FATIGUE OF HIGH STRENGTH CONCRETE

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SYNOPSIS

In this investigation, the fatigue properties of high strength concrete in compression were studied. Two types of normal density concrete, ND65 and ND95, and one type of lightweight aggregate concrete, LWA75, have been tested. The numbers indicate the planned mean strength in MPa of 100*100*100 mm cubes.

The main parameters in the experimental part were the influence of concrete strength, aggregate types and variation in stress levels on the fatigue life. Test conditions with constant maximum stress levels showed significantly longer lives when the stress range was reduced. However, if the load levels were defined relatively to the static strength, there was no obvious

difference between the fatigue properties of the concrete qualities included in these tests.

Based on the results of the experimental work, an improved design proposal for fatigue of concrete in compression is established, and discussed with respect to earlier design proposals.

1. INTRODUCTION

This investigation was carried out as a part of the High Strength Concrete Research Project at SINTEF FCB /1/, and its aim was to study the fatigue properties of high strength normal density (ND) and lightweight aggregate (LWA) concrete. The main attention was paid to ND95 and LWA75 concretes, where the numbers indicate the planned mean strengths in MPa of 100*100*100 mm cubes. Some tests on ND65 quality were also performed so as to include an intermediate strength lying closer to previously performed tests.

An introductory investigation had the aim of exploring the relationship between moisture conditions and specimen size on the fatigue life of HSC /2/. Three moisture conditions were applied: - the air condition, implying that the specimens were stored and tested in air, - the sealed condition, where the specimens were covered with a watertight tape on the surface so as to keep their natural content of water, and - the water condition, where the specimens were stored and tested in seawater. The intention of using different sizes of cylinders was to verify the moisture effects as a surface phenomenon.

The results showed that there was a significant difference in fatigue life of the three conditions for Ø100 mm cylinders. By sinusoidal loading at load levels equal to 70 and 5 percent of the static strength, the fatigue life of the air, sealed and water condition was about 500 000, 10 000 and 5 000 cycles, respectively. At the same loading condition of Ø450 mm cylinders, the fatigue life was about 10 000 cycles for all the three moisture conditions.

On the basis of these results it was decided to continue further investigations in this project on sealed specimens. The sealed condition is assumed to be most representative for the behaviour of normally sized structural elements since drying and water penetration usually are most dominant in the outer layer of the structures.

The test specimens in the investigation were Ø100*300 mm cylinders. The loading form was sinusoidal and the frequency was 1 Hz. The age of the specimens at testing was about 3 months.

The main part of the experiments consisted of constant amplitude tests for different levels of loading. The loading was sinusoidal with S_{max} and S_{min} as maximum and minimum stress values, respectively. The values for S_{max} and S_{min} are relative stresses, where the reference strength is the static strength of the test specimens. The main intention of the tests was to evaluate the effect of the change in minimum stress levels on the fatigue life. Since the test programme was the same for both ND95 and LWA75 it was also possible to make a direct comparison of the two qualities.

The fatigue behavior was also studied by means of parameters that indirectly describe the endurance under cyclic loading. Particularly, the strain rate in the region with stable strain development has been found to be an important parameter for the evaluation of fatigue properties. The strain measurements were particularly important in some separate variable amplitude tests to investigate the existence of an endurance limit for concrete /3/.

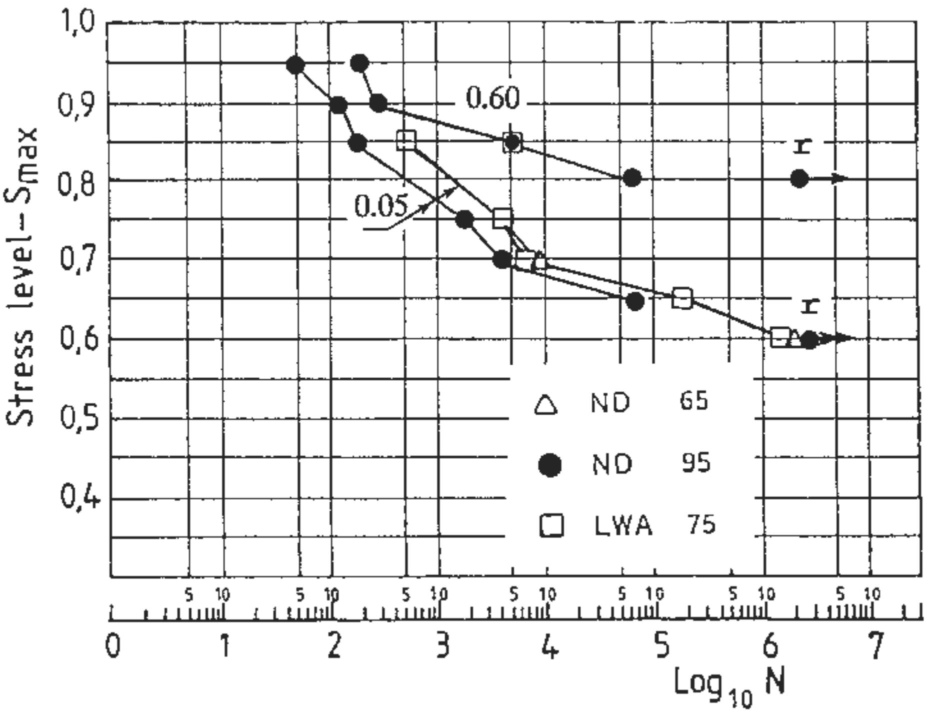
This paper presents only the results that form the background for the subsequent design formulations. It is focused on statistical and practical considerations that were necessary for the determination of the S-N curves.

2. EVALUATION OF THE TEST RESULTS

The usual way of presenting concrete fatigue results is in the form of an S-N diagram, which shows the relationship between the stress levels and the logarithm of the number of loading cycles to failure. The mean results of the constant amplitude tests for the three concrete qualities in this investigation are presented in such a form in Fig 1. From these diagrams the effect of the minimum stress level is quite evident. The fatigue lives obtained at a certain maximum level are longer the higher the minimum level, for all the three qualities.

The effect of the concrete quality is not as obvious, and the variation in the mutual location for different stress combinations may imply that the variations are incidental and only caused by scatter. For the test condition with $S_{min}=0.05$, however, there seems to be a systematic difference between LWA75 and ND95 concrete. Nevertheless, a systematic displacement of the results may be caused by an erroneous estimation of the static reference strength. It is, therefore, interesting to look into the scatter of the static strength and its consequences on the fatigue results.

The static reference strength of the test cylinders was about 75 and 80 MPa for the ND95 and LWA75 concretes, respectively. Based upon a representative standard deviation of 3.0 MPa in these tests for both the qualities, the 90 percent confidence interval for the mean strength was found to be about ± 1.9 MPa.



