Discussion on a paper published in the

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Some fatigue tests of high-strength concrete in axial compression*

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Contribution by Professor John A. Neal, PhD

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The authors are to be commended for a research effort which was obviously carried out with considerable care. The lack of scatter in the data presented in the *S–N* diagram is particularly impressive, although it would be even more so if the width of the confidence band at, say, 95% had been indicated.

It is very encouraging to see this verification of our conclusion(1) presented in 1965 that the fatigue strength of plain concrete, expressed as a percentage of the static ultimate strength, is invariant and is the same for both axial and flexural fatigue. The authors have presented data for one million cycles which yield a fatigue strength for both strengths of concrete (corrected by the Goodman relation) of 60% of static strength, which correlates very well with the results just mentioned(1). The fact that the permanent strain increased throughout the test can be explained by summing two effects, the creep of the concrete under the action of the mean stress and the progressive damage of the concrete due to increasing microcracking in the material. This is supported by the fact that some of this permanent strain is recoverable, just as part of the creep of plain concrete is recoverable.

One truly remarkable result presented by the authors, albeit indirectly, is that the rest periods (during which static stress-strain characteristics were measured) did not increase the fatigue strength of the concrete. For, if there had been such an influence, the authors' results would not have supported those of Neal and Kesler which represented tests with no rest periods. This is in direct contradiction with results for lower-strength concretes(2) and would appear to be an area where further research would be valuable.

* Pages 113–117 of *Magazine* No. 59.

Contribution by G. P. Saha, MSc, PhD

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In their conclusion the authors have stated that "The fatigue strength after one million repetitions varied between 66 and 71% of the static strength". They have drawn the *S–N* curve in Figure 1 showing the regression line of *S* upon *N* calculated for those tests which terminated in fatigue failure. This Figure shows that the failure took place in the specimens which were subjected to a maximum load greater than 70% of the ultimate, and the number of cycles endured was up to 10^5 cycles. From 10^6 cycles onwards, none of the test specimens appears to have failed in fatigue. On the contrary, instead of progressive damage, eleven of the 'run-out' specimens were reported to have an increase in strength from 1 to 23% compared with their non-fatigued companions, and these specimens were subjected to a maximum load of below 70% of the ultimate. If the modified Goodman diagram shown indicates the fatigue strength which is the strength for any predetermined number of cycles of load, it is not clear to the writer how the authors have concluded that the fatigue strength at 10^6 cycles is 66 to 71% of the ultimate. They have also stated that "In common with other results for concrete there is no indication of fatigue limit at less than ten million repetitions". This is also not clear to the writer when, instead of progressive damage, increase of strength of the concrete took place with a maximum load of less than 70% of the ultimate in this particular test series.

Probst may be quoted who, after an extensive investigation concluded: "There exists a critical stress for concrete in compression and tension. Loadings below this stress strengthen the material..."[3, p. 428] He also stated that: "This critical stress is about 47 to 60 per cent of the ultimate static strength, and is identical with an endurance limit for an indefinite number of cycles of stresses"[3, p. 421] The minimum stress in his tests was about 5%. This critical stress most probably is dependent upon the fatigue load range, i.e. upon the values of maximum and minimum stress. However, when in the authors' tests the specimens with the maximum stress of less than 70% of the ultimate did not show a decrease of strength, can it not be said that they reached an endurance limit for an indefinite number of cycles of repetitions and that the neutral equilibrium was reached in some zone between 10^5 and 10^6 cycles?

Contribution by D. A. Stewart

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This research has brought out some interesting points in regard to high-strength mixes, quite apart from those directly associated with the research project, but which may have some bearing upon the interpretation of the results.

The value of this work would be increased if the authors had specified the two mixes used more precisely: for instance, whether the ratios mentioned are by weight or volume. The gradings of the combined aggregates must be of interest to any concrete technologist and the particulars of their shape and surface texture. Evidently there was no attempt to design either mix to possess specific qualities and no mention is made of any variation in the workability of the mixes resulting from changing the maximum size of aggregate from ¾ to ⅜ in.

For instance, provided the water/cement ratio law holds good, it might be expected that, for particular mix proportions and water/cement ratio, the concretes would have very similar strengths. In fact, the concretes having the smaller maximum size aggregate produce the greater compressive strength at both water/cement ratios (0·35 and 0·5). It therefore seems that, by increasing the specific surface and/or reducing the workability of the concrete, the efficiency of the cement can be improved or the mortar-aggregate bond increased. On the other hand, if the aggregates used in this research were oven-dried, one would expect the concrete made with the smaller coarse aggregate to absorb a larger volume of water than that made with the ¾ in. material; purely on the basis of the total absorption surface available, the effective water/cement ratio of the finer mix would be less than stated, giving a logical explanation of this concrete's higher strength.

Referring to the 'run-out' specimens, it is very obvious that the performance of the coarser concrete is very much superior to that of the ⅜ in. concrete, as is indicated by the fact that twelve ¾ in. specimens as against three ⅜ in. specimens, a 4:1 ratio, withstood 10^6 or more load variations.

