FRACTURE MECHANISM OF CONCRETE UNDER CYCLIC LOADS AND TEST METHOD OF FAILURE PROCESSES

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ABSTRACT

A test method based on the assessment of the volumetric changes of concrete subjected to load is presented and conclusions are drawn regarding the failure process of concrete. By the adaptation of the method the process of defect formation in concrete under cyclic loads can be described.

KEYWORDS

Concrete; cyclic load; failure process; test method; volumetric changes.

INTRODUCTION

The development of technology in the building industry has brought about an increase in the magnitude and frequency of occurrence of cyclic loads acting on load-bearing structures. With this the failure hazard of structures also increases. To be able to maintain the probability of failure on a planned level, the basic requirement is to gain a deeper insight into the reasons for and the mechanism of failure.

CHARACTER OF THE STRUCTURE OF CONCRETE

The properties and failure mechanism of concrete are fundamentally influenced by the inhomogeneity of its structure. To study the processes taking place in the structure of concrete it is feasible to distinguish between the various levels of the structure, depending on the "depth" of the investigation. In conformity with these levels we may speak of the macro-, micro- and molecular structure of concrete.

The macrostructure of concrete consists of two basic structural components:

1) the mortar phase filling the available space quasi-continuously, and

2) the coarse aggregate phase dispersed in the mortar phase.

The entity of the two fundamental phases integrated into a system is called macrostructure.

FAILURE PROCESS OF THE STRUCTURE OF CONCRETE

The results of a number of previous investigations (1, 2, 3, 4, 5) have shown that the failure of concrete takes place fundamentally on macrostructural level. Therefore the investigation of the mechanical failure of concrete can be restricted to showing that the bond between the two fundamental phases of the macrostructure and/or the continuity within each phase no longer exist. The changes in the macrostructure manifest themselves in the relation between the closing tendency due to loading of the various cavities to be found in concrete even in the unloaded state (gaps developing during the placing of concrete, shrinkage and thermal dilation cracks, etc.) on the one hand, and the opening and growing tendency of the mentioned cavities and other types of cracks, on the other. Consequently, the process of the phenomenon, i.e. the mechanism of failure can be well described by the volumetric changes of cavities in the concrete specimen.

According to the laws of elasticity, the volume of the concrete specimen is reduced in proportion to stress, if a uniformly distributed axial pressure is assumed. Linearity is not influenced by the rheological properties of concrete or by the progress of the loading process in time, as, theoretically, the volume of the specimen is not changed by the viscous and plastic deformations occurring in the course of loading. Therefore, any deviation from linearity may be ascribed to one reason only: the volumetric change of cavities inside the concrete specimen.

The phenomenon and its individual components are illustrated in Fig. 1. Fig. 1c shows the variation of the specific volumetric change of a concrete specimen loaded to failure by axial pressure, as a function of loading rate. Figs. 1a and 1b show the variation ot the two components of total volumetric change: elastic volumetric change and the volumetric change of cavities. The dashed lines in Fig. 1b show the variation of volume reduction due to the closing of part of the cavities and that of volume expansion due to the opening of other cavities and the appearance of new ones, respectively. The resultant of the two opposite tendencies is the actual volumetric change of the cavities.

It can be seen in the Figure that in the initial stage of the loading process the volume of cavities is reduced continuously, the concrete specimen is being compacted. The inflexion point marked by 1 indicates the boundary value of the rate of the volumetric change of cavities. The fact that the rate of compaction tendency stagnates, in spite of the fact that with the increase of loading rate the volume of cavities is reduced further, indicates that the appearance of new cracks becomes predominant. The volume of cavities is the smallest at point 2. From that point the volume of cavities starts to expand abruptly. At point 4 the volume of cavities attains a value corresponding to the initial stage, while at point 3 the volume of the concrete specimen is the smallest. At this level of loading the macrostructure is already in a heavily cracked, spalled state, a stage directly preceding the failure of the concrete specimen. In some cases a volumetric change equal to (point 5) or greater (point 6) than that in the unloaded state can be attained.