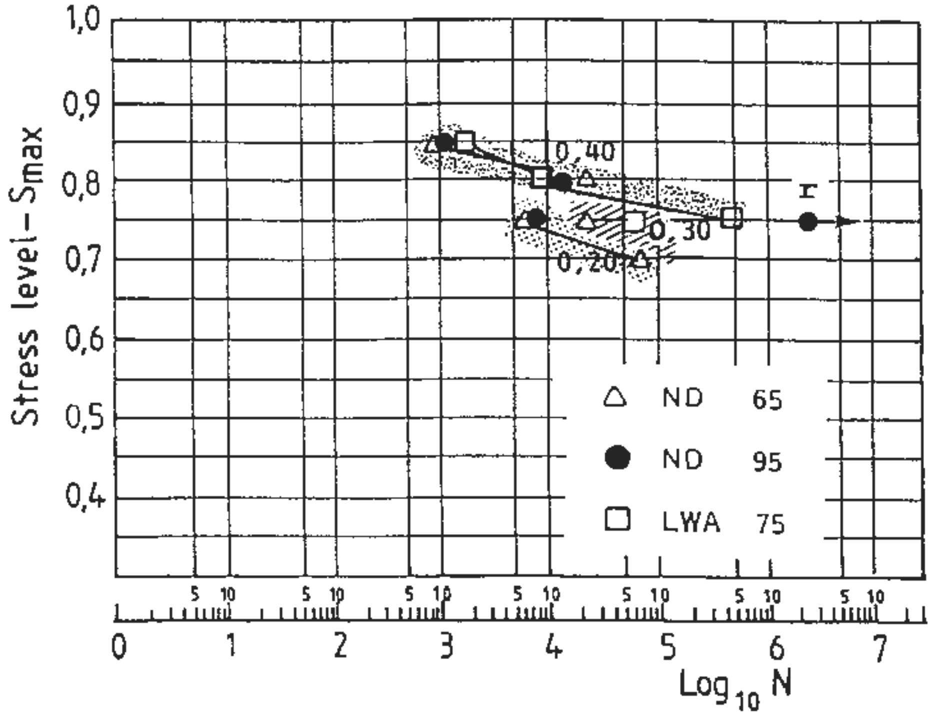


Fig 1. Comparison of the mean fatigue lives of ND65, ND95 and LWA75 for different minimum stress levels. In the upper figure for S_{min}=0.05 and 0.60, and in the lower figure for S_{min}=0.20, 0.30 and 0.40, R means run out

In the relative scale, the corresponding S_{max} interval will be dependent on the stress level. Taking $S_{max}=0.75$ as a representative value, ΔS_{max} will be about ± 1.9 percent for the ND95 and about ± 1.7 percent for the LWA75 concrete. This difference in ΔS_{max} would result in a logarithmic displacement of the mean results equal to ± 0.24 and ± 0.19, for the two concretes. Besides, based upon the test results at $S_{min}=0.05$ and S_{max} between 0.65 and 0.85, the 90 percent confidence interval of log N for the mean regression lines was found to be about 0.2 for both qualities.

Since these two sources of error are independent of each other, the sum of the two scatters should be compared with Fig 1. It can then be seen that the calculated scatter is more than sufficient to cover the differences in the position of the fatigue results of the two concrete qualities. A factor analysis that was performed also supported that conclusion.

The scatter in fatigue observations at a certain stress level has usually been explained by the scatter in the static strength. This was also confirmed in this investigation, where the static strength scatter corresponded to about 85 percent of the scatter in the log N observations.

The statistic evaluation thus showed that there was no reason for distinguishing between the three concrete qualities in this investigation. They were, therefore, treated as one when the final regression lines for the different minimum stress levels were calculated.

The regression lines based upon the results of all three qualities, except run-out specimens, are calculated for $S_{min}=0.05$, 0.40, and 0.60, respectively in Fig 2. It is not logical that the S-N lines cross each other, since higher stress levels are expected to give shorter fatigue lives for a certain S_{max} value.

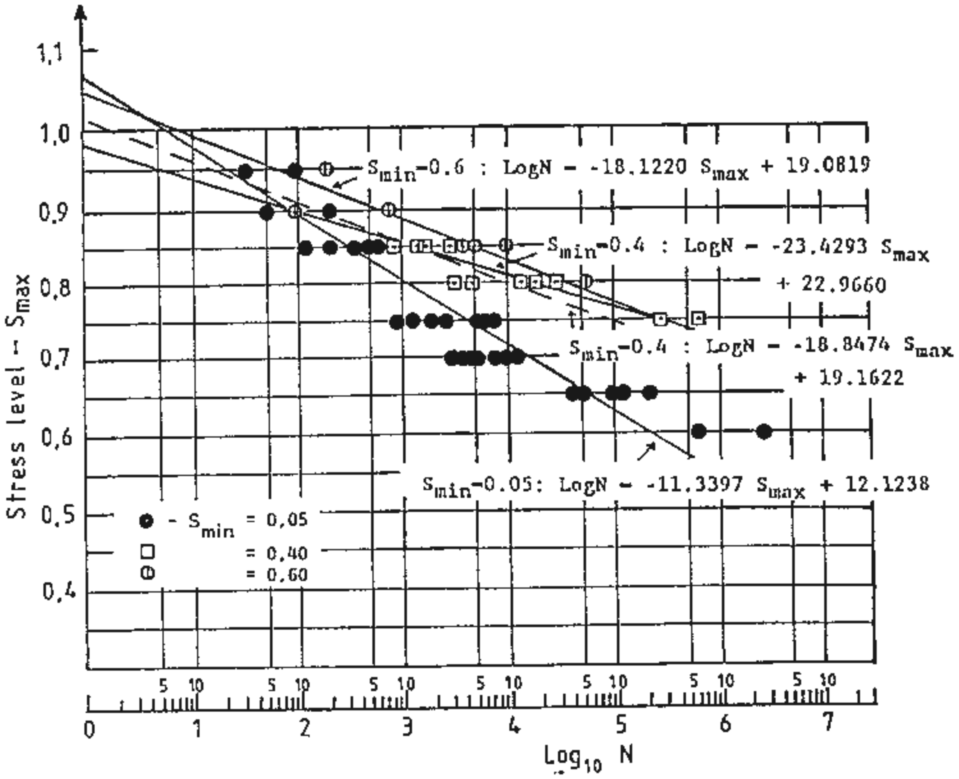


Fig 2. Regression lines based upon the results of the three concrete qualities for S_{min}=0.05, 0.40 and 0.60. The dashed line shows the change of the line for S_{min}=0.4 when the two results at S_{max}=0.75 are excluded

