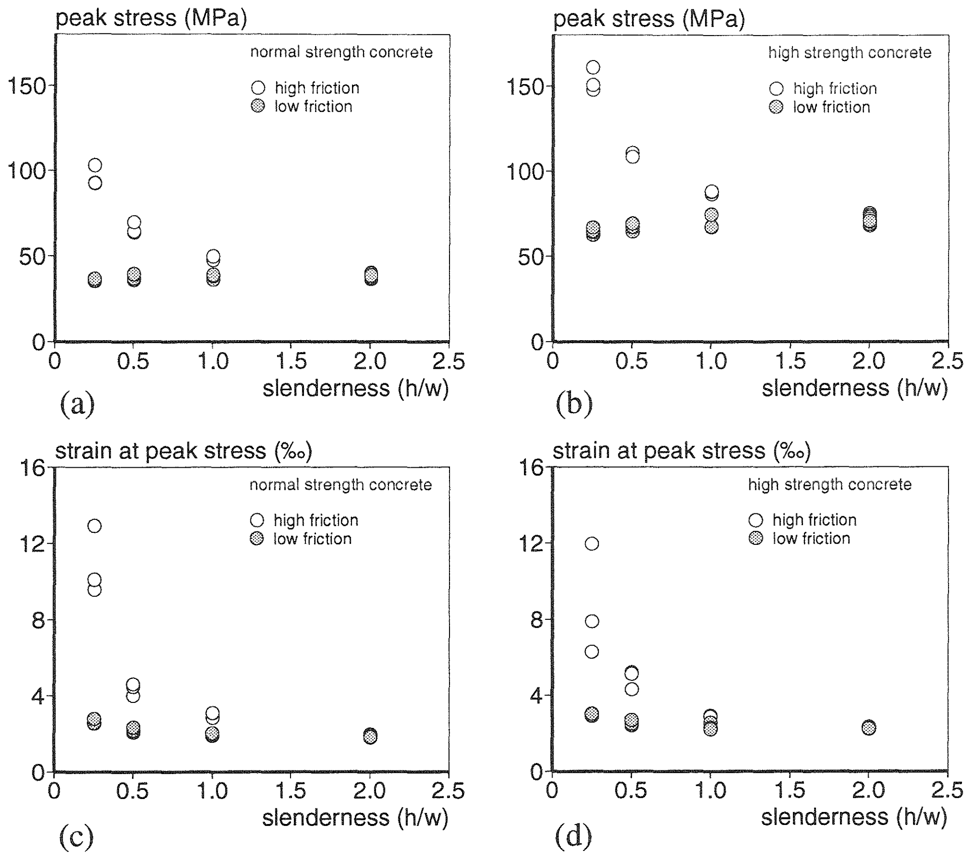
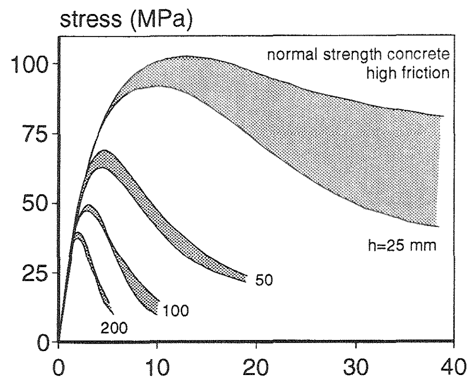


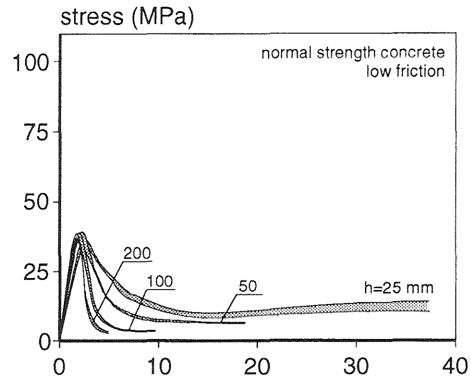

Fig. 7. Peak stresses (a,b) and strains (c,d) for NSC (a,c) and HSC (b,d)

case of the HF tests the scatter in peak stresses and peak strains becomes smaller with increasing specimen height. For the HF tests, the large difference in the standard deviation for the peak stresses is due to boundary and other influences on the stress distribution inside the specimen. In case of a substantial discontinuity in the concrete, the influence will be bigger for a small specimen than for a large one, as in the latter case the influence is averaged over a larger area. Such discontinuities might also be the reason for the decrease of the peak stress that is found for slenderness values smaller than 1, see Fig. 7.

The scatter in the peak strains found in the HF tests is due to effects of the loading platens. These influence the strain distribution within the specimen as well as the real deformations of the loading platens and the contact area between loading platen and specimen. Although the measured deformations have been corrected for the computed elastic deformation of the steel loading platens, the real deformations of loading platens and contact area are not known. As this effect is still included in the deformation values used to compute the peak strains, the scatter will be more pronounced for the 25 mm specimens than for the 200 mm ones. Apart from this effect the strain distribution in the specimen near the loading platens is far from constant. This phenomenon can here unfortunately not be distinguished from the deformation of loading platens and contact area that was mentioned first.