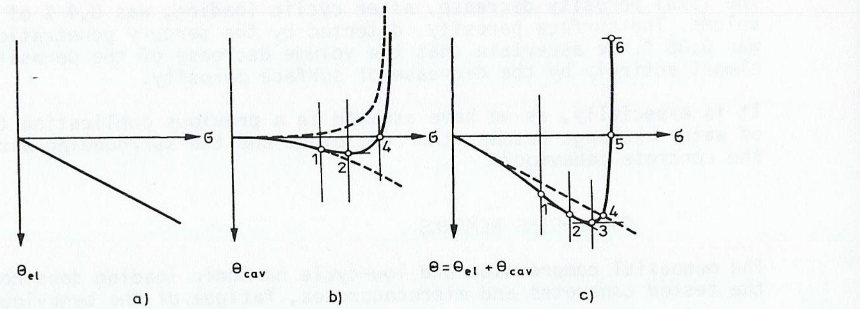

Fig. 1

If a concrete specimen is loaded and subsequently load is removed, the change in the volume of cavities in the unloaded state can be regarded as the measure of macrostructural changes (defects) occurring in the concrete specimen.

TEST METHOD OF DETERMINE THE FAILURE PROCESS

To determine the residual changes of the volume of cavities in a concrete specimen under compression the author has developed the following test method:

The concrete specimen is to be loaded to failure, by applying several (in practice approx. 20) identical load increments. Having reached each particular load level, the volumetric change of the specimen as compared to the initial stage is to be assessed. Then load is to be removed in each case. (For technical reasons the value of load should not be decreased to zero, but only to a value approaching it, e.g. to the first level of loading.) The volumetric change of the test specimen should be measured in the unloaded state as well. The resulting value gives the residual volumetric change of cavities.

Assigning to each load level the value of residual volumetric change assessed during the removal of load subsequent to that level and representing it on a graph, the result is a highly illustrative picture characteristic of the changes taking place in the strucure of the specimen. The latter procedure is demonstrated in Fig. 2a, based on the results of a test actually undertaken. Fig. 2b shows the total measurable volumetric changes and the elastic volumetric changes assessed with the aid of residual volumetric changes pertaining to the lower load values of the concrete specimen.

The volumetric changes can be assessed by various measuring methods. In the experiment carried out by the author strain gauges were applied in parallel with and perpendicularly to the direction of force and the values of volumetric changes were calculated from the values of deformations measured on the surface of the specimens.

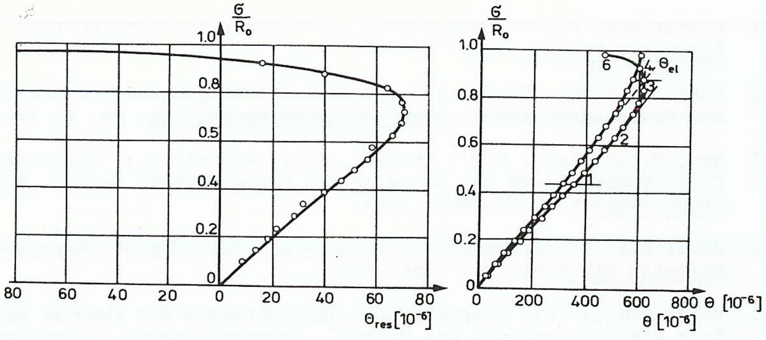

Fig. 2

EXPERIMENTAL METHOD TO STUDY FAILURE DUE TO CYCLIC LOADING

In spite of the fact that a considerable amount of literature is available on the research and testing of the fatigue strength of compressed concrete, practically no information can be found on the pre-failure behaviour of concrete, subjected to cyclic loads, that is on the character and mechanism of the fatigue process.

On the analogy of concrete testing to failure due to short-time loading the author has worked out an experimental method to study the process of failure due to cyclic loading. The main feature of the method is that the specific volumetric changes of the concrete specimen are to be assessed at identical points of each loading cycle (feasibly at points pertaining to the σ_{min} or σ_{max} values) by measuring the surface deformations. From the variation of volumetric changes as function of the cycle number conclusions can be drawn regarding the state and the changes in the state of the macrostructure.