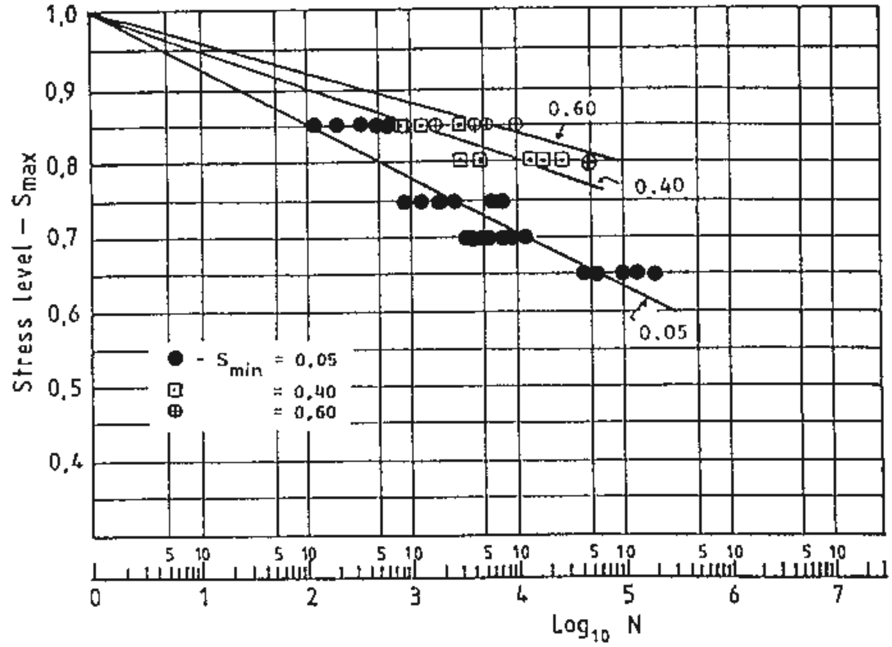


Fig 3. Regression lines through S_{max}=1.0 for S_{min}=0.05, 0.40 and 0.60. The lines are based upon the results of all the three concrete qualities at S_{max} between 0.65 and 0.85

The intersections of the regression lines on the S_{max} axis in Fig 2 were 1.07, 0.98, and 1.05 for the three S_{min} values, respectively. This is relatively close to $S_{max}=1.0$, which corresponds to the static strength of the specimens.

It is, however, well known that fatigue tests at very high stress levels are frequency dependent in a way that the number of cycles to failure will be smaller the longer the cyclic periods are /4/. The fatigue results obtained at S_{max} above 0.85, particularly for $S_{min}=0.05$, indicate longer fatigue lives than found from a linear adjustment of only the results at S_{max} lower than 0.85. This is, however, not surprising if one takes into consideration the different rate of loading applied in the fatigue tests compared to the static reference tests.

The frequency of 1 Hz in our tests is not realistic for the cyclic exposure of real structures to high load levels, which usually have a period between 10 and 15 seconds. Hence, if a more realistic frequency had been used at the highest load levels, the fatigue lives would be approaching $S_{max}=1.0$ for $\log N=0$. This shows that $S_{max}=1.0$ should be related to the static short term strength of concrete.

Another important effect that the results showed is that the lifetime at lower S_{max} values tended to be longer than indicated by the linear relationship. This points out the stress levels where it is reasonable to change the inclination of the regression lines.

Generally, the position of the fatigue results does not indicate a fully linear relationship between the maximum stress and the fatigue life. For reasons of simplicity, however, we can assume that the relationship consists of linear segments and perform a linear regression calculation for the middle part of our S_{max} range. An omission of the results at the lowest and highest S_{max} values then improves the accuracy of the regression lines in the region where they are assumed to be representative for the fatigue behaviour.

Including now the requirement that all the S-N curves start from 1.0 on the S_{max} axis, the regression lines for the different S_{min} levels were found as:

$S_{min} = 0.05$ $\quad$ $\log N = -13.72\, S_{max} + 13.72$

$S_{min} = 0.20$ $\quad$ $\log N = -16.48\, S_{max} + 16.48$

$S_{min} = 0.30$ $\quad$ $\log N = -17.80\, S_{max} + 17.80$

$S_{min} = 0.40$ $\quad$ $\log N = -20.60\, S_{max} + 20.60$

$S_{min} = 0.60$ $\quad$ $\log N = -24.53\, S_{max} + 24.53$

The regression lines for S_{min}=0.05, 0.40 and 0.60 are compared with the experimental results in Fig 3.

The last number in the expressions above locates the intersection points of the lines with the log N axis. These values are plotted relatively to S_{min} in Fig 4 and the relationship between them appears to be linear. This also means that there was a linear relationship between S_{min} and log N within the range of S_{max} applied in this investigation.

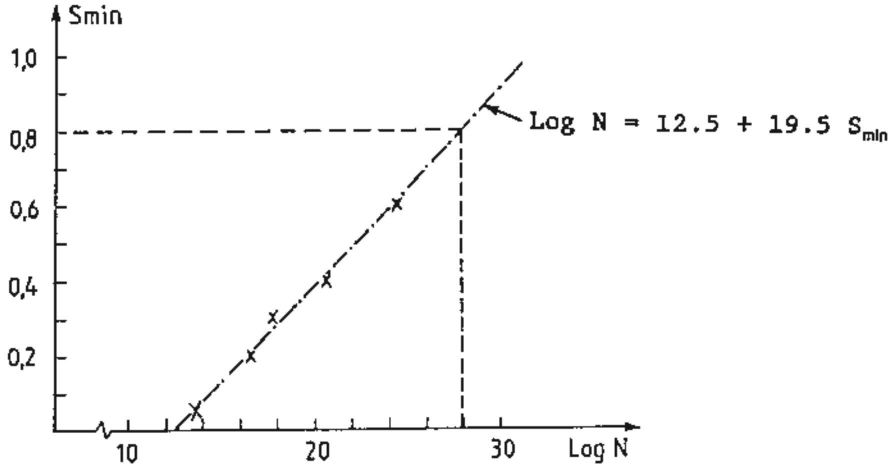


Fig 4. Relationship between S_{min} and log N for S_{max}=0 based upon the regression lines for S_{min}=0.05, 0.20, 0.30, 0.40 and 0.60

3. FATIGUE DESIGN

3.1. Review of existing design proposals

The design check for fatigue failure of concrete has so far been treated in a simplified way in most of the National Codes. Concerning fatigue of concrete in compression there has usually only been a limitation on the maximum advisable stress at cyclic loading. This means that the maximum load level is detrimental for design independent on the form of the load histogram.