(a)



(b)

Fig. 8. Range of results NSC specimens with HF and LF boundaries

The influence of the specimen height on the values for the peak stress and the peak strain strongly decreases for the specimens with a length of 100 mm or more. For the 100 mm specimens the peak stresses are close to those of the 150 mm control cubes (they are about 5 MPa lower). Differences are however likely to occur as the specimens have been ground in contrast to the control cubes. The frictional stresses that will develop between the ground surface of the specimen and the steel loading platens will therefore be lower compared to the control cubes, resulting in a lower peak stress. Moreover, the 150 mm control cubes were loaded immediately after they were removed from the water. In contrast, the (100 mm) specimens were loaded only after 6-8 hours of removal from the plastic bags. Consequently eigenstresses will develop, causing a lower apparent tensile strength.

### 3.4 Normalized curves

Normalized stress-strain curves can be used to provide insight into the specific differences in the behaviour of specimens of varying heights under different loading conditions. By dividing the stresses and strains by the stress and strain values at the peak, a comparison can be made of the pre-peak and the post-peak specimen behaviour. In Fig. 9 the normalized stress-strain curves for the NSC tests are shown.

With regard to the HF tests, the non-linearity of the pre-peak curve increases with decreasing specimen height, see Fig. 9a. Although the differences in curve shape are not too large for specimens with heights of 50 mm, 100 mm and 200 mm, for a specimen height of 25 mm a gradual decrease of the slope is found for forces larger than 60% of peak load. The curves of the LF tests however, do not show this behaviour which confirms the difference in crack growth due to HF or LF boundary conditions. Decrease of the pre-peak slope is caused by the development of mortar cracks, the coalescence of cracks and premature spalling of the specimens outerlayers. For the LF specimens and the HF specimens higher than 100 mm these processes start between 80% and 90% of the peak load. At lower loads micro cracks originate in the bond zones between mortar and aggregate. This formation of microcracks however, is hardly possible in the 50 mm, and especially the 25 mm specimens tested under HF boundary conditions. Owing to the boundary restraint in case of the HF boundary conditions, these low specimens are almost totally confined in horizontal direction, allowing less micro-cracks to develop. As a result the process of mortar crack development, coalescence of cracks and macro crack formation will already start at lower load levels causing a decrease of the slope of the stress-strain curve.

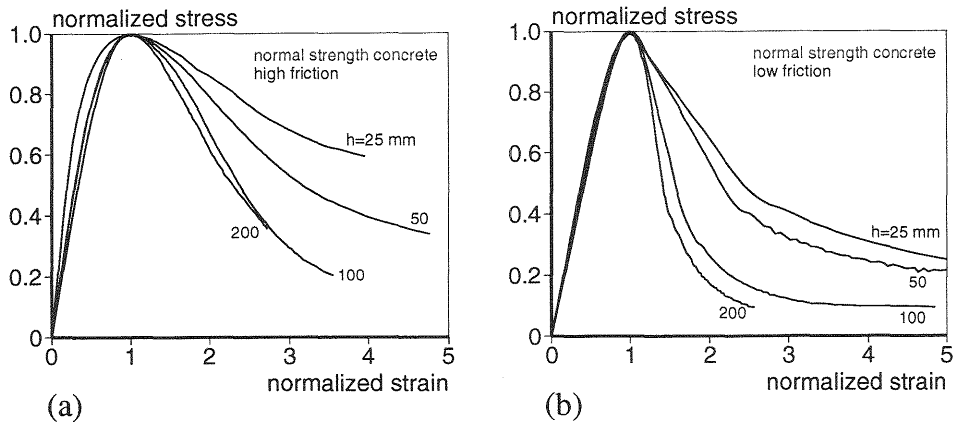



Fig. 9. Normalized stress-strain curves for the normal strength concrete

The post-peak parts of the normalized curves shown in Fig. 9, once again emphasize the influence of the specimen height on the softening behaviour of concrete. The influence of the specimen height on the softening behaviour of concrete is as strong for the HF as for the LF boundary conditions, and increases with decreasing specimen height. Consequently, testing specimens with a too low slenderness without active reduction of boundary friction, gives a too high tail of the softening curve of concrete.

In general one can say the ductility decreases considerably with increasing specimen height. Kotsovos (1983) stated when observing this behaviour that, if the friction reduction in the boundaries would be perfect, in the most extreme case the post-peak slope of the curve would be vertical. Therefore he suggested taking the post-peak strength of concrete under compression equal to zero. This seems too radical however. Although the load decreases rapidly for the 200 mm specimens, it does not become zero and a tail is clearly present. Furthermore, it is not unlikely his results were affected by snap-back behaviour, which would make his conclusions rather debatable.

## 4 Conclusions

Uniaxial compression tests on prisms of two different concretes, with different heights and under low and high frictional restraint, have shown that a stress-strain curve of concrete is not a material property but a mix of structural and material behaviour. By applying an interlayer of teflon and grease between specimen and loading platen the effect of the specimen height on the peak stresses and peak strains could be effectively reduced. The elastic energy release however, is still influenced by the specimen height for both the 50 MPa and the 80 MPa concrete. The difference between the two types of concrete is the release of elastic energy that is lower for the 80 MPa concrete. The effect of the specimen height on localized fracture modes is still subject of further study.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