In Figure 3 there is evidence that the leaner coarser concrete has a noticeably better performance than the two richer concretes. Since one of these richer concretes is also in the larger coarse aggregate group, it is suggested that the difference in performance between the 1:1:2 ¾ in. and 1:2:4 ¾ in. concretes is the total water content per unit volume. For the purpose of establishing that the 1:1:2 mix with the 0·35 water/cement ratio has the greater absolute volume of water, the mixes will be assumed to be by weight. The cement contents will be approximately as follows.

Mix	Cement content (lb/yd³)	Water/ cement ratio	Water content (lb/yd³)	Yield
1:1:2	900	0·35	315 lb	5·0 ft³
1:2:4	550	0·50	275 lb	4·4 ft³

This suggests that, as the volume of cement paste is decreased in a concrete, its physical properties will be dictated more and more by the properties of the aggregates of which it is formed.

Finally, we have an interesting comparison of the relationship between the strength and the cement content of the two concretes based upon the compressive strength of the 4 in. cubes.

Aggregate	Strength (lb/in²)		Cement content (lb per 4 in. cube)	Strength / Cement content	
	1:1:2	1:2:4		1:1:2	1:2:4
⅜ in.	11,155	8,460	1·230	9,050	6,880
¾ in.	9,825	7,800	0·755	13,000	10,300

This calculation demonstrates rather effectively the economic advantage of the leaner mixes.

Reply by the authors

The authors thank Professor Neal, Dr Saha and Mr Stewart for their contributions. They strongly agree with Professor Neal that further research into the effect of rest periods is necessary, for one cannot be at all certain whether the comparatively short interruptions made to enable a static loading cycle to be performed had a significant effect upon the fatigue strength, especially when compared with results obtained elsewhere.

The fatigue strengths given in Table 2 of the paper were calculated for each set of results from the regression line of S upon N at 10^6 repetitions, this duration of loading being entirely arbitrary. Dr Saha suggests that the results support a true fatigue limit ($N = \infty$) of just below 70% of the static strength, reached at between 10^5 and 10^6 repetitions, but the authors are unable to accept either of the two grounds given for such a conclusion. First, although only one fatigue failure occurred at above 10^5 repetitions, this result ($1{\cdot}35 \times 10^6$, 0·65), which unfortunately does not show clearly in Figure 1, lies on the regression line for all the results. The 'run-out' tests are by their nature indecisive and cannot be held to conflict with the given relationship, if regard is paid to the amount of scatter which is normal in these tests. On the other hand, tests carried out since the early work of Probst have all failed to establish a fatigue limit below 10^7 repetitions.[4]

The second reason concerns the enhanced static strength of the 'run-out' specimens. Here Dr Saha appears to have misread the paper by Probst,[3] for it is made clear in the discussion that the term 'strengthening' was used to denote an increase in the modulus of elasticity, which should more correctly have been described as 'stiffening'. Although repeated loading does cause some increase in the static strength, the reasons are not yet fully understood and there is no evidence that it does not occur above the fatigue limit or that it is governed by the same factors as fatigue damage. We are not justified in regarding this increase of static strength and cumulative fatigue damage as mutually exclusive phenomena.

It is difficult to answer all Mr Stewart's questions in detail, because he is trying to use the results for a different purpose from that of the authors in planning the programme. It can be stated, however, that the proportions given were measured by weight using saturated surface-dry materials, and that typical gradings of Finningley sand and gravel taken from our laboratory records at that period were as follows.

B.S. sieve size	Percentage passing		
	Sand	$\frac{3}{8}$ in. gravel	$\frac{3}{4}$ in. gravel
No. 200	1		
No. 100	5		
No. 52	45		
No. 25	80		
No. 14	88		
No. 7	95	0	
$\frac{3}{16}$ in.		32	0
$\frac{1}{4}$ in.		74	—
$\frac{3}{8}$ in.		100	20
$\frac{3}{4}$ in.			100

Some further information about this aggregate is given in two papers[5,6] where the $\frac{3}{4}$ in. coarse aggregate is described as "Gravel A" and the sand as "Fine aggregate A". Included in the data for the former are: flakiness index 19·4, voids ratio 38·4%, specific surface (oil permeameter) 22 cm²/g, and for the latter: voids ratio 52%, specific surface (water permeameter) 43·5 cm²/g.

The work of Walker and Bloem[7] clearly demonstrates the greater strength of concrete with smaller maximum aggregate size, particularly at low water/cement ratios, and the reason may well lie in the improved mortar-aggregate bond, as Mr Stewart suggests. Although our results show the same trend, it should be noted that our static tests were not all carried out at exactly the same age.

No significance can be attached to the greater number of run-out tests with coarse aggregate, because eight of these were loaded at a ratio S_{max}/S_u of less than 0·65, for which failure would not be expected to occur at less than about $1{\cdot}5 \times 10^6$ repetitions. We attribute the lower strains of the leaner concrete to the stiffening effect of a greater proportion of aggregate, which has been shown in earlier tests to increase the static and dynamic modulus of elasticity[5] as is to be expected since the modulus of elasticity of the aggregate is normally much greater than that of neat cement paste or cement-sand mortar. The work of Hansen[8,9] is also of interest here. We are therefore in general agreement with Mr Stewart but would maintain that it is the relative volumes of the aggregate and matrix rather than the water content in itself that is important.

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