The absolute values of the advised stresses at cycling have varied quite a lot within the codes. In the ACI-Manual of Concrete Practice /5/ the maximum advisable stress is 0.5 of the cylinder strength and in the previous edition of the Norwegian Code (NS 3473) this limit was 0.5 of the design strength. This means that for a concrete with a cylinder strength of 45 MPa there is a factor of about 2 between the advisable stresses for fatigue in the two guidelines.

The idea behind this simplified method was to limit the maximum stress at a level which was meant to be an endurance limit for concrete, implying that stress variations below this level had no detrimental effect on the load capacity. However, the gradual development towards utilization of higher concrete strengths and more use of concrete structures where a major part of the loading is cyclic have made it essential to obtain more detailed design requirements for fatigue.

Different formulations have been proposed for the fatigue properties of concrete in compression. Most of the equations have a semilogarithmic form where $\log N = f(\sigma_{max}, \sigma_{min})$, but there might be quite a difference in their description of the fatigue properties.

Three of the most discussed formulae are:

$$\text{Log } N = C_1 \ (1-S_{max}) \ / \ (1-S_{min}) \qquad (1)$$

$$\text{Log } N = C_1 \ (1-S_{max}) \ / \ (1-R) \qquad (2)$$

$$\text{Log } N = C_1 \ (1-S_{max}) \ / \ (1-R)^{1/2} \qquad (3)$$

where:

C_1 is a constant which has in literature been suggested to lie between 10 and 15 for fatigue in pure compression (dependent on the moisture conditions under which the tests have been performed).

S_{max}, S_{min} and R are σ_{max}/f_{rd}, σ_{min}/f_{rd} and $\sigma_{min}/\sigma_{max}$, respectively, where σ_{max} and σ_{min} are the maximum and minimum levels of loading in a cycle and f_{rd} means the reference strength for fatigue design corresponding to S_{max}=1.0 in the S-N diagram.

The three equations give the same S-N line for σ_{min}=0. Hence, the only difference is the way of considering the influence of variable minimum stress levels. The S-N curves for each of the three alternatives are shown for S_{min}=0, 0.25, 0.50, 0.75 and 1.0, when assuming C_1=12, in Fig 5.

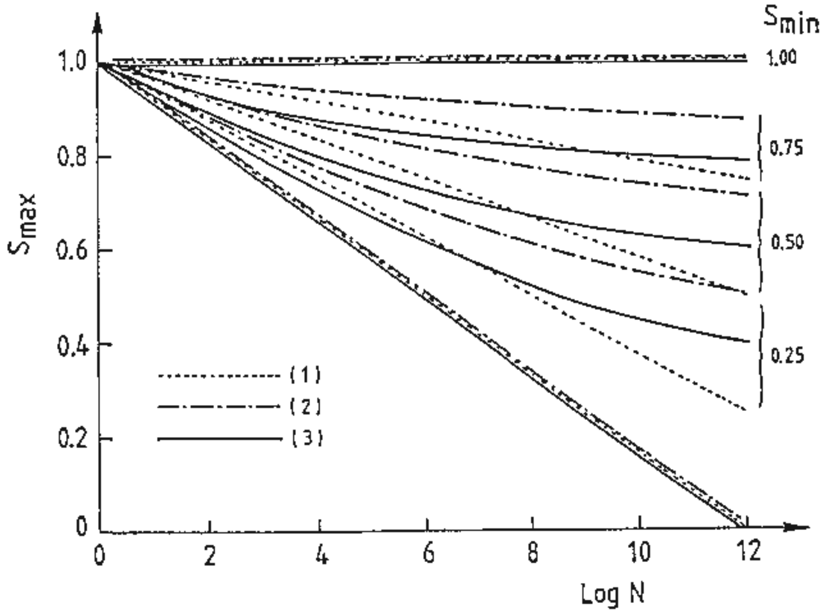


Fig 5. Comparison of the S-N curves of Eq (1)-(3) for fatigue of concrete in compression

Equation (1) was first proposed by Veritas for design of offshore concrete structures /6/. The main objection made to that expression has been the relatively short fatigue lives obtained for S_{max} values lower than about 0.5. The fatigue relationship in the lower part of the diagram was determined by only extrapolating downwards to the log N axis the regression lines obtained on test data in the loading range of S_{max} between 0.65 and 0.90. To solve that problem, cut-offs by means of vertical lines at different log N values have been proposed.

Equation (2) was first proposed by Knut AAs-Jakobsen /7/, but later this formula was also mentioned as an alternative for fatigue design in the state of the art report on fatigue prepared by RILEM /8/. This expression gives a curved S-N relationship when plotted for different S_{min} values. Compared to Eq (1) there is a significant increase in the number of cycles to failure for all stress combinations except $S_{min}=0$. An advantage of Eq (2) is that it gives infinite lifetime when S_{min} approaches S_{max}.

Equation (3) with $(1-R)^{1/2}$ as denominator was proposed in the design specifications prepared by CEB/FIP-GTG15 for the new revision of CEB Model Code /9/. The background for this formulation was that fatigue tests carried out in the Netherlands, for different values of R, had shown that the (1-R) formulation was too favourable for the effect of increasing minimum stresses /10/.

A comparison of the equations for three different values of S_{max} and $C_1=12$ is shown in Fig 6. The (1-R) formula always gives the longest life. The relationship between the two other formulae is changing, $(1-R)^{1/2}$ gives the shortest life for the main range of S_{min} at high S_{max} values, while it gives longer life in the whole range of S_{min} for S_{max} smaller than about 0.55. There is, however, an obvious difference between the three formulations considering

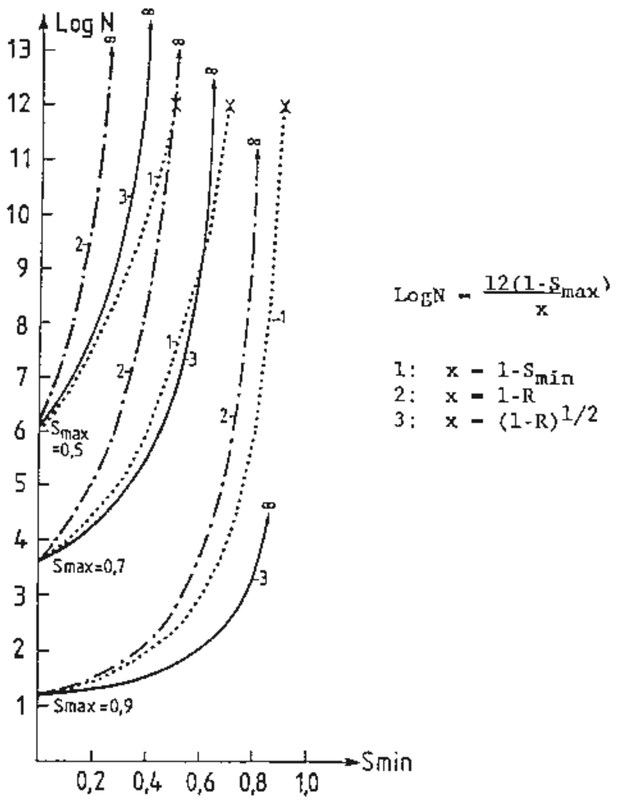


Fig 6. Comparison of Eq (1)-(3) for S_{max}=0.5, 0.7 and 0.9 when C_1=12 for the calculation of the fatigue life

the influence of S_{min}, and the main reason for this is the lack of sufficient experimental documentation.