Under cyclic loading the volume of concrete is generally reduced at the beginning (compaction of structure), later it expands (spalling of structure), and fatigue failure occurs when a volume much greater than that of the unloaded state (considerably exceeding even the volume observed in failure due to short-time loading) is attained that is when the specimen is in a heavily cracked state. The beginning of intensive spalling can be given by the number of load cycles pertaining to the maximum of volumetric change, which number can thus be regarded as a characteristic value of the fatigue process.

INVESTIGATIONS

By applying the experimental method the author has carried out permanent cycle fatigue tests on concrete prisms. The minimum of cyclic load has always been a value approximate to zero, while its maximum varied between values corresponding to 43 and 93 % ot the strength determined by short-time

loading. The variation of volumetric changes pertaining to maximum load as a function of cycle number is presented in Fig. 3 on the basis of test results.

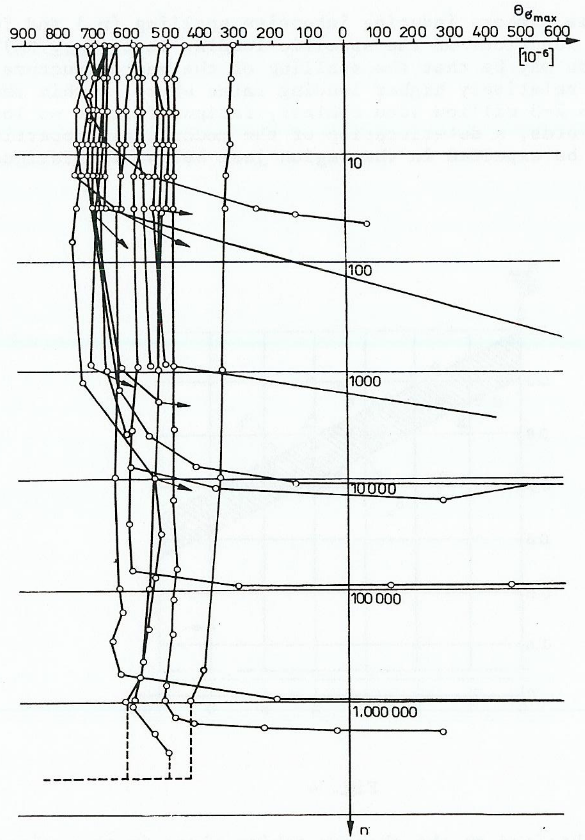

Fig. 3

RESULTS

A linear relation has been established between the logarithms of the cycle number (n_s) indicating the beginning of intensive spalling and of the cycle number producing failure (n_f) ($\lg n_s = \lg n_f - 1.99$). The relation shows that intensive spalling starts already about the first one hundredth of the full lifetime.

Plotting the cycle numbers inducing intensive spalling (n_s) and failure (n_f), respectively, as functions of the specific loading rate (σ_{max}/R_o) (Fig. 4) a further conclusion may be that the spalling of the macrostructure also starts in the region of relatively higher loading rates where, within the framework of testing (up to 2-3 million load cycles), fatigue failure no longer takes place. In other words, a deterioration of the mechanical properties of concrete is also to be expected in the region just below the fatigue limit.

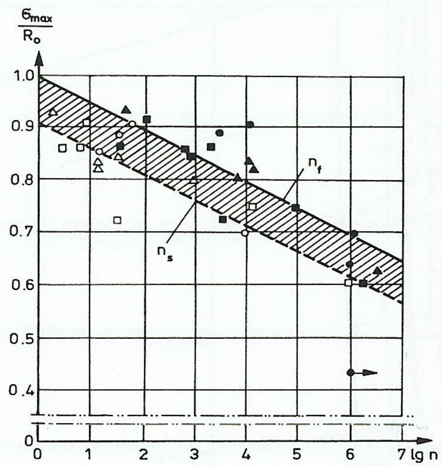

Fig. 4

The information obtained on the changes taking place in the macrostructure of concrete owing to cyclic loads makes it possible to find a theoretical explanation for the controversies in the experimental results on concrete specimens subjected to fatigue tests (e.g. for the time-dependent variation of the Poisson ratio). At the same time the test results may provide a basis for developing an in situ method to detect material defects in concrete and reinforced concrete structures under cyclic loads.

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