Another way of comparing the three formulae is by plotting mean stress versus stress range. In this case, as shown in Fig 7, the (1-R) formula gives a simultaneous increase in both stress range and mean stress for small minimum stresses (large stress amplitudes) in the case of more than about 10^6 cycles to failure. This is not logical and shows that the (1-R) formula, at least in the long endurance range, overestimates the S_{min} effect.

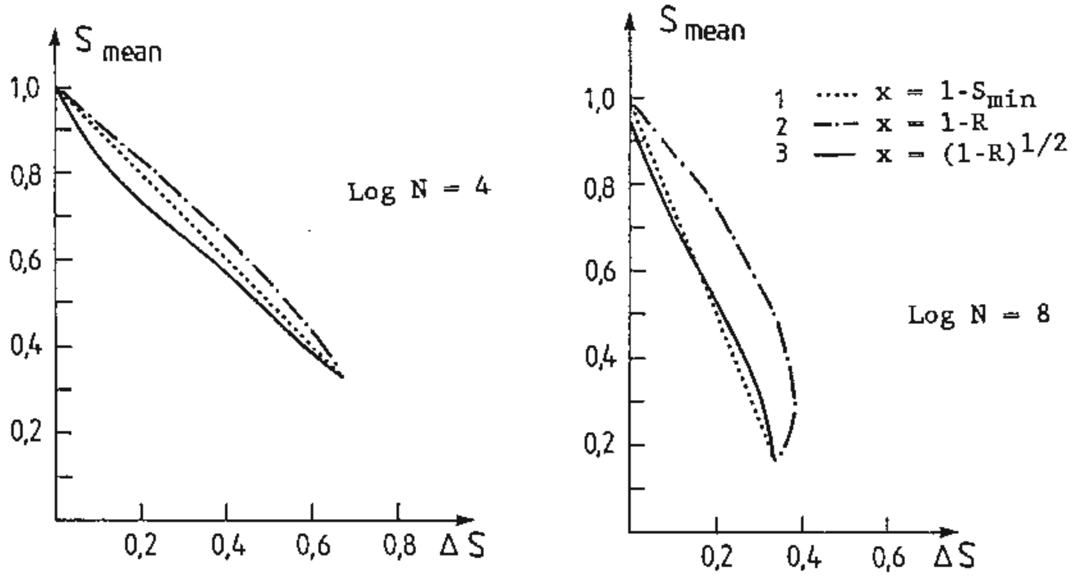


Fig 7. Relationship between mean stress and stress range of Eq (1)-(3) for logN=4 and 8, the constant C is assumed to be 12

In the recent revision of NS 3473 /11/, Eq (1) is used as the basic formula for fatigue of concrete in compression:

$$\text{Log } N = C_1 \; (1-S_{max}) \; / \; (1-S_{min}) \qquad (1)$$

where:

C_1 = 12 for structures in air, and 10 and 8 for structures in water by only compression and compression-tension, respectively.

When log N according to the basic formula is larger than a certain value X expressed as:

$$X = C_1 \; / \; (1 - S_{min} + 0.1 * C_1) \qquad (4)$$

the real lifetime for that particular stress situation is found by multiplying log N in the basic formula by a factor C_2 equal to:

$$C_2 = (1 + 0.2 * (\log N - X)) > 1.0 \qquad (5)$$

The S-N diagram according to this approach is shown in Fig 8 for a selection of S_{min} values.

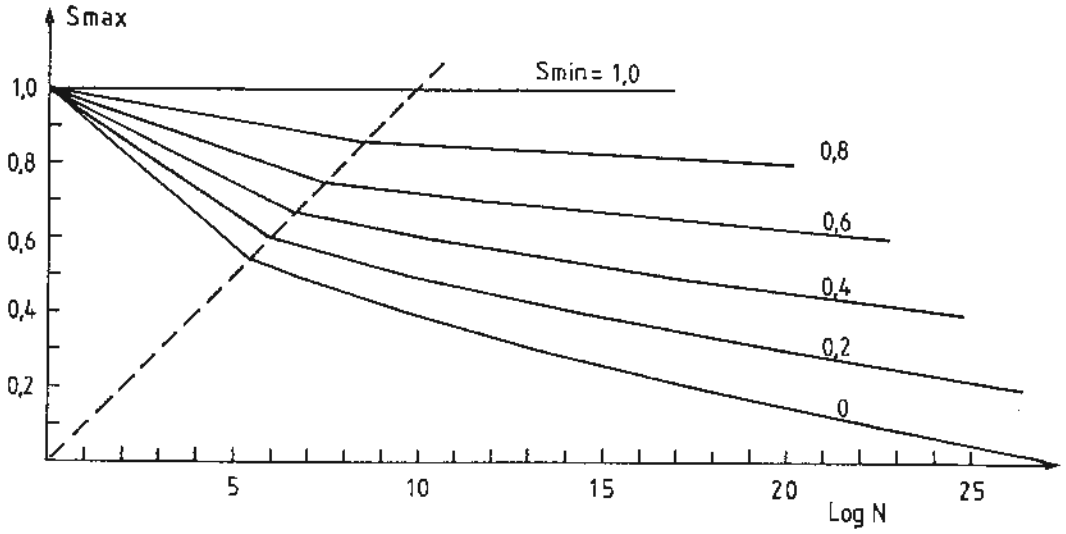


Fig 8. S-N curves for fatigue of concrete in compression according to NS 3473 for C_1=12

3.2. Design proposal for fatigue of concrete in compression based upon the experimental results of this investigation

The effect of S_{min} from the constant amplitude tests in this investigation, as reflected by the regression lines in the case of S_{max}=0.8, is compared with the three earlier discussed design proposals, Eq (1)-(3), in Fig 9. It appears that only the denominator $(1-R)^{1/2}$ is on the safe side within the range of S_{min} tested in this case. Besides, the earlier design proposals have a curved progression, while the tests showed an almost linear relationship between S_{min} and log N. The main difference appearing at relatively small stress ranges when S_{min} approaches S_{max} can, however, be related to the meaning of the reference strength.

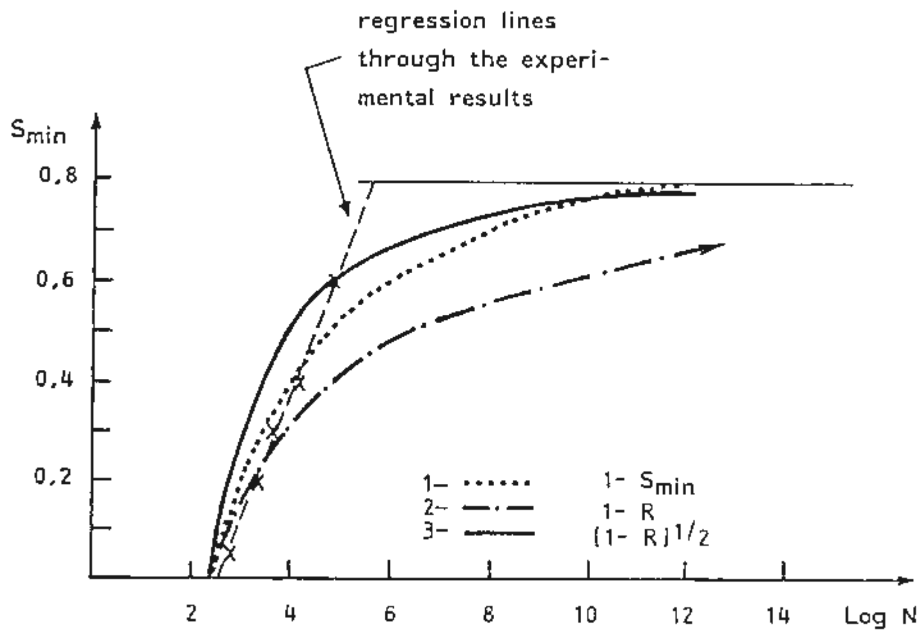


Fig 9. Comparison of the experimental results with the design proposals Eq (1)-(3) for S_{max}=0.8 and C_1=12

If a fan of lines for increasing S_{min} values with a horizontal tangent at S_{max}=S_{min}=1.0 should be possible, the reference strength must be related to the long term strength. For concrete, the sustained long term strength can be more than 20 percent lower than that obtained by a constant loading rate of 0.25 MPa/s, as used in the static tests for the determination of the reference strength in this investigation.

In Section 2 it was found that the point S_{max}=1.0 in the S-N diagram should be related to the static strength of concrete. If S_{max}=1.0 had been a long term strength, corresponding to for instance 80 percent of the short term strength, the intersection point of the regression lines with the S_{max} axis should have been 1.25.

For this reason it is quite obvious that fatigue tests with load levels above the long term strength must have a finite and not infinite life as predicted by the existing design proposals.

The crosses on the lines in Fig 10, which indicate the cyclic levels where the experimental results started to deflect towards longer lives than indicated by the regression lines, were all positioned between 5 and 6 on the log N axis. A break at log N=6 is then on the safe side with respect to the experiments. The uncertainty connected to the behaviour in water for tests of long duration speaks in favour of some extra safety in this parameter.

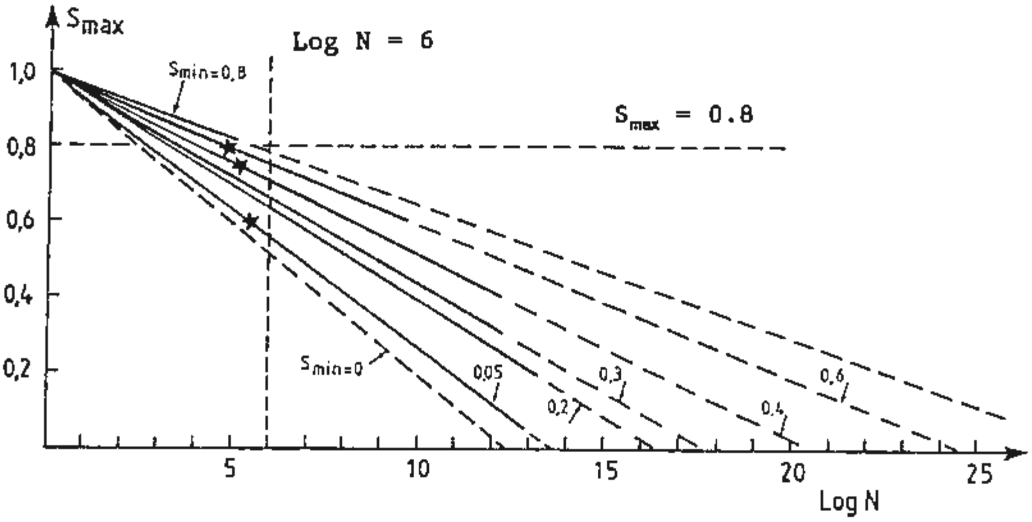


Fig 10. S-N lines found for the different S_{min} levels in this investigation. The stars indicate the stress levels where the results indicated a change in the inclination of the lines

Hence, if the long term strength is assumed to be 80 percent of the short term strength, two lines can be drawn in the S-N diagram, one for $S_{max}=0.8$ and one for log N=6. The construction of the diagram would, however, be simpler if the line for $S_{min}=0.8$ was passing through the intersection point of these two lines. This additional requirement is satisfied by an expression on the form:

$$\text{Log } N = (12 + 16\, S_{min} + 8\, S_{min}^2) * (1 - S_{max}) \qquad (6)$$

The intersection points of this expression with the log N axis are compared to the experimental results and Eq (1) in Fig 11.

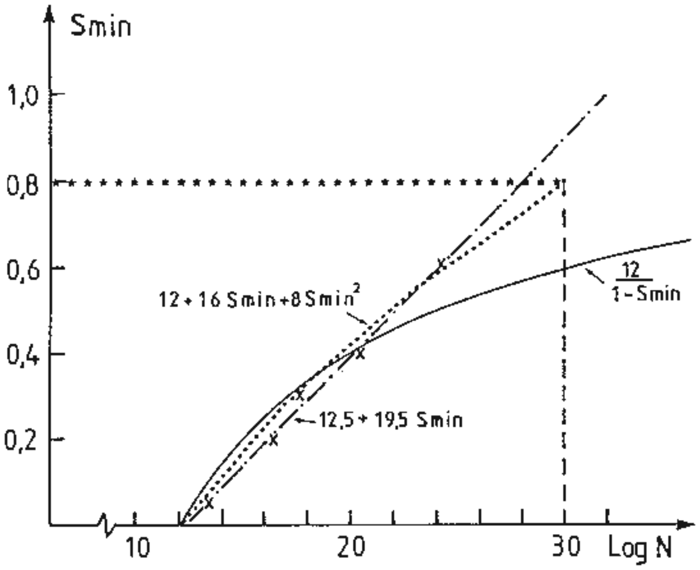


Fig 11. Comparison of the proposed S_{min} - log N relationship with the experimental results and Eq (1) for the fictitious load situation $S_{max}=0$

The chosen relationship for the effect of S_{min} has a slightly curved progression, which means that the increase in log N for a certain ΔS_{min} is smaller the lower S_{min} is. This tendency is also in agreement with the results, particularly for lower S_{max} values.

In Eq (6), 12 is chosen as the intersection point with the log N axis for $S_{min}=0$ instead of 12.5 as indicated by the results. This is just a small simplification that lies on the safe side, and is in accordance with that for landbased structures in NS 3473 /11/.

Equation (6) is thus assumed to describe the S-N lines for all values of S_{min} up to log N=6, beyond which the experimental results require a change in the inclination of the lines. It is convenient to perform this change by means of a coefficient, which the log N values according to the basic formula must be multiplied by. Following the principles of NS 3473, this coefficient is taken to be:

$$X = 1 + 0.2 * (\log N - 6) \qquad (7)$$

Multiplication by this coefficient will result in a slightly curved continuation of the lines beyond the breaking points. The proposed change in inclination of the lines described by $\Delta \log N$ / 0.1 S_{max} is shown in Fig 12. It can be seen that the ratio between the inclinations before and after log N=6 is almost independent of S_{min}.

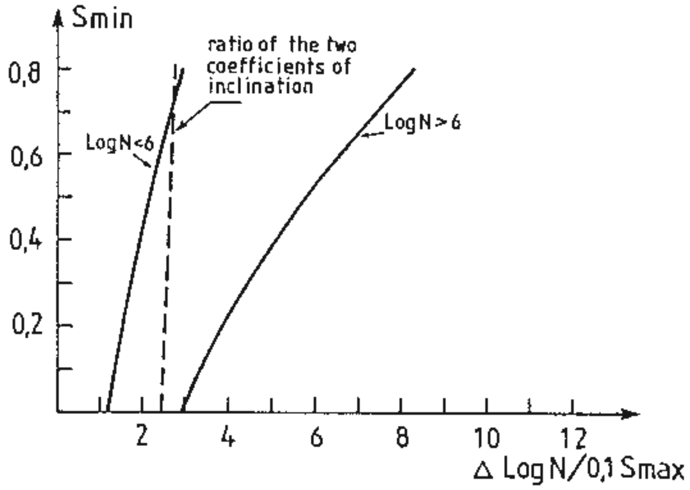


Fig 12. Increase in log N as a function of S_{min} within an interval ΔS_{max}=0.1 at both sides of the line log N=6

The existence of an endurance limit has been discussed in the literature by different authors /12/. From a fracture mechanic point of view, such a limit does not exist, because all stress variations contribute to the damage and failure is only a question of time. It should, however, be possible to speak about an endurance limit for practical design, since most of the structures are exposed to a limited number of cycles during their lifetime. The variable amplitude tests in this investigation gave only indications of an endurance limit. The values used for the endurance limit in this proposal are, therefore, determined by the help of assumptions which are reasonable for the fatigue behaviour of concrete.

Since the fatigue properties of concrete are described by means of the variables S_{max} and S_{min}, it would be appropriate to express the endurance limit as a function of the stress range, i.e. the difference between the two variables. From the experimental observations it is clear that this limit can not be a constant, but that it must be a function of the stress situations. The simple linear relationship in Fig 13 where $\Delta S=0.3$ and 0 for $S_{min}=0$ and 0.8, respectively, seems to be a reasonable assumption at the present level of knowledge.

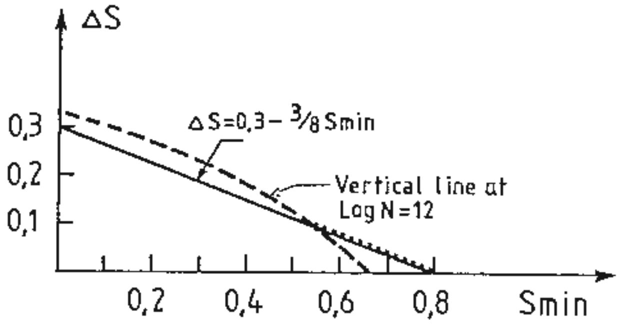


Fig 13. Proposed progressions of the endurance limit as a function of S_{min}

The final S-N diagram for a selection of S_{min} values will than be as shown in Fig 14. The increase in logarithm of cycles at the transfer to the endurance limit when S_{min} increases from 0 to 0.3 has no relevance to the fatigue phenomenon and is only a consequence of the chosen triangular relationship between the stress range and S_{min} in the endurance limit expression. An alternative form of the endurance limit could for instance be a vertical line at logN=12 up to $S_{min}=0.6$ in the design diagram, but the stress range at transfer to the limit would then be more complicated, as shown by the dashed curve in Fig 13. Besides, it is not logical to express the endurance limit by log N values since it is the stress levels which are the detrimental factor for the material.

In the design diagram it is suggested that the S-N line for $S_{min}=0.8$ forms the outer limit for $\log N < 6$. If higher S_{min} values should be included, the outer limit for $S_{max}=S_{min}$ would have a curved form for S_{max} values between 0.8 and 1.0. This would, however, only be an extra complication of insignificant practical interest. Therefore, it is suggested that fatigue lives for S_{min} higher than 0.8 should be limited to the $S_{min}=0.8$ line.

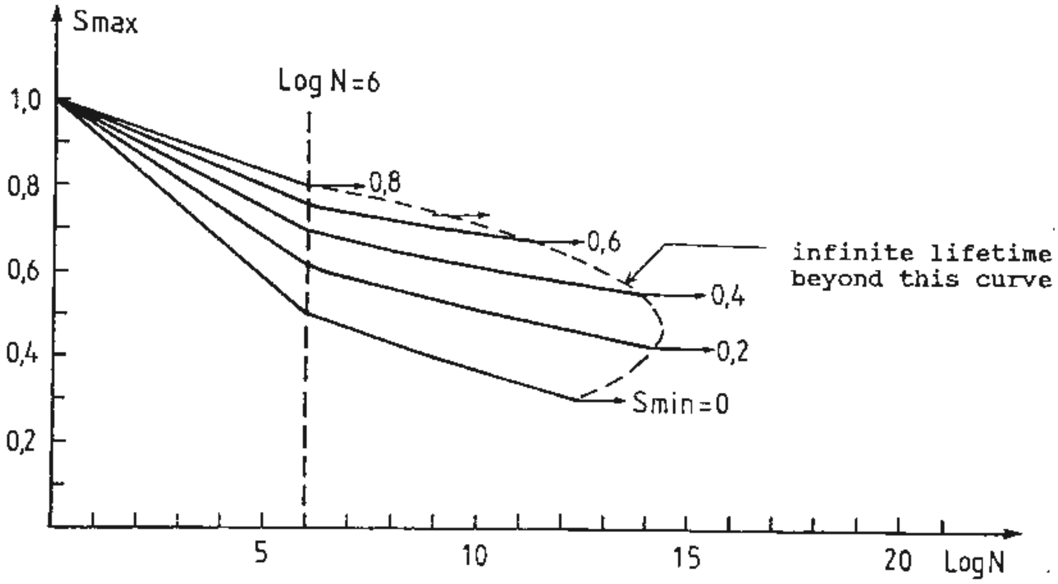


Fig 14. Final S-N diagram for fatigue of concrete in compression according to this proposal

The final design proposal for fatigue of concrete in compression can then be summarized as:

$$\text{Log } N = (12 + 16\, S_{min} + 8\, S_{min}^2) * (1 - S_{max}) \qquad (6)$$

At log N = 6 the S-N lines according to Eq (6) are broken and the number of cycles to failure in the range outside log N = 6 are found by multiplying the log N value according to Eq (6) by a factor:

$$X = 1 + 0.2 * (\log N - 6) \qquad (7)$$

Concrete in compression is assumed to have infinite lifetime for S_{min} values smaller than 0.8 if the stress range ($\Delta S = S_{max} - S_{min}$) is smaller or equal to:

$$\Delta S < 0.3 - 3/8\, S_{min} \qquad \text{for} \quad 0 < S_{min} < 0.8$$

For S_{max} values larger than 0.8, it is not recommended to use higher S_{min} values than 0.8 in the calculations.

This proposal is compared with the S-N diagram in the new Norwegian Code for C_1=12 in Fig 15.

The S-N curves above are assumed to express the mean fatigue behaviour under the different stress conditions. Safety must be taken care of by a corresponding reduction in the reference strength for fatigue as that undertaken for the utilization of the static strength. In the fatigue tests the static short term strength of the specimens was used as reference for the load levels, but the idea is that the same curves would be attained for an arbitrary concrete structure if the corresponding structural strength was used as reference.

In NS 3473 /11/ the connection between the strength of a standard cylinder, f_c' (Ø150*300 mm stored 28 days in water and tested wet), and a cylinder of equal size taken from a structure is assumed to be (0.775 f_c'+3.1) MPa for cylinder strengths above 45 MPa. This ratio is reduced by 0.95 to take into account size effects, and by another 0.95 for a load duration of one day. The relationship between the standard cylinder and the structural strength is thus (0.7 f_c'+2.8) MPa.

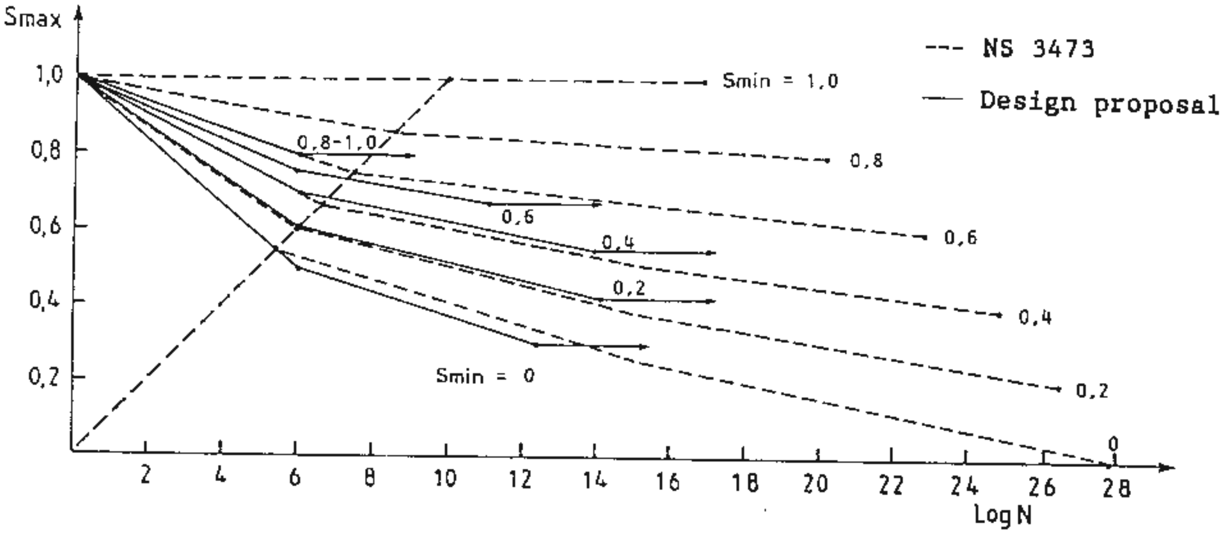


Fig 15. Comparison of the S-N diagram according to this proposal with that of NS 3473 by the use of C_1=12

The partial coefficient γ_m for reinforced concrete in ULS is 1.4 in NS 3473. There is, however, no reason for justification of a lower partial coefficient for fatigue than for static loading. Both the safety connected to the characteristic values and the consequences of failure are the same in the two situations. Hence the only difference between static and fatigue loading that can be considered are the time and duration of loading.

The probability for the occurrence of heavy cyclic loads at a early age is relatively small, and each cycle of exposure must be looked upon as a short term load. This implies that it is reasonable to use the strength at an age beyond 28 days as reference for fatigue calculations. If the six-month strength is used, an increase of the standard 28 days strength with about 10 percent might be representative for most of the concrete qualities. The design reference strength for fatigue design of concrete, corresponding to S_{max}=1.0 in the S-N diagram, would then be (0.57 f_c'+2.1) MPa.

4. CONCLUSIONS

The results of the constant amplitude tests showed no reason for distinguishing between the fatigue properties of ND65, ND95 and LWA75 in design rules, when the load levels are expressed relatively to the static reference strength of the concretes.

The experimentally obtained S-N lines showed that $S_{max}=1.0$ corresponding to the static strength of the test specimens is a reasonable assumption.

Regression lines through $S_{max}=1.0$ in the S-N diagram indicated an almost linear relationship between the minimum stress level and the logarithm of the number of cycles to failure for the tested range of S_{min} between 0.05 and 0.60.

The fatigue life of concrete is limited for all stress combinations when S_{max} is higher than the long term strength of concrete.

The real S-N relationship for concrete in compression definitely has a curved progression. However, at the present level of knowledge and as a simplification, an approximate stepwise linear relationship has been proposed.

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